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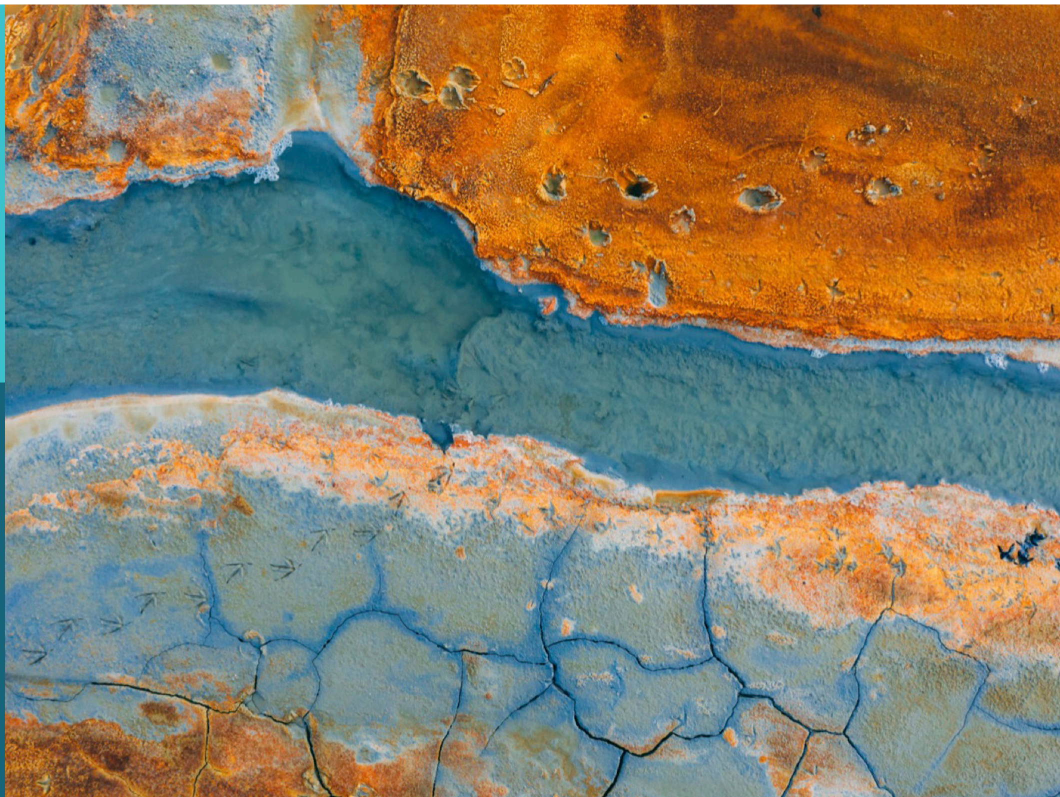

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Water security and sustainable development in an uncertain world

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Infrastructural Violence: Five Axes of Inequities in Water Supply in Delhi, India

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Inequity is deeply embedded in the supply of drinking water in Delhi, India. Using the concept of infrastructural violence, this paper exposes how past and present governance of water has resulted in unequal distribution of supply across the city to exclude vulnerable communities from accessing drinking water. This perspective broadens the gaze away from a narrow gaze on the technical and structural aspects of infrastructure to encompass the socio-political dimensions. This paper starts by outlining the history of the water supply in Delhi. We then outline five axes of exclusion which can be read as infrastructural violence and explores how aspects of water policy, legislation, and planning uphold these injustices. Our discussion centers on how economics, political ideology, and power infiltrate governing mechanisms to influence water infrastructure to entrench poverty and marginalization. Attempts to improve water security for Delhi's residents face minimal impact without addressing these embedded inequities. Therefore, our analysis offers a framework to systematically create awareness of the factors to be addressed to enable a more equitable governance of water supply.

Keywords: infrastructural violence, active infrastructural violence, passive infrastructural violence, water inequities, five axes of exclusions

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INTRODUCTION

The city of Delhi in India has undergone extensive transformations over the recent decades. The roots of this change are embedded in the drive for liberalization since the early 1990s, which stimulated infrastructural planning to establish Delhi as a global city and as a world leader on the international stage (Dupont, 2011; Ghertner, 2015; Baviskar, 2020). Actions to achieve this status are epitomized by the hosting of the Commonwealth Games in 2010, where the authorities used this event as a "catalyst for urban change" and an opportunity to showcase global ambitions of making the city "world class." Throughout this period and, particularly in a more recent on-going restructuring of the urban landscape, analysis suggests that the socio-economic realities which underpin this drive for urban change, and the nefarious routes taken to achieve this vision has resulted in the marginalization and displacement of the urban poor (Dupont, 2008; Bhan and Shivanand, 2013; Bhan, 2016).

India implemented Liberalization, Privatization, and Globalization (LPG) reforms in 1991 which opened up various sectors, including water utilities, for global private companies. As a consequence, the state passed responsibility for the delivery of basic water and sanitation services to private companies whose primary aim was to maximize their profits. This new water discourse was further bolstered by the Ministry of Water Resources (2002) encouraged public-private partnerships in "planning, development, and management of water projects for diverse uses, wherever feasible"

(Ministry of Water Resources, Government of India, 2012). A secret attempt was made to privatize the Delhi Jal Board (DJB), the state institution delegated with the responsibility of water supply and sanitation provisioning, just its establishment in 1998. During the same period, Sonia Vihar Water Treatment Plant whose construction, operation and management were awarded by the DJB to global water giant Ondeo Degremont exacerbated water inequity in parts of the city as initially it was decided that Delhi's new supply from Sonia Vihar will go to the richer South Delhi areas, and not to poor neighborhoods (Shiva, 2006). Water from Sonia Vihar WTP is supplied round the clock, and is meant for residents of DJB's South zones II and III, which comprises more advantaged residents.

This period witnessed the development agenda shift from welfare-oriented policy regimes to market-led policies; cities transforming themselves, rhetorically at least, to hubs of economic creation, urbanization, and industrialization. Due to the negligible return from agricultural activities and the negative connotations of them being viewed as "backward" occupations (Bentinck, 2000, p. 100); there has been a structural economic transformation, with people moving from agriculture to the service sector. Moreover, increasing wealth and income inequality have shifted the social narrative of poverty (Fernandes, 2006). Now slum dwellers are not suffering from poverty but are deemed a nuisance. They do not fit in with global aspirations, their lived reality, if not erased, is hidden. This was evidenced by the "*Pushta* settlement evictions" before the 2010 Commonwealth Games, when slum dwellers were hidden from view by bamboo screens (Baviskar, 2019). Intolerance to poverty is now within the moral and ethical compass. Moreover, justifications for evictions of the poor used by the state, police and press, frames the evicted as foreigners. During the *Pushta* demolition, residents were repeatedly referred to as Bangladeshi and Pakistani (Adve, 2004).

There is a frustration seen among the middle class against the welfare programs provided to the weaker sections of the society (Chaplin, 2011, p. 66). This change has made it possible to *villainizing* slum dwellers and paved the path for their evictions and relocation. This can be seen in the narrative of the state, the judiciary, the media, and the middle-class population leading up to the Commonwealth Games (Ghertner, 2015). Many infrastructure policies were launched by the government in the wake of the Commonwealth Games. These were supported by moralizing, modernizing, and cleanup policies (Baviskar, 2019, p. 89). If the urban poor came in the way of implementation of these policies, they were to be set aside. The building of the Delhi Metro (underground and overground public transport) and Akshardham Temple are recent notable examples. Redevelopment of slum lands is another illustration of restructuring and modernizing the city. This type of transformative development of the city displaces the poor and embeds inequality (Kumar, 2020; also see Kumar et al., 2021).

Evidence suggests that displacements and evictions of low-income families are the visible spatial manifestations of inequitable urbanization in India. Over-riding reasons for displacements and evictions in Indian cities are clashes and conflicts between the needs of the urban poor and the aspirational classes (Baviskar, 2019). Moreover, while the middle class meets its demand through unauthorized colonies, which in time are legitimized and recognized by the government, whereas the unauthorized residents of slums are more likely to be evicted. Roy (2011, p. 259) refers to this as the "expansion of the urban frontier, a making way and making space for the new Indian middle class, through the smashing of the homes and livelihoods of the urban poor," a theme also explored by Watson (2009) and Bentinck (2000).

This paper proposes that the concept of infrastructural violence allows us to make sense of the processes which drive and underpin inequalities in water access in Delhi.

Infrastructural violence questions the perceived material and technical innocuousness of infrastructure, whilst highlighting infrastructure's ability to create and shape deep inequalities within urban environments. We then turn our focus onto the domestic water supply in Delhi and outline how the city's colonial legacy has shaped infrastructural inequality and exclusion in contemporary Delhi. Within this context we identify five axes of inequality and exclusion which drive infrastructural inequality and then finally, we consider how these axes shape water infrastructural violence in Delhi and set out the challenges that need to be addressed to enable a more just and equitable future.

INFRASTRUCTURAL VIOLENCE IN THE "WORLD CLASS CITY"

Official disregard for the urban poor is fundamentally illustrated by inequitable access to basic services and the planning, governance, and decision-making processes that sit behind infrastructure provision. These decision-making processes are embedded across multiple layers of governments, agencies, and actors in a way that impedes accountability to the public and obscures the responsibility of the state. Rodgers and O'Neill (2012) refer to this phenomenon as "infrastructural violence" derived from the concepts of "infrastructural power" by Mann (1984) emphasizing institutional regulation of society by elites. Infrastructural violence also links up with "infrastructural warfare" coined by Graham (2004, 2006, 2010) producing infrastructure provision that induces human suffering (Rodgers and O'Neill, 2012, p. 403).

The concept of infrastructural violence shifts our perceptions from the conventional understanding of infrastructure as material and technical urban systems to infrastructure as socio-technical regimes. So, infrastructural violence occurs when residents are either excluded from essential infrastructures such as water or sanitation services by acts of displacement or inadequate infrastructure provisioning. Both denial and exclusion cause human suffering. Infrastructural violence also takes place through "articulations of infrastructure that are designed to be violent" (Rodgers and O'Neill, 2012, p. 402). Renu Desai explains that infrastructure is designed to be violent by "the ways in which urban planning, policies and governance forge infrastructure that produces … inadequacies and everyday deprivations, burdens, inequities, tensions and conflicts in residents' lives" (Desai, 2018, p. 89).

Rodgers and O'Neill (2012) identify two types of infrastructural violence: active and passive. When infrastructure is intentionally designed to be violent, it is active, for instance, the building of elite infrastructure such as a promenade for sportspersons during the 2010 Commonwealth Games in Delhi after the demolition of slums. Passive infrastructural violence refers to the "socially harmful effects derived from infrastructure's limitations and omissions." For example, people are being excluded from infrastructure networks. Truelove and O'Reilly (2020, p. 5) further highlight the role of infrastructure as a force that shapes social experiences and subjectivities, bringing into focus the distinct position it has in mediating relations between humans and their environment through the maintenance of, for example, regulatory standards, corporate interests, social expectations, and historical legacies of organization and supply (Amin, 2014, p. 138).

Viewing infrastructure provision in this way highlights the agency, power relations, and ideologies which sit behind decision making and resourcing. In addition it draws attention to uneven rights, application of regulations and distribution of infrastructure; not only in the present but also as legacies from the past where historical decisions collide with future aspirations to produce and reproduce inequalities (Rodgers and O'Neill, 2012; Truelove and O'Reilly, 2020). Inequalities are further entrenched through the socio-spatial decisions of infrastructure providers, the rules of supply and tariffs, and the gulf of access between geographical areas and demographic groups. Truelove and O'Reilly (2020) probe further into these structural injustices through the theme "infrastructural intersectionality" which explores how the intersections of social identities such as gender, class, caste, and power relations are further preserved or exacerbated through infrastructures. This is illustrated in Delhi by the development of the Delhi Metro, Akshardham Temple, and the Commonwealth Games, where the intersectionality of power, caste, religion, and class saw the clearing of poor settlements and slums to make way for the aesthetics and needs of the middle class. On similar lines, Sims' (2021) fieldwork in Laos shows that large infrastructure projects frequently manifest in infrastructural violence for more disadvantaged populations.

Infrastructural violence in Delhi is by no means isolated to these large, impactful showcase developments but also extends to other (essential) infrastructural systems. In this paper, we explore the extent to which this form of violence is inherent within the supply of drinking water. Access to drinking water in Delhi is deeply inequitable across all of its approximately 20 million inhabitants. An estimated half of these residents are not connected to the centralized water network and have to rely on other means such as tankers, private taps, tube wells, and standpoints. Shortages of water are common in many areas of the city. Many who are connected generally have water only for 2–4 h a day, whereas some neighborhoods have 24-h access (Truelove, 2019).

So, why do these inequities exist and why do they persist? This is the question that underpins this paper. Here, we seek to understand the actions and decisions which produce discriminatory governance of the drinking water supply for the urban poor. Through a historical and structured analysis, we aim to make a contribution to the theme of infrastructural violence by providing examples of how the relationships of hierarchy and power manifest to create inequitable access.

We initially outline the context of demographic marginalization in Delhi and how this relates to the water supply. We then briefly turn to the history of water supply to marginalized communities in Delhi to provide context as to how inequity in the present-day system has become embedded. This then frames five axes of exclusion relating to aspects of water policy, legislation, and planning which continue to reproduce water injustices. Our discussion centers on how economics, political ideology, and power infiltrate governing mechanisms to influence water infrastructure to entrench inequitable access to services through forms of infrastructural violence.

WATER ACCESS AND MARGINALIZATION IN DELHI

Many of Delhi's residents live in slums or unauthorized residential developments with high levels of deprivation, with sub-standard accommodation and residents struggling to access basic amenities like water and sanitation. The development of Delhi as a world-class city has resulted in a mass influx of poor migrants seeking employment whilst their cheap labor sustained the "modernization" of the city (Biswas, 2020). It is estimated that there are 450 million informal sector workers in India, nearly 90% of the entire workforce. The total number of workers in Delhi was 5,587,000 as per the Census of India 2011 (Government of the National Capital Territory of Delhi, 2019, p. 89). Based on the assumption that 90% of the working population is engaged in the informal sector, the number of informal sector workers might be in the region of 5,028,300. Informal workers are vulnerable, characterized by low wages. They often lack medical insurance (Bora, 2014), access to adequate housing and infrastructure, and have limited collective bargaining capacity (Baviskar, 2019).

Current urban policies have perpetuated displacements and evictions, and consequently continued to push the poor toward the physical and societal periphery. Evictions of slums and squatters from the city to its margins could be treated as the domination of urban space by the elite; when evicted spaces are rendered out of reach of the urban poor, owing to new land uses such as malls and entertainment plazas. Geographical distance from employment opportunities marginalizes the poor by making access to these places potentially expensive for travel. Long shifts make it impossible for the workers to travel from the outskirts of the city to work. Moreover, there are no formal residential areas planned for these workers near construction sites and factories. As a result, they have little option other than to build homes near their work areas. Here, exploitation in the form of loss of livelihoods and domination in the form of evictions from the city to the margins are not only socially and spatially manifested, but also socially and spatially produced and reproduced (Speak, 2012).

Most of these informal urban dwellers live in 6–10 m^2 huts in slums, where water is accessed through public taps, tankers, and tube wells. According to the Comptroller and Auditor General

TABLE 1 | Daily water supplied and population served through tankers in the DJB's administrative divisions.

S. No.	Division	Quantum of water supplied in Million Gallons (MG)			Population ('000)			Per capita water availability per day in liters (L)		
		2009–10	2010–11	2011–12	2009–10	2010–11	2011–12	2009–10	2010–11	2011–12
1.	Central II	10.64	15.54	21.51	45	45	45	2.94	4.3	5.95
2.	North West I	131.4	131.4	146	425	450	475	3.85	3.63	3.82
3.	North West II	200.29	165.27	171.72	99.65	82.23	85.44	25	25	25
4.	North West III	5.07	5.27	5.71	50	50	50	1.26	1.31	1.42
5.	North East I	51.82	48.97	48.15	98	95	90	6.58	6.41	6.65
6.	North East II	49.52	51.41	53.56	56	60	62	11	10.66	10.75
7.	North East III	14.85	13.55	12.22	100	100	100	1.85	1.69	1.52
8.	East I	15.41	15.45	15.41	66	66	66	2.9	2.91	2.9
9.	East II	10.78	9.8	10.08	52.4	52.4	52.4	2.56	2.33	2.39
10.	South I	70.44	60.19	80.79	310	310	310	2.83	2.42	3.24
11.	South III	36.84	46.74	50.36	676	676	676	0.68	0.86	0.93
12.	South IV	130	130	130	500	500	500	3.23	3.23	3.23
13.	South West I	90	90	100	270	270	27	4.15	4.15	46.07
14.	West III	106.93	106.93	106.93	215	215	215	6.19	6.19	6.19
15.	North	3.5	46	48.5	400	450	500	0.11	1.27	1.21
Total		927.49	936.52	1000.94	3363.05	3421.63	3253.84	3.42	3.4	3.82

Source: *Comptroller and Auditor General of India (2013).*

of India (2013) report, during 2011–12 period 24.8% of the households in Delhi were not connected to the DJB's water supply network. A majority of these households were part of the unauthorized colonies and Jhuggi Jhopari clusters situated on the periphery of the city. In the absence of formal water supply infrastructure, water was being supplied through water tankers and just 1,000.94 Million Gallon (MG) of water was supplied for the whole year at the rate of 3.82 liters per capita per day (LPCD) against the official norm of 172 LPCD (Comptroller and Auditor General of India, 2013). **Table 1** shows the quantum of water supplied to around 3,300,000 people living is various parts of Delhi out of which around 2,553,000 people were living in informal settlements. This large portion of Delhi's population was relying on the provision of water through tankers in absence of access to the centralized piped water supply system.

In extreme peripheral areas, residents are forced to buy expensive bottled water from the private vendors, who buy water from the DJB. Community toilets, if provided by the government, generally do not work because the water for flushing is provided only for few hours. Over a period of time, these community toilets become dysfunctional and people have to resort to open defecation. Census of India 2011 has reported that Delhi's 10% (2 million people) population openly defecates. Results of the 76th NSO survey conducted between July and December 2018 showed that 0.5% of Delhi's population have no access to toilets and 4.8% population uses community toilets with payment. Since most community toilets do not work, in Delhi, 5.1% population (867,000) has no option but to defecate in the open (NSO, 2018, p. 99).

Moreover, after centuries of caste-based discrimination, the lower castes have higher levels of poverty. Even if people have the same economic status, it has been reported that due to exclusion, the lower castes will still have lesser water and sanitation facilities (Kumar, 2014, p. 129). As a result, caste plays a prominent role in infrastructure fragmentation. Despite the important role these workers played in the development of Delhi, they are not treated as full citizens, with the state viewing these communities as on the margins of economic and social class. This is done by creating an exclusionary citizenship narrative where the upper-middle-class refers to themselves as "lawful citizens of Delhi" (Bhan, 2016). This marks the rest as unlawful and non-citizens, targeting them and stripping them of their rights. A manifestation of this view can be seen when it comes to the city's approach in supplying drinking water (Biswas, 2020). We first examine the colonial roots of present day inequalities.

Colonial Legacy of Infrastructural Exclusion

Divisions within communities and access to water are not a recent phenomenon and can be traced back to the Mughal times in the sixteenth century. Delhi, the new capital city of the British Empire was built in the first half of the twentieth century. The city was built based on the modernist principles of order and functionality. However, surveillance, discipline, and control of the locals was also a prime motivation (Gooptu, 2001, p. 71). Piped water and sanitation services were provided to all ruling classes living in the white town, the Lutyens Delhi, named after Edwin Lutyens, designer and planner of the city.

In contrast, from the twelveth to nineteenth century, residents of Old Delhi predominantly relied on *Baoli* (a tank with steps on four sides leading down to the water), neighborhood wells, individual household wells, canals, and rivers. There were 607 wells in Delhi during the Mughal times. Due to the decentralized system, locals had various ways of accessing water such as by using the Persian wheel, a mechanical device used for lifting water where the wheel is pulled by animals like bullocks, buffaloes, or camels. Water was distributed locally in leather bags (Hardiman, 2002, p. 112). Class differentiation existed during the Mughal times. Poor residents took water from rivers and canals while the rich had dug wells in their houses and neighborhoods (Hosagrahar, 2010, p. 114–116). Thus, the lower castes had to rely on the upper castes. Moreover, this decentralized system was not supported by the kings and could be disrupted by them. For example, Sultan Alauddin Khilji forbade devotees to dig a *baoli* at Sufi saint Nizamuddin Auliya's shrine (Wescoat, 2014). In this way, the Mughal and the British colonial legacies laid the foundations of inequitable water supply systems in the city over several centuries.

The water supply system was mostly decentralized in the pre-British era. This continued until the revolt of 1857 prior to which the Europeans and the Indians lived in a mixed settlement. However, the post-1857 period residents saw clear segregation of living spaces, and one-third of the city was demolished and rebuilt to "sanitize, improve, and modernize." There was a need felt to "enlighten and civilize" the locals through superior science and technology (Sharan, 2006, p. 4906). These steps were also motivated by the safety of the British residents and the health of the troops. Urban governance measures that were being carried out in Britain since the 1840s were replicated in India. Sanitary concerns of the "Indian" became important to the British after the sanitation recommendations given by the Royal Commission on the Sanitary State of the Indian Army in 1863. The sanitary concerns however were strategic as the new army and governmental zones were provided with water and sanitation facilities and not the older parts of the town (Gooptu, 2001, p. 71).

The decentralized system of wells was classified as un-modern, unimproved, and unsanitary and thus had to be replaced. The state claimed ownership of all natural resources and instituted taxation (Broich, 2007, p. 346). The introduction of piped water in the 1890s resulted in a gradual but deliberate decay and closure of wells (Gupta, 1981). It can be claimed that this centralization of the water supply was a step closer to controlling and policing the Indians efficiently.

While piped water was resisted in many parts of the British Empire, in India the resistance focused on two major points. Firstly, religious protests against piped water were carried out by the Hindu community as piped water was believed to be impure and could not be used in many religious ceremonies. Additionally, the sealing of wells caused protests motivated by traditional worship practices (Broich, 2007, p. 360). Secondly, newspapers such as "*Safir-i-Hind*" and "*Anjuman-i-Panjab*" raised voices against taxation demanded from locals to cover infrastructure costs (Kishore, 2015, p. 457). However, Indians gradually integrated piped water into their daily lives and religious practices.

Along with replacing the wells, the wide network of Mughal drains was replaced with a network of underground drains by the Delhi Municipal Committee to modernize the system. However, the inefficiency of this project can be seen by the statement issued by the Sanitary Commissioner of Punjab in 1873 calling the drains aimless and haphazard. Due to a purported shortage of funds, piped water could not be made available to the Indian part of the city. As a result, it was implemented in a targeted way, prioritizing the white areas and the troops (Kishore, 2015, p. 452). This questions the enlightenment quest claimed by the British officials. Another change in water governance was the application of public nuisance laws. While this law was borrowed from the English judiciary, its Indian application saw extensive use. It covered the destruction of public property that included centralized water systems such as rivers and lakes (Anderson, 2011). As a result, mostly the economically lower sections of the society, which mainly comprised lower castes and enjoyed using water from public sources, were rendered as illegal users.

Therefore, three distinct water supply systems existed during the British colonial period. A "modern" piped water supply network covered New Delhi. This network was meant exclusively for white rulers and Indian bureaucrats who served the Empire. Rich Indians had dug wells within their houses, which formed the second system of water supply. Other Indians, mostly poor classes, procured water from public wells, canals, ponds, etc. Therefore, a majority of the population did not have access to safe drinking water. Limited access to the modern piped water supply is clearly a visible form of active infrastructural violence where infrastructure designed creates a form of violence toward the poor Indian population.

The security and comfort of the colonial population appear to be the underlying motivation in planning separate infrastructure for the British ruling elite and the dominated Indians. However, the situation was also more complex. Religious belief systems agitating against the installation of modern networks of water supply and provisioning of sanitation services combined with caste and class produced a water supply infrastructure that embeds violence to those most disadvantaged within it.

Caste identity played a huge part in preventing access to water to lower castes, particularly the erstwhile untouchables who were prohibited from using water bodies meant for the higher castes. Those who protested against this unjust water practice faced violence. A progressive resolution was passed in 1926 when the government of Bombay Provinces abolished this unjust practice against the untouchables. The Chavdar Lake, the largest reservoir in the Mahad municipality became the focal point for asserting the untouchables' right to water. On 19 March 1927 Babasaheb Bhim Rao Ambedkar led tens of thousands of people gathered at the Chavdar Lake to exert their right to water. Soon after touching the water of the Chavdar Lake, violence followed. The higher castes "spared no one–men, women, or children–knocking our food into the dirt and pounding our utensils" (Jadhav, 2003, p. 39). Since peaceful existence was the pre-requisite for the perpetuation of the colonialist regime, the British supported the higher castes. Consequently, on 4 August 1927, the progressive resolution was revoked by the Mahad municipality. This incident might be short-lived, but it gave rise to a movement to secure water rights for the untouchables.

Overcoming historical legacies of power and privilege is onerous because transcending these legacies requires actions to dismantle the established regimes of which current political parties have become an integral part. So the "civilizing mission" of the colonial regime got easily extended into the Indian republic's polity after 1947 (Fischer-Tine and Mann, 2004).

Extension of this geographically and temporally uneven and inequitable water regime has been so firmly established that changing this system into a more egalitarian regime appears to be an impossibility in the near future.

Post-colonial Water Supply: The Continuation and Embeddedness of Infrastructural Inequality

When elite Indians led by the first Prime Minister Jawaharlal Nehru took reins of power from the British colonists in 1947, the modernist policies of city building continued. Nehru looked upon slums with disdain and wanted them demolished. He aspired that all Indians should live in planned areas with access to potable water and sanitation services. Modernist at heart, Nehru wanted to build new towns such as Chandigarh. In Delhi, it was he who brought in the Ford Foundation for the preparation of the Master Plan for Delhi, 1981. Expectedly, the development plan contained policies on slum rehabilitation and resettlement (Delhi Development Authority, 1981). Delhi Master Plan, 1981 paved the way for active and passive infrastructure violence toward slum dwellers and general residents of Delhi. The old city of Shahjahanabad had a gross density of 350 persons per acre with congested built structures, lacking community facilities resulting in poor living conditions. To improve the built environment of the area its population density was proposed to be brought down to 250 persons per acre. As a result, houses were demolished and people were forced to relocate. The same measures were proposed for other areas also to reduce the population density between 200 and 250 persons per acre. On a similar trajectory, quarry laborers working and living in the Anand Parbat area were proposed to relocate in the cheap housing units in the North and South of Delhi. In order to provide housing to slum dwellers by relocation, poor quality housing and infrastructure were built. The poor housing and infrastructure were justified in the name of cost-cutting and building by-laws, making a classic example of active infrastructural violence toward the resettled (Delhi Development Authority, 1981).

Active infrastructure violence was also seen when Prime Minister, Indira Gandhi followed the principles of modernity during the Emergency between 1975 and 1977 (Hameed, 2017, p. 111). In Delhi, there were large-scale expulsions of people from the center to peripheral locations (Tarlo, 2003). While around 700,000 families were evicted (Baviskar, 2020, p. 152), only 152,300 were resettled (Dupont, 2004, p. 161). Muslim settlements in Old Delhi were especially targeted by Mr Jagmohan Malhotra, then Vice-Chairman of DDA, also known as the "demolition man" (Hameed, 2017, p. 111). Through these acts of active infrastructural violence, slum dwellers are forced into long-term insecurity. Their fate depended on the leadership of political parties and their agendas.

Drinking water production and distribution became an increasing challenge for the post-colonial regimes in urban India with a fast increasing city population, diminishing water resources, inadequate financial resources to build water and sanitation networks, and deteriorating quality of groundwater. An old and inequitable system of water planning was easily adopted in spite of loud political rhetoric of equal and universal access.

Delhi has a long history of networked water supply. Delhi Joint Water and Sewage Board (DJW& SB) was set up in 1926 by the British colonists and was responsible for the operation and maintenance of waterworks in Delhi. However, its primary beneficiaries were areas with colonial settlements. This included the area of the Delhi Municipal Committee where a large majority of ruling classes lived (Delhi Administration, 1976, p. 725).

The two most important governing arrangements that exist today are DJB and the Delhi Development Authority (DDA). These play a vital role in both the active and passive infrastructural violence related to the water supply in Delhi. We will explore this further below through a discussion of five axes of infrastructural exclusion. Within 6 years of the formation of the Delhi state, the DJB was created in 1998 by an act of the Government of the National Capital Territory of Delhi. Delhi Jal Board was responsible for procuring, processing, and distributing water in Delhi Municipal Corporation area (now divided into three corporations). It was also responsible for supplying bulk water to New Delhi Municipal Council and Delhi Cantonment Board. Moreover, it provides sanitation services in the entire city of Delhi.

Delhi Development Authority was set up by an act of Parliament in 1957. The DDA was made responsible for the planned and orderly development of the city-state by preparing master development plans. In addition to DJB, the DDA also formulates water policies and norms through successive master plans. When new areas are developed, the DDA declares them as "development areas" where it is responsible for building infrastructure and providing all utilities including water and sanitation services before handing over these areas to a municipality.

IDENTIFYING AXES OF INFRASTRUCTURAL EXCLUSION IN DELHI

Exclusion and denial both form part of infrastructural violence. Exclusion of the poor from accessing piped water occurs in multiple ways. In this section, we examine five dynamic forms of exclusion in current water infrastructure provision: legal exclusion; commodification and privatization; poor co-ordination; planning exclusion; and over-estimation of water supply.

Infrastructural Violence Through Legal Exclusion

A clear example of exclusion is illustrated within legislation governing water supply. The DJB is well aware that it under-serves the poor and marginal groups. For example, DJB's internal note of 2004 concludes that "there is a need for targeted interventions to cater to the water and sanitation needs of the poor" (p. 8 as quoted in Sheikh et al., 2015). Rhetorical concern about the poor of Delhi is laudable. But in actual practice, Delhi Jal Board Act is openly discriminatory. For instance, section 9(1a) of the DJB Act 1998 says that DJB will not "provide water supply

TABLE 2 | Population residing in informal settlements of Delhi, 2014.

S. No.	Type of informal settlement	Population
1.	Jhuggi Basti	1,700,000
2.	Unauthorized colonies	4,000,000
3.	Homeless and pavement dwellers	16,000
Total population residing in informal settlements		5,716,000
Percent of total population		33.62

Source: Planning Department, Government of NCT of Delhi (2019).

to any premises which have been constructed in contravention of any law . . . ."

Once unauthorized colonies and slums are regularized, the DJB becomes responsible for providing water in these areas. In non-notified slums, those slums that are deemed illegal occupation, the DJB has no obligation to provide water or sanitation services. However, under pressure from political leaders and courts, the DJB provides water to non-notified slums. But the main point is that legally speaking the DJB is not obliged to provide water to any illegally built residential areas, which include most of the unauthorized settlements and slums, where a large majority of Delhi residents live. The legislation governing water supply illustrates active infrastructural violence. The DJB has no legal obligation to provide water to non-notified or illegal occupations. However, this active violence is limited by the state to some extent through the provision of water and sanitation services to non-notified areas overlooking their illegalities. Provisions of the DJB Act 1998 clearly marginalize and exclude a large proportion of citizens living in Delhi from accessing water from the network (see **Table 2**). So, it can be argued that the water provisioning statute is exclusionary.

However, complications in this picture arise when enough political and legal pressure (through court verdicts) is exerted on the state bureaucracy that the same state stands with the citizens and ensures water provisioning through tankers and other means. Here, the state is simultaneously complacent in generating infrastructural violence by enacting laws to make such provisioning illegal, presumably with the intention of putting a stop to the spread of illegal developments. But when the state fails to contain illegal developments, it acts to limit infrastructural violence by temporarily providing water to thirsty populations. For example, on 31 August 2020, the Supreme Court ordered the removal of 48,000 slum clusters located within the safety zone of railway lines in Delhi. The Government of India informed the court through a submission by the Solicitor General that it was not possible immediately without exploring alternatives because over 200,000 families would be displaced if these people are evicted. One of the petitioners from the opposition party further noted: "Slum dwellers have a fundamental right to the city. They are an integral part of the social and economic fabric of the town... If the demolition of slums is carried out amidst the current pandemic, more than 250,000 persons will be forced to move around the city in search of shelter and livelihood" (The Hindu, 2020). Under such political pressure, infrastructure violence is temporarily put on hold and slum dwellers continue to access water and other services. This process of excluding the poor from potable water is therefore active violence as the state actively refuses to supply fixed infrastructure but transforms this into, passive violence because of the uncertainty of water provisioning provided through irregular and inequitable supply of water by tankers.

Infrastructural Violence Through Commodification and Privatization

If all else fails, one way to get access to potable water in Delhi is bottled water. The DJB and private vendors sell bottled water in Delhi. Millions of bottles of one liter or half a liter are served every day by private corporate vendors. However, what is most striking is the fact that the DJB sells 20-L water canisters to private vendors who in turn sell them to households who cannot access potable water from any other source. They are generally poor people who either do not have access to water through the network because they are not connected or water through the network is insufficient for their basic needs.

The DJB's bottled water is expensive when compared with its piped water price per liter. For example, the starting tariff in Delhi is Rs 2.42/kl for piped water supply. Dwarka's middle-class residents pay Rs. 11/kl for piped supply and Rs. 47/kl for water supplied through tankers (Times of India, 2015). Corporate vendors sell 1 kl of water in canisters to the poor at the steep rate of Rs. 2,600 (Delhi Jal Board, 2015), which is 236 times higher than water supplied through the network. Treating water as a commodity with an instrumental value alone excludes the most vulnerable. This system of water supply through 20-L water canisters represents another example of active infrastructural violence, where infrastructure is designed to be violent through pricing (Desai, 2018). The way in which infrastructure is put together generates deprivations, inequities, conflicts, and denials.

Infrastructural violence also takes place through the privatization of the water supply. The Government of National Capital Territory of Delhi has made attempts to involve the private sector in selected areas with the objective of enhancing the level of water services, meaning making water available 24 × 7. The aim of the policy is to provide better services to those who can afford. This policy is meant to increase the level of service by providing 24 h piped water supply to residents with improved water infrastructure. This project includes Mehrauli and Vasant Vihar, which are largely high middle income and rich-class areas (see **Figure 1**). To provide a better water supply, the MVV Water Utility Private Limited has been selected through a tendering process and tasked to improve the level of service in Mehrauli and Vasant Vihar. Work is awarded to a consortium of SPML Infra, Tahal Consulting Engineers and Hagihon Jerusalem Water and Wastewater Works (MVV), on Design,Build, Operate and Transfer basis by the DJB. The agreement to carry out this project was signed on 12 September 2012, some 9 years ago. The improved systems would be managed by the MVV for 2 years (MVV Water Utility Private Limited, 2013, p. 8).

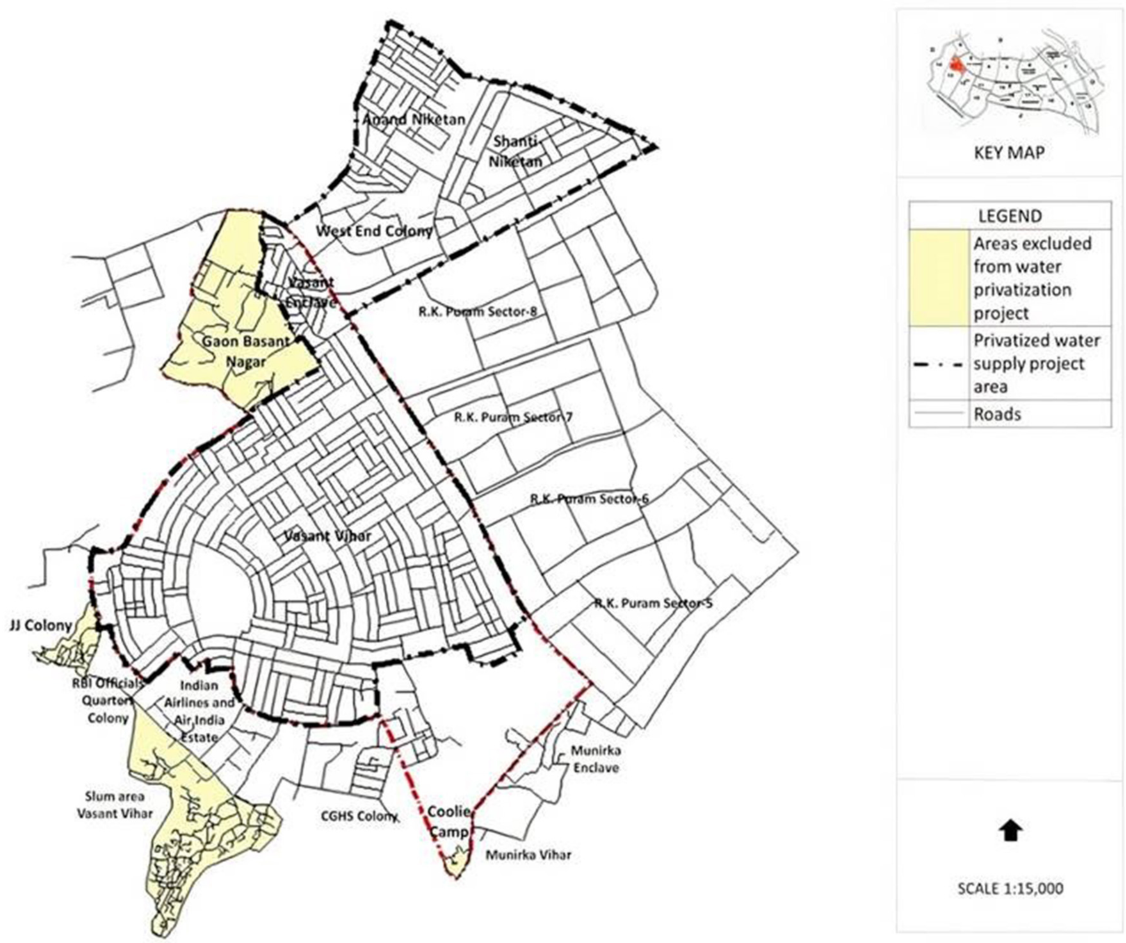

FIGURE 1 | Excluded areas from the project for enhancing level of service.

The President of the Vasant Vihar RWA gave consent to this project. With the World Bank loan of US$ 224 million, it targeted 150,000 meter network and 500,000 populations with 200 LPCD target. Initially, the project with the support of the World Bank was initiated in 2002, and this project would have ended by 2005 and entire Delhi by 2015. Some scholars have likened this project of 24 × 7 water supply scheme in Vasant Vihar, southern Delhi to "exit the penury syndrome" (Ruet, 2007, p. 17). Exit the penury syndrome placed within the exclusionary global city narrative represents the Indian cities as spaces capable of sustaining higher standards of infrastructure provisioning and water supply services for specific classes.

Nevertheless, as we can see from **Figure 1**, this project deliberately excludes the poor areas shown in light yellow color on the edges of the project area. These areas are Coolie Camp, Slum Area Vasant Vihar, JJ Colony in the southern parts of the project site, and Gaon Basant Nagar in the eastern parts. Exclusion of these poor areas could not be seen more visibly, there is not even a pretense of inclusion. This is an episode of active infrastructural violence.

Infrastructural Violence Through Lack of Coordination

Passive infrastructural violence can also result from a lack of coordination between the DJB and the DDA. This can be seen by the Dwarka sub-city planning among other examples. Dwarka is a comprehensively planned new sub-city of 1,000,000 population near the Indira Gandhi International airport. This large township was planned and built in the early 1990s by the DDA for the rising population of middle and elite groups. In the initial years, water was provided through 400 tankers twice a week. The DDA bought water in bulk from the DJB and provided it to the residents of Dwarka However full requirements could not be met through tankers due to their limited capacity (see **Figure 2** for the location of the sub-city).

A relevant question is why no piped water was supplied for 15 years to the residents of Dwarka. The DJB officers tell us that the township was built without bothering to consult the DJB for water supplies. Dwarka got piped water supply from the DJB in February 2015 after nearly 15 years of the existence of the new town. Similarly, another DDA planned settlement

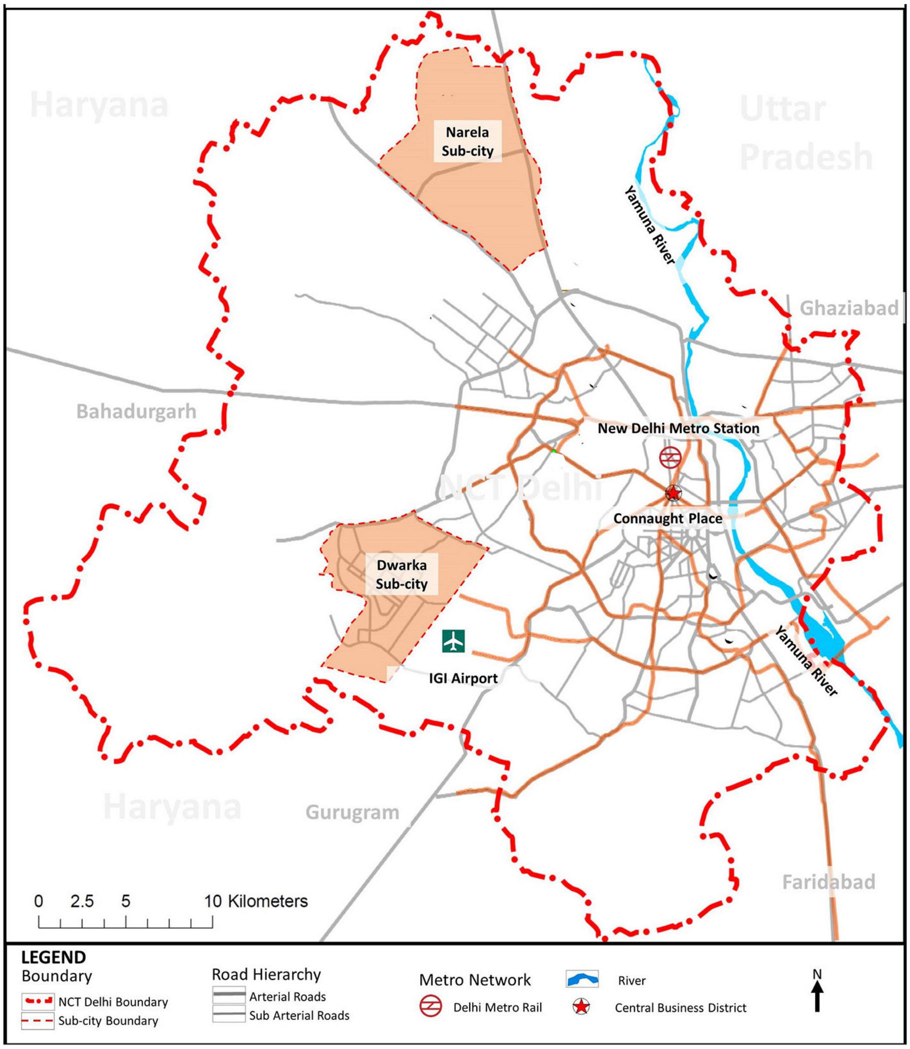

FIGURE 2 | Location of Dwarka and Narela sub-city in NCT of Delhi.

called Narela with a population of 225,000 does not have access to the piped water supply. As for Dwarka, until recently Narela got water supplies through tankers. The same pattern of violence caused through lack of coordination can be expected to continue as the DJB has not been consulted for the recently approved Land Pooling Policy 2013, which would result in 1.7 million housing units in the near future (Master Plan for Delhi-2021, Delhi Development Authority, 2007) with little consideration of water supply.

Failure of coordination among agencies with different responsibilities falling under different legislations is a cause of infrastructural violence against all income classes through exclusion from networked water supplies for many years. Planning and development of new townships in Delhi appear to proceed without careful consideration of supply of potable water. Even middle-class residents have to rely on water provided through tankers. Water networks become operational only after several years of township development.

Infrastructural Violence via City Planning

Passive infrastructural violence is also illustrated in the city's planning system seen by studying the various versions of the master plans of Delhi. The inequitable intent of the city planning agency is highly visible through the three Master Plans of 1981, 2001, and 2021.

The first Master Plan for Delhi[1] was prepared by the DDA with the help of the Ford Foundation team led by Albert Meyer and came into force in 1962. This plan had the horizon year

[1]Master Plan for Delhi is a physical development plan for the city. It has two parts, one containing city planning policies and the other planning norms and standards. The document is supported by a land use map for the horizon year, effectively proposing how land would be used in the next 20 years.

of 1981. In the Plan, while work studies were comprehensive, it only spared one paragraph for water policy, giving little space and thought to water planning. After we closely examined the Master Plan for Delhi, 1981, and associated work studies, we made several interesting discoveries.

The DDA divided Delhi into three parts: Class A: Delhi Urban Area; Class B: Ghaziabad, Faridabad, and Ballabgarh; Class C: Gurgaon, Bahadurgarh, Narela, and Loni. These three settlement classes are based on location, stage of development, and population. The master plan policy clearly suggests that central place with large population (Delhi Urban Area) where the most powerful politicians and bureaucrats reside, deserves more water than smaller towns located on the periphery of the metropolis. So, the DDA proposed different water supply standards and different times for supply of water to these areas. The standard of water supply for Class A i.e., Delhi Urban Area was set at 50 gallons per capita per day. The standard for Class B including Ghaziabad, Faridabad, and Ballabgarh was set at 45 gallons per capita per day and for Class C i.e., Gurgaon, Bahadurgarh, Narela, and Loni, at that time upcoming future towns, the standard was set at a much reduced rate of 35 gallons per capita per day. The Master Plan for Delhi, 1981 also proposed that water will be supplied in Delhi and the Ring Towns with different time durations. For Class A i.e., Delhi Urban Area, the planning agency intended to supply water for 24 h. However, in practice, it was found that water could be supplied only for 18 h. In Class B towns such as Ghaziabad, Faridabad, and Ballabgarh, the intent of the planning agency was to supply water for 18 h. But it could supply water in these areas only for 16 h. In Class C areas i.e., Gurgaon, Bahadurgarh, Narela, and Loni water was proposed and supplied for 12 h (Delhi Development Authority, 1981; also see **Table 4**).

Moreover, the availability of water determined the growth potential and economic significance of various ring towns, towns located around Delhi. Ghaziabad was the most populated town with a total population of 357,000 in 1981 and it was envisaged as an industrial town with 50,000 workers in manufacturing work. Similarly, Faridabad, Ballabgarh towns of Haryana state and Loni and Narela towns in Delhi had strong manufacturing units. Water requirements of these two adjacent towns were expected to be met easily by tube wells and good underground water resources. However, due to the absence of good water resources, the development and growth of Gurgaon and Bahadurgarh towns were expected to be low (Delhi Development Authority, 1981). The act of leaving behind certain ring towns in the plan due to low water resources instead of the plan facilitating equitable growth is in itself a form of active infrastructural violence.

This practice of making essential services like water supplies available in different areas for different time durations and with different standards is exclusionary at its root. Mostly, people living in the periphery of the city would get reduced amounts of water for reduced time periods (also see **Table 4**). Heavy reliance on government framed norms appears to be the most probable reason for different standards for different areas. Like the colonists, elected governments have also provided more water per capita per person to people living in or close to the seat of power. New Delhi Municipal Council gets more water than any other area (Hosagrahar, 2005, 2010; Sharan, 2006; also see **Table 3**).

TABLE 3 | Water supply variations in different areas of Delhi, 1999–2018.

Area category	Name of the area	Water supply norm, 1999 (LPCD)	Water supply norm, 2018 (LPCD)
Comprehensively planned	NDMC	462	440
	Delhi Cantonment Board Area	509	509
	New Delhi and South Delhi	148	228
	Civil Lines and Rohini	274	228
	Shadhara	130	228
	West Delhi	202	228
Unplanned/Old city	Old Delhi	277	–
	Karol Bagh	337	–
	Pahar Ganj	201	–
Outer Delhi	Narela	31	40
	Najafgarh	74	40
	Dwarka	74	228
	Mehrauli	29	40

Source: Delhi 1999–A Fact Sheet NCRPB; Planning Department, Government of NCT of Delhi (2019) and Delhi Jal Board (2016).

TABLE 4 | Different time durations and different standards of water supply, 2007.

Class A—Delhi (Delhi Urban Area)	Class B—Ring Towns (Ghaziabad, Faridabad, Ballabgarh)	Class C—Ring Towns (Gurgaon, Bahadurgarh, Narela, Loni)
Per capita supply 50 gallons	Per capita supply 45 gallons	Per capita supply 35 gallons
24 h supply per day	16 h supply per day	12 h supply per day
Must supply between 4 a.m. and 10 p.m.	Continuous supply from 4 a.m. to 10 p.m.	Continuous supply 5–11 a.m. and 4–10 pm in domestic areas, major industries should meet their requirements from tube wells
–	Sources to be ground water, infiltration galleries, and wells	Sources to be tube wells, infiltration wells to avoid mechanical treatment
	Major industry should meet their requirement from bore to small size tube well	Road washing, horticulture from local wells and ponds

Source: Compiled by the authors from Master Plan for Delhi (2021).

The next version of the Master Plan for Delhi was enforced in 1990 with the time horizon of 2001. Based on self-devised norms, this development plan proposed a uniform standard of water supply at the rate of 80 gallons per capita per day throughout Delhi. Out of 80 gallons per capita per day, 50 gallons per capita per day was meant for drinking purposes throughout Delhi. Ring

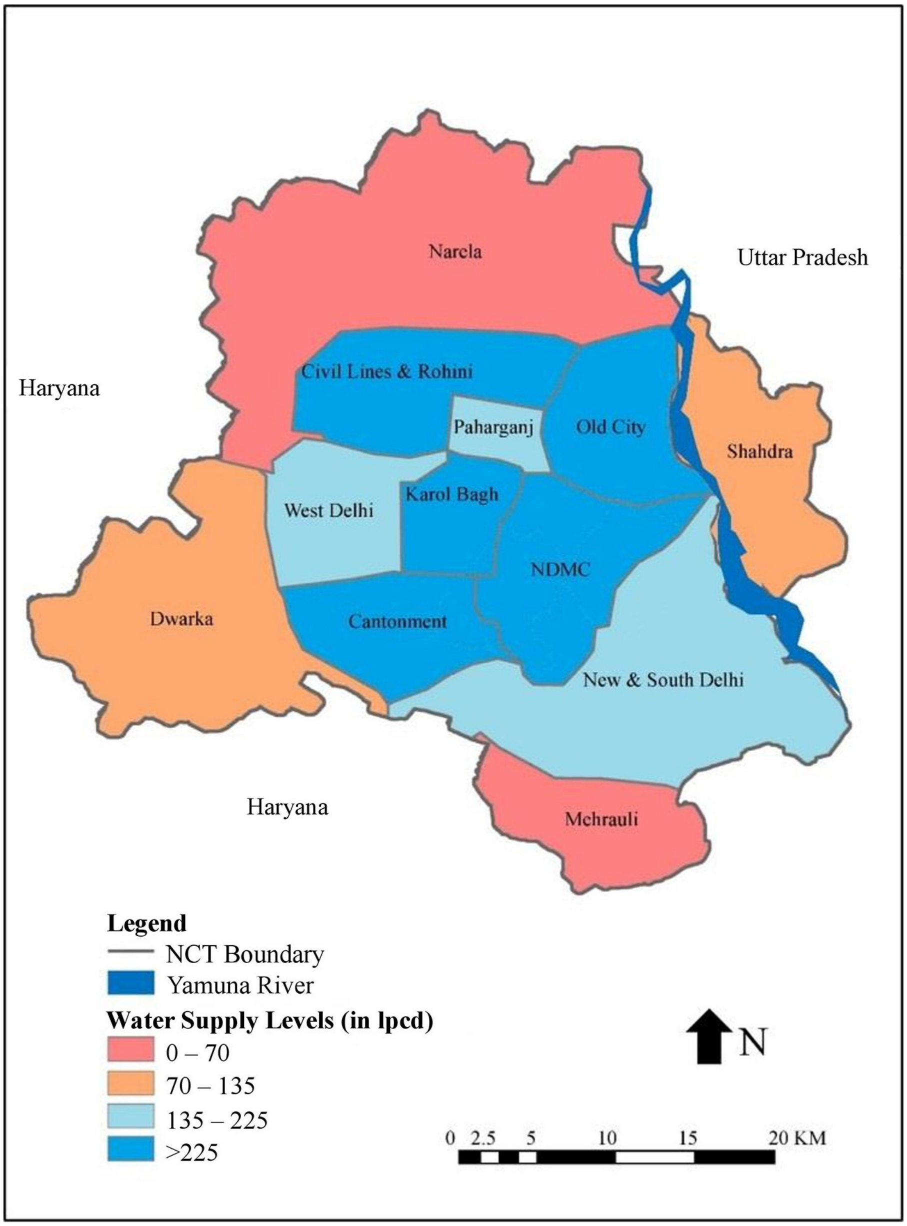

FIGURE 3 | Water inequities in Delhi, 1999.

towns[2] were not discussed in this plan, probably because the Regional Plan, 2001 was notified in 1989. Additionally, DDA being the land owning agency in Delhi, allocated land to the DJB for building water treatment plants and sewage treatment plants. Although it was an improvement over the previous master plan, and a high standard of water supply was set for domestic purposes, inequities in water supply persisted.

Analysis of the Master Plan for Delhi 2001 revealed that the development plan was highly aspirational in terms of high-end developments like building malls, middle class, and elite housing, but did not take into account the important issue of inequities of water in Delhi as not a single word was written in the plan on equitable distribution of water among various types of areas and populations. Due to this limitation, the Master plan policies and DJB policies on water could not eliminate water inequities in the city and remained inherently violent (see **Figure 3**). As the map shows, clearly, inner areas receive more water per person per day than peripheral areas. Some areas like the NDMC receive nearly 500 L of water per person per day in comparison to other areas only receiving 25 L per person per day. So far, the

[2]Towns located around Delhi and forming a ring are called ring towns.

planning agency's focus remained on aggregate water production and distribution, and also on setting high water supply standards.

Elite areas like New Delhi Municipal Council and Delhi Cantonment buy water in bulk and therefore these areas do not form part of DJB's water zones. However, areas located in central parts of the city like Old Delhi and Karol Bagh receive considerably higher amounts (over 250 LPCD) of water. These areas are located in Northwest IV, Central I and Central II zones of the DJB. Similarly, Civil Lines and Rohini, two high income planned areas, also receive higher amounts of daily water supplies and they are located in North West I, part of North West II, and part of West III. West Delhi, New Delhi and South Delhi are also inhabited by high and middle income groups and receive moderately higher amounts (135–225 LPCD) of water. These three areas are located in South West I and II, West I, South I to IV and South West III zones. Narela is located in the DJB's North West II, North I and West III while Mehrauli is located in South I zone. Both Narela and Rohini house low income resettlement areas and receive lower quantities of daily water supplies. Shadhara is located in the DJB's North East I and II, East I and East II zones. This area receives comparatively less amounts of daily water compared to the central parts of the city as most of its residents belong to middle income and low income groups. Dwarka, a planned sub-city located in South West I and II zones of the DJB, receives moderate quantities of water for daily use. As we move away from the city center, daily water supplied to residents living in different zones also reduces and least amount of water is supplied in resettlements areas (read **Figure 3** with **Table 1**).

Trying to find a middle ground, the DDA ended up providing a high standard of water supply at the rate of 45 gallons per capita per day in its Master Plan for Delhi 2021, which was enforced on 7 February 2007. The plan argues that there is a need for capacity building through the principle of "user pays approach" and this policy should be implemented through public-private partnerships. This is very typical of the mainstream international language on the water in this period based on the neoliberal approach to service delivery. Commodification and privatization are central to this plan when neoliberal economic and political thinking took the center stage after structural economic reforms (Hope et al., 2013; see Mohan, 2017). Privatization of potable water was also seen in the Plan through the Land Pooling Policy 2013 by the DDA. This policy handed over future development to the private sector, which gives further credence to the continued inequitable and violent distribution of potable water.

The plan also emphasized that there is a need to improve efficiency through better community participation and decentralized management. Promoting efficiency further, the plan also proposed that the percent of non-revenue water should be reduced as the estimated water losses stand at 40%. The plan was also concerned about water conservation through an integrated community-driven model. To pursue this line of thinking, the DDA made proposals for making amendments to the Delhi Water Board Act, 1998. However, it should be noted that the DJB itself is responsible for the largest proportion of the non-revenue water. Moreover, it is estimated that the planned areas, due to faulty meters, are the next highest contributors to the non-revenue water after the DJB (Comptroller and Auditor General of India, 2013). However, the informal settlements are the ones who are blamed and targeted by various governmental agencies and the middle class and elite for the alleged theft of water (Truelove, 2018). This can be seen in past community-driven models which were meant to serve the middle classes and penalized the informal settlements (Truelove and Mawdsley, 2011, p. 419). As a result, while improving the efficiency by reducing non-revenue water through community-driven models is commendable, it targets the already most marginalized.

The Master Plan for Delhi 2021 acknowledges water inequities but provides no mechanisms to reduce them because of its entire focus on efficient production and distribution of potable water in line with the central government's neoliberal economic policies. There is no word on balancing efficiency with equity in the plan. In fact, as discussed above, DDA does not acknowledge the existence of slum areas as they are regarded as an illegal occupation on public lands and so deserve demolition. In the Master for Delhi, 2021, the approach to water planning changed from water provisioning to water management with an emphasis on water commodification and privatization. However, water inequities continue to persist enabling the continuation of infrastructural violence.

Furthermore, the DDA has outsourced the preparation of the Master Plan for Delhi, 2041 to a central government controlled urban studies research organization, the National Institute of Urban Affairs. Considering that this agency has neoliberal leanings in line with the controlling Ministry of Housing and Urban Affairs, it is expected that the plan will say less on the removal of inequities and more on the commodification of water.

Infrastructural Violence via Over-estimation of Actual Water Supply

Overestimation causes passive infrastructural violence by hiding inequalities, first, of the quantity of water supplied and second, about irregularities within the extraction of non-revenue water. The DJB measures its success in terms of aggregate water supplied from all the treatment plants rather than the number of people who receive adequate, affordable, and quality water regularly. Moreover, non-revenue water or the water lost during distribution too is calculated in absolute terms. As a result, water shortages faced by informal settlements, both due to low water supply by the state and loss of water due to extraction in large quantities by actors such as industries, remain hidden.

In 2013, the Comptroller and Auditor General of India (CAG) through its comprehensive audit found that the DJB lacked an information system to collect and analyse data on water production and distribution of potable water. The auditors argued that the DJB looks at the total treated raw water per day as the total installed capacity of its treatment plants in Delhi and then divides by the current population, theoretically obtaining per capita per day water produced. Water treatment plants are assumed to be working at 100% capacity. For example, the installed capacity of all water treatment plants in Delhi is estimated to be 833 million gallons per day (MGD), and if this is divided by Delhi's population of nearly 17 million, it gives a figure of 200 L per person per day (Truelove, 2018, p. 8–10). But this figure is notional because one does not know how much water came into treatment plants and how much water reached each district, household, or industry. The DJB also cannot tell with any certainty how much water is actually distributed to the residents connected with the network because it does not have systems like functional pump meters in district metering areas. Moreover, the available water is pulled using electric motors by the underserved middle-class residents. Their ability to fulfill the shortages by technical solutions causes direct violence to the informal settlements by pulling water away from them.

Most importantly, over 40% of the total water is estimated to be non-revenue water i.e., water lost during distribution. A hidden distributive injustice and violence masks the differential allocations of water in practice. For example, due to over-extraction by influential consumers like the industry or private tankers, less water per person reaches a majority of the networked but poor populations. As a result, as discussed above, informal settlements must pay for this loss of water by being unproportionately fined for illegal extraction and through getting reduced water supply.

In the absence and irregularity of all this information, it is an erroneous calculation that the DJB supplies water at the rate of 200 L per person per day. Truelove (2018) argues that water inadequacies and exclusions are erased through deliberate overestimation of water production, a form of active violence.

DISCUSSION

We have explored five axes of infrastructural exclusion in the water supply of Delhi in the contemporary period. Through the conceptual lens of infrastructural violence, we have argued that the combination of legal statutes, commodification and privatization of water, and infrastructure planning decisions all constitute active forms of infrastructural violence.

Second, infrastructural violence expresses spatialization of injustices through the use of state/elite power. Here, exploring the historical context of how "people, materials, and territories have been controlled and organized" is important to understand the context and flows of power. Hawkins (2014, p. 300) explores the formation of the state over the years, and concludes that state sustains elite power and draws on elite power to maintain and enhance state power and capacity. This epitomizes the notion of "infrastructural power" as stated by Mann (1984) when referring to the development and manipulation of infrastructure to uphold dominant social class structures in order to suppress the lower classes (Rodgers and O'Neill, 2012, p. 404). A poignant example is discussed by both Hawkins (2014) and Tarrow (2018) who show the central role of a country's security, and the necessity of the state to hold political power over the military by controlling resources. So, it is possible to sustain and strengthen state power/elite power by designing and provisioning infrastructure in specific ways. We could therefore argue that the state and infrastructural violence normally go together.

Third, the historical perspective, of the organization of water supply within both Mughal and British colonial eras, provides context and credence to the acceptance and normalization of division and inequity we witness today at the political, legal, economic, social, and technical levels of water supply. The paper has shown that the historical continuity of water inequities has enabled the displacement of a water equity agenda.

Fourth, infrastructural violence, among other things, is a class phenomenon. The objective of provisioning water services

TABLE 5 | Forms of water infrastructural violence.

S. no.	Elements	Description	Consequences	Infrastructural violence
1.	Legal infrastructural violence	When statutory provisions actively consider water provisioning to illegally built areas beyond their responsibility.	People living in non-notified un-authorized areas and slums get excluded from provisioning of water by the DJB.	Active infrastructural violence
2.	Infrastructural violence via planning	The DJB provides water at different rates and time durations.	Peripheral and comparatively low income areas and populations get less water per person per day.	Passive infrastructural violence
3a.	Infrastructural violence through commodification	A new water supply system is built to exclude the poor and marginalized populations.	Inadequate access to potable water, for example, 20 L water canisters are being supplied by private vendors.	Active infrastructural violence
3b.	Infrastructural violence through privatization	Level of water service to be enhanced for the middle income and elite groups.	Exclusion of the poor areas and populations.	Active and passive infrastructural violence
4.	Infrastructural violence through lack of coordination	The planning agency and water supply agency fail to coordinate.	The DDA developed planned areas get excluded from water supplies.	Passive infrastructural violence
5.	Infrastructural violence via over-estimation	Total treated water from all WTPs is assumed to have been supplied to individuals and households. Water supply calculations are based on erroneous assumptions.	On average one may arrive at a decent supply per person per day. On the ground poor people lose out and get little water as nearly half the water is lost (stolen) during distribution.	Passive infrastructural violence

to high income groups not only excludes slum dwellers from piped water networks; it also inflicts infrastructural violence by proportionately reducing quality as well as quantity of water supplied to them via disconnection (see **Table 1**). A discussion on exclusions alone does not sufficiently focus on violent policy outcomes. For instance, in the case of water supply in Delhi, it assumes away bad intentions of water provisioning in illegally built areas without debating contextual factors such as poverty that led to illegal occupation of public lands by the urban poor. Exclusions pay no attention to the failure of implementation of planning policies to build affordable housing because of which the poor have to live in slums with little access to infrastructure.

Fifth, infrastructural violence based on commodification and privatization of water is also ideological. In the present times, neoliberalism is the dominant paradigm of planning and development promoting marketization and its supporting institutional scaffolding. Delhi like many cities worldwide has joined the race for global recognition under the influence of neoliberal ideology, which seeks to promote unfettered markets, free flows of capital, and "discourses of symbolic formations arranged around [such] persuasive political ideas" (Ahmed, 2011, p. 164). Cities being the mainstay of wealth creation, this ideological shift has resulted in the accentuation of poverty, inequality, and class divisions in Delhi as governments continue to focus on profit maximization (Ghosh, 2020).

Sixth, cultural practices such as an entrenched caste system and gender norms work in combination with the dominant neoliberal economic ideology to enable the elite to maintain control over the state. In turn, unaccountable governments and religious identity based discriminations continuously reproduce infrastructural violence. Discriminatory ideologies are thus performed and enacted through water policies, plans, laws, and practices via the exercise of state/elite power.

Seventh, blurred lines of accountability is an important attribute of infrastructural violence. Blurring due to lack of credible information in the public sphere likely shapes infrastructural violence as it reduces the possibility of fixing responsibility and accountability of water providers. With the case of Tanzania, Mdee and Thorley (2016) argue that trying to unpack lines of blame for service delivery failure is a necessary first step to any possibility of accountability. In the case of Delhi, infrastructural violence is also inflicted via over-estimation of potable water supplied per person per day, which is based on problematic and limited calculations.

Finally, a lack of transparency and a culture of secrecy perpetuates infrastructural violence as these acts reduce accountability and fixing of responsibility becomes difficult. Data on the water provisioning system in Delhi is highly secretive and sharing data with researchers is limited and the data is ambiguous. As Truelove (2018, p. 1) underscores, secrecy and ambiguity underpins political abuse. However, pinning responsibility on particular organizations and individuals—the primary goal of attempting to understand infrastructural violence—is perplexing because the "very nature of the scale, pace and in a conceptual space from which infrastructure develops support in the difficulty in attributing blame and responsibility" (Rodgers and O'Neill, 2012, p. 402). Another difficulty about attribution of policy consequences is that all outcomes are not planned in advance. Deeper investigations through the lens of infrastructural violence help us in shedding light on the questions of sustainability and perpetuation of accountable water provisioning systems by treating infrastructure as more than physical collection of technologies (Amin, 2014; also see **Table 5**).

We assert that our five identified axes exclusion in water supply also underpin the wider dynamics of infrastructural violence. We end this section with a summary of the five axes observed in Delhi in **Table 5**.

CONCLUDING REMARKS

Centered on five axes of exclusion, this paper delineates the contours of infrastructural violence in the provisioning of potable water in Delhi. We argue that infrastructural violence takes place due to five exclusions suffered by the most marginalized groups of population living in slums. To a great extent responsibility for these exclusions can be pinned on the state through design of policies, plans, statutes, and cultural practices. Clearly showing the workings of the five dimensions of infrastructural violence, we have provided evidence for both historical roots and contemporary dynamics of exclusions' based on infrastructural violence.

Historical legacies of colonialism have set the stage for fragmented provision of water supplies to people of different social identities and economic classes. The conditions created by the colonists historically prevented the poor and lower castes from accessing good quality water. Post-colonial democratic governments have followed similar policies in the absence of low levels of public accountability. Lack of transparency and rent seeking behavior of government servants has further made it nearly impossible to have better access to safe water. Of course, the same water systems serve middle and elite classes (the civil society) very well because of their influential civic agency (Chatterjee, 2004, p. 38; also see Chaplin, 2011). Unjust water laws such as the Delhi Jal Board Act, 1998 are brutally violent, particularly through their avoidance of responsibility for residents living in slums. Instead of addressing this inequity, the process of backdoor privatization, justified through a narrative of enhancing level of service, reinforces historical dynamics of exclusion. Commodification of water by the DJB, leading to the sale of bottled water, among others, to people living off the network promulgates active infrastructural violence. Bottled water produced by the DJB and sold to the poor through private vendors is violent in design.

Building on the theoretical framework of "infrastructural violence," our analysis has shown that policies and laws have persistently contained elements of infrastructural violence. More recent enabling policies of the neoliberal state have only accentuated infrastructural violence and increased inequality. Untangling these exclusions will not be easy and requires extensive reforms including political willingness, and institutional capability.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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frontiers in Water

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(Re-)orienting the Concept of Water Risk to Better Understand Inequities in Water Security

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As populations grow and climate patterns change, difficult trade-offs in water security must be made. Re-allocation of water resources and re-distribution of water security outcomes will inevitably raise questions of equity. Equity is a central component of water security but often underemphasised, hence we still lack nuanced insights to how equity is understood and operationalised by water managers and users. The concept of risk is increasingly used in water security policy and practise but has been weakly integrated with equity considerations. We offer a contextual study that explicitly unpacks risk and inequity in water security across multiple scales; we have analysed lived water experiences and their hydrosocial drivers in a major river basin in Ethiopia. This is based on 61 interviews from seven rural kebeles, government organisations at woreda, zonal, regional and federal level and local and international NGOs as well as 17 industrial water user surveys. With our findings, and drawing on existing studies, we offer a theoretical framework for embedding water risk in equitable water security considerations. We find that when water risk is (re-)oriented from a biophysical framing, towards one centred on water-related values, it can be suitably embedded within hydrosocial framings of water security. This approach offers unique insights into how inequities are understood, within uneven power and political dynamics, which is critical for interventions that seek to deliver more equitable water security and meet social development targets.

Keywords: water security, water risk, water values and ethics, poverty & inequality, sustainable develop goals

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INTRODUCTION

There are inequities in water security—the unfair distribution of water security risks and benefits—that exist on a spectrum and can be delineated across contexts. Even just considering water access, inequities exist across social divides in wealth and ethnicity (JMP, 2019). Inequities in water security are shaped by a combination of social and natural drivers, requiring an interdisciplinary approach to understand them. Natural endowments in water security are inherently unequal, due to the quantity and reliability of water resources, and frequency of water-related hazards (Dadson et al., 2017). Social structures can mediate or exacerbate these inequalities, leading to inequities. In arenas of water scarcity, water resources are often prioritised for economic activities to the detriment of social development through market mechanisms (Swyngedouw, 2009) and governance norms (Woodhouse and Muller, 2017). Inequity is acutely observed in developing countries where institutional arrangements to govern water security are weak (Hepworth et al., 2013), while Sustainable Development Goal (SDG) 6 calls for safe and affordable water for all, placing the poorest and most marginalised in the spotlight (UN, 2019a).

Questions of equity will become more prominent within water security trade-off decisions in the future meaning that a holistic understanding and operation of water security is needed. As populations grow (UN, 2019b) and climate patterns change (IPCC, 2014), difficult trade-offs in water security will have to be made. Re-allocation of water resources and re-distribution of water security outcomes will inevitably raise equity issues. Hoekstra et al. (2018) have argued that equity is a central component of water security; equity is also a foundational principle of water justice (Boelens et al., 2018). However, we still lack nuanced and local perspectives on what this can mean in practise and how equity is understood differently by water managers and users.

The concept of risk is increasingly used in water security policy and practise but has been weakly integrated with equity considerations. Water security is complex, comprising multiple conceptual bases and often defined according to Grey and Sadoff (2007) as "*an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environments and economies.*" The operation of risk in water security has primarily been with a physical science framing, such as focusing on frequency and size of flood hazards, where risk is typically defined as: (hazard x exposure x vulnerability) (Nofal and Van De Lindt, 2020). This conceptualisation insufficiently explores what is at risk, for whom and to what degree, limiting the alignment of risk with equity. Drawing on existing scholarly work, and with a case study of the Awash River basin in Ethiopia, this paper reveals how equity and risk in water security are inherently interlinked through values and we highlight the inequitable lived experiences, perspectives and values of water security and the socio-natural processes that influence them.

We offer a conceptual framework for studying equity in water security, including the concept of water risk—understood with water-related values. This framework is a hydrosocial framing that enables the root causes of inequities in water security to be understood, particularly through the consideration of power and political arrangements. We begin with a discussion of existing frameworks that are used for studying water security, their differences, and limitations. We then expand on why our framework is necessary and relevant. Following this, we enter the case study of the Awash River basin in Ethiopia to further explain why our framework has been developed and to justify the essentiality of (re-)orienting the concept of water risk in terms of human values in hydrosocial studies of water equity. Finally, we conclude that water security interventions need to include water-related values and address water equity explicitly to meet social development targets.

A SOCIO-NATURAL FRAMEWORK FOR STUDYING INEQUITIES IN WATER SECURITY

Critiques of siloed water security research have highlighted the need for interdisciplinary studies (Zeitoun, 2011; Cook and Bakker, 2012; Lankford et al., 2013) which has supported a move towards hydrosocial and socio-hydrological approaches. While not completely divergent (Rusca and Di Baldassarre, 2019), there are significant differences between the two. First, hydrosocial approaches are exemplified by the hydrosocial cycle, developed by Linton and Budds (2014), that posits that water and society continually remake each other while putting society at the centre of water security enquiry, stressing the subjectivity of knowledge. Second, socio-hydrology approaches, originally proposed by Sivapalan et al. (2012), seek to integrate society in the examination of natural systems and have been criticised for focusing on engineering solutions with insufficient consideration of the complexity and irrationality of human behaviour (Wesselink et al., 2017), despite recent scholarly work that seeks to address this (e.g., Savelli et al., 2021) Hydrosocial approaches to studying water security are also not without limitations.

We propose a socio-natural framework (**Figure 1**) that is a bricolage of existing concepts and draws substantially on hydrosocial theory. Power and politics are central concepts in hydrosocial framings of water security (Bakker and Morinville, 2013; Woodhouse and Muller, 2017) and such approaches have revealed that uneven power relations play out through access to water (Swyngedouw, 2004). Power in the case of our framework is the ability to influence water security through socio-cultural (Crow and Sultana, 2002; Wutich et al., 2017), financial (Bues and Theesfeld, 2012), or political means (Strang, 2016). We broadly conceptualise "politics" as the institutional arrangements that govern water security as well as wider dynamics in political ecology and political economy, following Zwarteveen et al. (2017) who argue, "*that water governance at heart is about political choices as to where water should flow; about the norms, rules and laws on which such choices should be based; about who is best able or qualified to decide about this; and about the kind of societal future such choices support.*" We also include scale as a crucial concept as water security manifests at different scales (Srinivasan et al., 2017), from the global (Wada et al., 2016) to national (Calow and Mason, 2014), city (Grasham et al., 2019; Truelove, 2019) and through to the intra-household level (Wutich et al., 2017).

Hydrosocial approaches have been criticised for understating the natural system (Wesselink et al., 2017) and we acknowledge this criticism with the inclusion of the concept of place in our framework. Ideas of place in the water security literature have been discussed extensively and we draw on Boelens et al. (2016) who developed the term "hydrosocial territories." Their definition of territories has a socio-natural conceptual underpinning: "*Territories, although often considered natural, are actively constructed and historically produced through the interfaces amongst society, technology and nature.*" (Boelens et al., 2016). The idea of hydrosocial territories offers an interdisciplinary basis to study the relationship between inequities in water security mediated by geographical location. We will expand this conceptualisation further with case study evidence which reveals how intimately connected water security is to physical location.

At the centre of our framework we have equity. Equity is a philosophical concept with multiple interpretations. Perreault

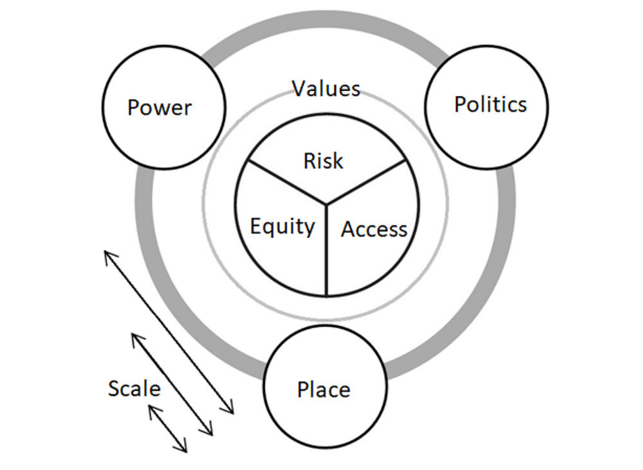

FIGURE 1 | Conceptual framework for evaluating inequities in water security.

(2014) has offered defining characteristics for thinking about equity in water governance which are useful for conceptualising equity in water security: *"Equity is fairness. Equity is impartiality. Equity is something defined in law, and yet informed by deeper ethical principles. Equity is justice."* In the same way as risk, ideas of equity are also centrally defined by values. When everyone's subjective values are met to avoid circumstances of unacceptable risk, it can be argued that water security is equitable. In the following section, we present our case study research from the Awash River basin that illustrates how our framework offers further insights into diverse understandings of inequities in water security.

Limitations in socio-hydrology and hydrosocial approaches partly stem from the way that they define water security, due to their differing epistemological positions (for good overviews of the current water security literature see: Zeitoun et al., 2016; Hoekstra et al., 2018). Hydrosocial approaches are grounded in constructivist approaches and tend to adopt definitions of water security based on the idea that water security is relational (Linton and Budds, 2014; Jepson et al., 2017). Socio-hydrology approaches to water security are underpinned by positivist notions of truth that lead to definitions of water security that can be quantified with objective measurement. Typically, Grey and Sadoff's (2007) definition is used in socio-hydrology approaches that centre on quantifiable indicators of water access and water risk. We lift the concept of water risk into our framework from socio-hydrology. Unusually for a hydrosocial study, we adopt Grey and Sadoff's definition of water security. This has been, in part, motivated by Yates et al. (2017) who highlight the importance of *"cross-pollinating scholarship across debates on water and multiple ontologies."*

(Re-)orienting the Concept of Risk With Embedded Values

Equity issues are easily overlooked in water security (Goff and Crow, 2014), depending on how risk and "acceptability" (or "tolerability") of risk are interpreted. Acceptability as a concept is problematic, commonly interpreted on an economic basis which implies cost-benefit analyses that determine that, *"a risk is acceptable if the economic savings arising out of action to reduce a risk outweigh the cost of such action"* (Hunter and Fewtrell, 2001). The risk approach to water security has been criticised for being reductionist and underemphasising equity, diversity, politics and sustainability (Zeitoun et al., 2016; Hoekstra et al., 2018). Inequities in water security will inevitably persist and this definition allows for an "acceptable" degree of inequity in water security after the SDGs are met.

As well as physical framings, the concept of risk has received significant scholarly attention from social science disciplines. The sociologist Giddens (1999) argued:

> *"There is no risk which can even be described without reference to a value. That value may be simply the preservation of human life, although it is usually more complex. When there is a clash of the different types of risk, there is a clash of values and a directly political set of questions."*

Embedding values in risk has been done in other oft considered "physical" disciplines but is insufficiently explored in the arena of water security. For example, in the IPCC report (2014), climate scientists include in their definition of risk: *"The potential for consequences where something of value is at stake and where the outcome is uncertain, recognising the diversity of values."* Using Giddens' conceptualisation, we argue that social relations are inherent in the concept of risk, due to the fundamental relationship between risk and values. We know that water risk is socially reproduced (Oulahen, 2021), hence suitable for inclusion in hydrosocial studies. (Re-)orienting the concept from a physical to a social framing allows for risk to be embedded within hydrosocial studies.

Overall, risk is a central component of water security but has predominantly been omitted from hydrosocial studies since the concept was born from positivist epistemologies and physical sciences approach to water security. However, if the concept of risk is oriented to a social science conceptualisation, centring on water-related values, the concept of risk can be embedded within hydrosocial studies of water security. We locate this approach within the existing body of work that understands risk through qualitative methodologies and social constructivist epistemologies (e.g., Beck, 1992). This will allow for subjective and diverse interpretations of the "acceptability" of risk based on human experience rather than economic criteria. Given this, we include water-related values in our socio-natural framework and define them as principles that guide action towards water security by water users or water managers in public, private or community groups, the latter drawing from Koehler et al.'s (2018) cultural theory of water risk.

RESEARCH DESIGN

The case study draws on the Awash River basin in Ethiopia. As an endorheic basin, in a country where much of the rainfall is in the transboundary Blue Nile basin and therefore subject to international treaties (Yihdego et al., 2017), the Awash basin has been a focus for intensive industrial and agricultural development by the Government of Ethiopia (AwBA, 2017). Therefore, the Awash basin has high national economic significance. Water governance in the Awash is complicated as the river is divided by five of Ethiopia's regional states, while the main river channel is predominantly shared between the Oromia and Afar regions (**Figure 2**). Water resources in the basin are over-allocated (Gedefaw et al., 2018), with rapid urbanisation and expansion of irrigation and industry increasing demand. The climate is highly variable (Bekele et al., 2016) with climate change projected to lead to future reductions in water resources availability (Taye et al., 2018; Hirpa et al., 2019). Water policies and legal frameworks are poorly implemented (Mosello et al., 2015; Hailu et al., 2018) and stakeholder responsibilities are fragmented (Hailu et al., 2019).

The regions reflect different ethnic groups and climates. Agro-ecological zones range from moisture-reliable highlands in the upper basin to the arid lowlands downstream. The climate influences the nature of rural livelihoods with rainfed farming common in the highlands where rainfall variability is low, agro-pastoralism in the centre and predominantly pastoralist livelihoods in the lower basin where variability is high. The basin is highly prone to flood (Wondim, 2016) and drought (Edossa et al., 2010), and subject to deteriorating water quality (Degefu et al., 2013). The expanding saline Lake Beseka (Dinka, 2017) in the middle basin is of critical interest to policy makers as it is a source of water-related risks to land, water and human health (Kebede and Zewdu, 2019).

To unpack the nature and drivers of unequal water security, three *woredas* were selected for the application of social research methods across the upper, middle and lower basin to capture ethnic diversity and different agro-ecologies. In the upper basin, in the Oromia region, a woreda was selected close to Koka dam; in the lower basin a woreda in the Afar region near to Tendaho dam was chosen; and an ethnically diverse woreda in the middle basin, adjacent to Lake Beseka, that sits on the regional border was selected. Similarly to the ethnic differences, there are two main climate zones (Taye et al., 2018), with the middle basin site located on interface between them. These three areas correspond with the government's allocated water management areas within the basin (AwBA, 2017).

There has been insufficient exploration of inequity in water security in this context which is necessary since: (1) inequalities in water services have recently increased in Ethiopia (JMP, 2019) and (2) the new national water resources policy draft is

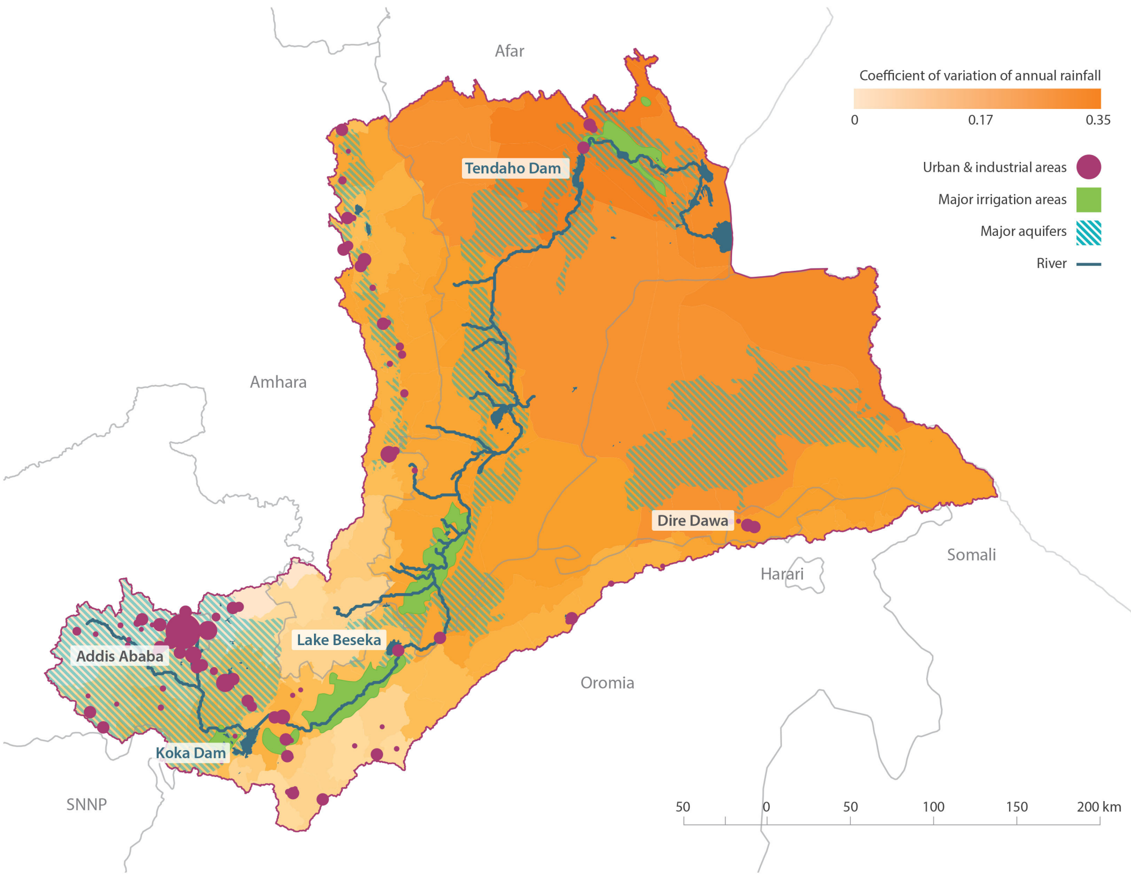

FIGURE 2 | Awash River basin, Ethiopia, highlighting key groundwater and surface water bodies. Climate variability ranges from high rainfall, low variability in the highlands, to low rainfall, high variability in the lowlands. Urban and industrial areas represent growing areas of water demand and pollution sources.

considering recognising diverse values related to water. National policies focus on economic development as a priority (e.g., the second Growth and Transformation Plan, GTP-2), hence the focus of social research in the Awash River basin has tended to align with this and has less closely addressed equity issues. There have been studies on integrated water resources management (IWRM) (Mersha et al., 2016, 2018), water governance (Hailu et al., 2018, 2019; Hailu and Tolossa, 2020), perceptions of agricultural water management (Desalegn et al., 2006) and hydro-economics (Borgomeo et al., 2018). We contribute to this body of knowledge with a focus on inequities in water security.

Methods and Analysis

Social research methods were used in three field visits to the Awash basin in 2018: Within the three *woredas* (administrative districts), seven *kebeles* (the lowest administrative unit) were selected for key informant interviews as well as complete enumeration of urban water utilities, industrial water users and systematically selected actors from selected government and international and national non-government organisations (**Table 1**).

Prior to fieldwork, ethical approval for this research was given through the departmental board of the Oxford University Central University Research Ethics Committee (CUREC). There was a team of two data collectors—one British female, and one Ethiopia male. There were uneven power relations between the field data collectors and participants and with this in mind, it was clearly stated what the benefits of the research would be. Informed verbal consent was given by each participant in this research on the basis that the data collected would be stored securely and that their responses would remain anonymous. None of the participants were actively incentivised or coerced in any way to engage with this research.

Interviews were conducted in rural kebeles selected from each woreda (14 male and 14 female, randomly selected with support from kebele officials). Interviews were secured with support from the kebele administration office. Key informant interviews ($n = 33$) were conducted with government and non-government organisations including woreda-, zonal-, regional and federal-level administrations responsible for managing pastoralism, agriculture (rainfed and irrigation), water supply (rural and urban), health and disaster prevention & preparedness. A mixed qualitative/quantitative industrial water user survey was used to collect values and perceptions of water security from large farms and factories ($n = 17$). The interview questions and industrial water user survey were piloted in Adama *woreda* (Oromia region, Awash River basin) in November 2017. The empirical evidence has been triangulated to enable a robust and reliable argument by reducing bias in the data with documentary analysis as well as through engagement with organisations in multiple and various fora since 2015.

NVivo was used to undertake systematic qualitative analysis of the empirical evidence to understand the inequity of access to water of an acceptable quality and differences in the lived experiences of water-related risks. The interviews were transcribed and translated where consent was given for recording. In cases where consent for recording was not given, detailed interview notes were used. We analysed the differences in experiences of water security between and within four groups of water managers that rely on water resources for different uses: private industries (farms and factories), state-owned sugarcane farms, urban water utilities and rural communities.

TABLE 1 | Overview of methods used in each woreda.

Upstream woreda	
Drought-prone kebele	Predominant livelihood: rainfed cultivation of grain crops (four interviews: two male, two female)
Lakeside kebele	Predominant livelihood: fishing (four interviews: two male, two female)
Flood-prone kebele	Predominant livelihood: Irrigated agriculture (four interviews: two male, two female)
Private, large-scale irrigated farms	Two flower farms, two fruit and vegetable farms (4)
Private factories	Eight tanneries, one water bottling company (9)
State-owned farms	(0)
Interviews with NGOs	Catholic Mission (1)
Interviews with Woreda government offices	Health; Land management; Agriculture and Natural Resources; Livestock and fisheries; Environment, forestry and climate change; Disaster prevention and preparedness commission (DPPC); Irrigation; Water, minerals and energy (WME) (8)
Middle basin woreda	
Drought-prone kebele	Agro-pastoralist livelihoods (6)
Flood-prone kebele	Mixed crop-livestock systems: settled agro-pastoralists with irrigated smallholds (6)
Private farms (large-scale)	-(0)
Private factories	One abattoir (1)
State-owned farms	Metehara sugarcane farm (1)
NGOs	Child Fund, Rift Valley Initiative for Rural Advancement (RIRA) (2)
Woreda Government Offices	Disaster prevention and preparedness commission; Agriculture and Natural Resources; Irrigation; Water, minerals and energy (4)
Downstream woreda	
Drought-prone kebele	Pastoralists (6)
Flood-prone kebele	Settled pastoralists—irrigating smallholders (6)
Private farms	-(0)
Private factories	One salt factory (1)
State-owned farms	Tendaho sugarcane farm (1)
NGOs	World Food Programme of the United Nations (WFP), United Nation's Children Fund (UNICEF) (2)
Others	Tendaho Dam Administration Office (1)
Other stakeholder interviews	
Zonal government administration offices	Zonal Administration Office, Zone 1, Afar; East Shewa DPPC office; East Shewa National Meteorological Agency (3)
Municipal water utilities	Seven municipal water utilities across the basin (7)
Afar regional government offices	Agriculture and pastoralism; DPPC Irrigation; Water Supply and Sanitation (4)
Oromia region	WME Bureau; Oromia DPPC (2)
Federal	Awash Basin Development Office, Upper Awash sub-branch, Adama; Awash Basin Development Office, lower Awash sub-branch, Dubti; National DPPC (3)

Our methods and analysis identified the values of water users and managers that were being protected or harmed with water access and risk. Every effort was made by the researchers to ascertain local values by using methodological tools that allowed water users and managers to identify their own values. Moreover, the analysis was conducted with the researchers' subjectivity in mind in order to reduce as much cultural bias as possible. Following this, the exposure and vulnerability to hazards were characterised in nodes as well as water users and managers experiences of water access. Seeking to understand the institutional arrangements of water security, two nodes were created: (1) planning and controlling exposure and vulnerability to hazards; (2) water allocation and access.

MULTI-SCALE LIVED EXPERIENCES OF UNEQUAL WATER SECURITY

To evaluate the multi-scale and unequal lived experiences of water security in the Awash River basin, we started with identifying water users, water-related hazards and values, in order to determine vulnerability to water risk. Reported vulnerabilities to biophysical water hazards (drought, flood and seasonal variability) by water user are given in **Table 2**. These were reported based on "normal" patterns of intra-annual climate and water vulnerability, as well as the most recent flood and drought event(s) that the respondent had experienced.

The results in **Table 2** are given by month, with the two main annual rainy seasons, *belg* and *kiremt*. However, water users in the downstream woreda reported rain commonly only falling in July and August and the middle basin user reported rain during *kiremt* only. Water users have been divided into: (1) three rural communities: upstream, middle and downstream; (2) urban water utilities; (3) private fruit/vegetable farms; (4) private flower farms and (5) state-owned sugar farms. We also surveyed 11 private factories that reported no vulnerability to climate shocks or variability, hence have been excluded from **Table 2**.

There were reported temporal changes in water demand that shaped which water-related values were being put at risk. Higher demands on urban and rural water systems in the dry season meant that water needs were not being met. In rural areas, for example, scarcity of surface water for livestock meant that animals were sometimes watered using government-managed, formal water supplies. Private fruit and vegetable farms had their highest demand in May and June due to little rainfall and the peak growing season. Since they are open-air farms, in the main rainy season (*Kiremt,* July-September), they reduced their river abstraction. Private flower farms, cultivating crops in had their peak abstraction rates from December to March, due to market demand. Despite not using rainwater for cultivation, their abstraction rates also reduced in the wet season.

Given that we define water-related values as, "principles that guide action towards water security by water users or water managers in public, private or community groups" we find that values are diverse across users. Private business users have 1 or 2 water-related values while members of rural communities have many, since so many areas of their lives are touched by, or depend on, water. Some of the values we have uncovered may appear obvious, nonetheless, it is essential to draw these out in order to garner a meaningful understanding of water risk.

The water-related values of water users and managers varied, closely aligned with their roles. The private farms and factories that we surveyed strived, above all, to be profitable, hence the primary water-related value expressed was that of secure water for productive purposes. When asked about their water use, 100% reported production processes first; only 40% reported drinking as a use of water, illustrating that drinking water was a less relevant water-related value than production. Unsurprisingly, the state-owned sugarcane farms in the three study sites placed the highest water-related value on sugarcane production, while urban water utilities prioritised the ability to deliver reliable and safe water supplies to urban communities.

Conceptualising these—seemingly obvious—water-using activities as water-related values is necessary and important to: (1) garner a meaningful understanding of water risk; (2) explore how water-related values are competing and; (3) to make comparisons across water user groups, about how inequities can be understood and re-distributed, especially in contexts with extreme inequities in water security. The latter is the case in the Awash River basin: rural communities are extremely water insecure, while private farms & factories enjoy high levels of water security. Water-related values offer a common framework for understanding what drives decision making of water users towards water security.

Rural community members hold a diverse set of personal values that have a temporal dimension and drive water- and climate-related risk adaptation strategies. The values we uncovered centred on: (1) agency over livelihood, place, mobility, self-sufficiency and the ability to partake in cultural activities; (2) well-being in terms of physical and mental health, safety and food security; (3) a secure livelihood and (4) specific values held for children now and for the future. By placing the values of the water users and managers at the centre of the analysis allows the lived experiences in the Awash River basin to explain unequal water security. We juxtapose the competing values of urban water managers, industrial water users and rural dwellers in this dynamic context.

Power

Uneven socio-cultural, financial and political power relations shape the differences in lived experiences, and ideas of, water insecurity. Power dynamics play out across scales; there are differences between water management groups and inter and intra-household inequities. Some water users have more power than others to access water through higher financial capacity, stronger influence in decision-making and social privilege. This is highly influenced by drivers within the wider political economy in Ethiopia and the fact that there are ingrained intra-household gender roles and gender inequities in rural Ethiopia (Semela et al., 2019) that shape these differences in vulnerability. We reveal evidence for how unequal water security is, in part, socially produced through uneven power relations.

TABLE 2 | Reported temporal changes recent extremes and recurrent water and climate-related hazards caused by expected and unexpected climate and water resources variability that resulted in exposure and vulnerability to water risk.

Water users	**Type of hazard**	**Long dry season**					***BELG***			**DRY&HOT**	***KIREMT***		
		Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**
Upstream rural communities	Flood		Occasional (unexpected) dry season flooding							Unexpected 2018 flood destroyed crops	Annual (expected) flooding		
	Drought										Inter-annual shortage of rainfall - most severe recent drought reported 2015/16		
Middle basin rural communities	Flood		Occasional (unexpected) dry season flooding that destroys crops, fodder							Unexpected 2018 flood destroyed crops	Annual (expected) flooding		
	Drought										Inter-annually recurrent below average rainfall (drought)		
	Seasonal variability	Water scarcity											
Downstream rural communities	Drought								Cultivation of irrigated agriculture. Water not always available in the irrigation canal (2015, completely dry)				
	Seasonal variability	Water scarcity							Most difficult months for water access (due to scarcity)		Water Scarcity		
Urban water utilities	Surface water						Surface water infrastructure blocked by debris in the river washed down from upstream						
	Groundwater	Groundwater levels decrease									Salinity of groundwater increases		
Privately owned fruit and vegetable farms	Hazards reported from 2018				Frost destroyed crops		River level was too low and crops were lost as a result						
State-owned sugar farms	Flood										Annual (expected) flooding that varies in intensity		
	Drought						Inter-annually recurrent below average rainfall (drought) affecting water availability (up to 25–30% reduction in cultivation in 2015/16)						
	Seasonal hazards								High evaporation and low rainfall				
Privately owned flower farms	Seasonal hazards										Decrease in surface water quality		

Source: complied from interview data.

Financial Power

Provision of safe and sufficient water to communities is the highest water value of providers but they lacked financial power to make investments to improve service delivery. In general, across the Awash River basin, government water supplies were reported to be intermittent and of poor quality. This was reported by urban water utilities, rural water service providers and private industries that were accessing water from government water supplies. In most rural and urban cases, water was not being treated before being distributed to community members, despite elevated fluoride and likely faecal contamination.

The ability of water users to be water secure is strongly influenced by their power to invest in water treatment technologies. Private factories and flower farms in the Awash basin were generally water secure; they had good access to water and their production processes were not vulnerable to water risks meaning that their values were not being compromised by water insecurity. Factories typically had deep, reliable boreholes and the flower farms were using raw river water and sophisticated water treatment systems. However, government water supply organisations lacked similar power and were forced to provide poor quality water to rural and urban communities.

Peoples' understanding of inequity in water security was strongly grounded in ideas of unfairness and injustice. Upstream, the groundwater resources were highly contaminated with fluoride. Most people were drinking untreated groundwater with unpleasant health impacts including browning of teeth, scoliosis of the spine and bone deformities. Next to the main town, a water bottling factory was abstracting groundwater, treating it to safe drinking water standards, bottling it and selling it for profit. The town residents refused to buy bottled water from this factory due to the unfairness they felt that they could not access safe water whereas a private company could. This forced the company to transport their product outside of the area. Here, a company, with enough financial power was able to access sufficient water and treat it to a high quality, in an area where the physical water resources were of poor quality and a less powerful water manager, the government water provider, was unable to.

Water users and managers were adapting to different degrees to access water and mitigate water-related risks. People living in rural areas were constrained in protecting their values by a lack of agency to engage in alternative income-generating activities. In some cases, this resulted in maladaptation producing adverse risks. Research participants from rural areas that reported having diversified livelihoods were more able to adapt when income was lost from flood, drought, seasonality or poor water management. However, rural residents reported making charcoal or selling firewood that was resulting in deforestation with the potential to accelerate land degradation and exacerbate flooding.

Households within rural areas were adapting by whatever means necessary when they were in crisis. However, they had insufficient financial power (money to buy water from more expensive sources) to secure safe, reliable water access for use at home. Many of the interview respondents cited cost as the reason for not accessing safer sources, such as transporting water from the local town or buying bottled water to drink. Hence, they were often relying on surface water bodies, or shallow groundwater to fulfil their domestic water needs, irrespective of the quality of the water. This dependence was particularly high at times when rural (or urban water supply systems, when being accessed by rural communities) did not provide enough water to meet household needs. One of the most difficult challenges to manage was the uncertainty around water availability through government supply systems experienced across the basin. Most rural research participants reported not knowing when water would be available or where, resulting in a time-use and emotional burden.

> *"We travel around to many different sources to find water with the mule or donkey and cart. Most of the time the children go but sometimes I go myself. During the dry season it is more difficult because we have to bring water for the cattle as well. In the dry season the distance is further. Often we go at night to collect water. We don't know which sources will be available and we do not have telephone numbers of people in the kebeles to check. There was a time when there was no water and we came back with an empty barrel and we were thirsty. It happens at some point every year."* (Male farmer, upper basin woreda, December 2018)

Across all the private industrial water users surveyed, there were no challenges reported to accessing water that were not overcome. There was good access to water due to their strong financial power for investment; electricity shortages that could potentially limit water abstraction were buffered with generators. Occasional infrastructure failure was reported that had very little impact on production or staff as they switched waters sources or had the economic power to quickly address issues. Borgomeo et al. (2018) argued that the industrial sector would lose 3% in GDP under future decreased rainfall available climate scenario in the Awash River basin. The empirical findings from this study suggest private industry would be less impacted than others due to the financial and adaptive capacity of industrial water users.

Social and Cultural Power

Considering intra-community power relations informs our understanding of equity in water security. When rural populations are considered as a homogenous group, or aggregated statistics on water coverage are used for information, the worst-case scenarios are often excluded from the narrative and gendered inequalities are hidden. Feminist approaches have been shown to be useful in revealing water-related inequities (Truelove, 2011). While many water risks may be related to place, the experience of them will differ for women, men, girls and boys. These gendered differences are shown in **Table 3**. This table is not comprehensive: gendered differences in responses to interview questions were drawn out and included in the table. Those water risks that significantly overlapped responses from men and women have not been included, but are discussed in the text. There were also a large number of non-water related community values collected, such as transportation, roads and land scarcity that have not been included.

In one case, a female farmer struggled to access water, in part, because the rural water supply system close to her home frequently failed due to a lack of electricity to pump groundwater. At these times, she would travel to the local town to collect water. When both the town and rural water supply systems were not

TABLE 3 | Overview of intra-basin differences in rural experiences of water-relates risks, with embedded water-related values.

Water users	Upper woreda			Middle woreda		Lower woreda	
Rural Communities	**Fishing community**	**Drought-prone rainfed cultivators**	**Flood-prone irrigating smallholders**	**Drought prone agro-pastoralists**	**Flood prone irrigating smallholders**	**Settled agro-pastoralists with mixed livelihoods: livestock and irrigated smallholdings**	**Drought-prone pastoralist community**
Male	Flooding results in lost farm investments. Feeling angry during a flood.	Drinking water scarcity. Climate variability impacts on rainfed cultivation.	Worried about food and income when crops destroyed by flood. Anxiety, fear for house during flood.	Conflict over rangeland during drought. Lake Beseka and Kassam Dam have consumed the rangelands limiting fodder access.	Insufficient irrigation. Feeling like a failure and weak when crops destroyed by flood.	Irrigation shortage during drought.	Livestock loss during drought.
Female	Flooding: reduces fish in lake; Prevents livestock watering; Poor household water quality. Worry for self and sadness for affected.	Huge emotional, time and workload burden of securing income for children during drought. Water, food and soap price hikes during drought.	Worried to buy food for children due to market price rises during drought. Worried for life during flood.	During drought: worry about insufficient drinking water and food. Large workload during drought fetching water and weak livestock	Flooding and fear for life and house. Rainfed farming—lack of rain and prosopis invasion.	Loss of human and animal lives during drought. High workload taking livestock to feed. Physical health impacts from collecting water.	Households without a donkey struggle to secure household water access.
Children	In the dry season, flash floods interrupt schooling. The well-water causes illness. Children unsafe when collecting water along the busy road.	During drought school missed for labour including: livestock watering, household and private farm work. Life at risk from diseases such as cholera.	Flood causes malaria and typhoid. Child labour during drought.	During drought: not enough milk for children's nutritional needs. Increase in waterborne diseases.	Flood causes: interruption to schooling; Malaria; and Food insecurity.	Drought results in an increase in waterborne diseases and missed education.	Child labour to tend to livestock—missed school and high workload during drought.

operating, she had to buy bottled water at high expense. In the interview she was asked: *"When you compare yourself with the community in this area, what is your level of accessing drinking water: top, medium or least?"* She responded: *"I don't have any jerrycans, a donkey or a cart. I have to bring water by carrying it on my back. I am the least."*

We found gendered differences between lived experiences of the mental health affects of water insecurity from risks to livelihoods and household water security (Wutich et al., 2020). In line with Vins et al. (2015) we found that men experienced the emotional burden of being the household "provider" when climate shocks resulted in crop destruction or loss of livestock. Male informants reported feeling "angry" "disturbed" and "great worry." Women were primarily responsible for managing household water, a common finding in literature (Geere and Cortobius, 2017) and experienced various risks that men did not. There is existing evidence that women's mental health is adversely affected by household water insecurity (Brewis et al., 2021). Women also experience livelihood risks, for example, one fisherwoman reported:

> *"When I work this work, there are many issues; there are thieves waiting for you at the roadside so you fear for your physical safety and your materials may be stolen. I bought my fishing materials for around 20,000 Birr [633 USD]. If you are not watching, the [fishing] materials will be stolen because they are at the fishing site most of the time. For example [my fishing materials] have been stolen twice… There are some people who are not happy if you are strong in your work especially when you are a woman and working effectively."* (Female member of fishing community, upper basin woreda, December 2018)

Children experience wide-ranging water-related health risks during drought and flood events (World Health Organisation, 2014) that include adverse effects of food insecurity (Belesova et al., 2019). One farmer revealed that her daughter had died many years before during a drought shock after contracting cholera. When discussing water-related health risks, one informant reported being ill himself from dysentery but in general, most reported that their children had become ill from typhoid or with unspecified diarrhoeal disease. Respondents talked about a lack of nutritious food for their children during times of droughts, particularly in relation to livestock who stop producing milk.

Climate shocks take children out of school and interrupt education (Randell and Gray, 2016). At a time of flood, one farmer revealed that he kept his son home from school for fear that it would affect his health. *"He was young and sometimes we feared the bad smell from the water. You, yourself may feel that bad smell when you come here. So, it was for the health of the boy. We prevented him from going to school for this reason."*

Additionally, climate shocks were resulting in children working as child labourers in homesteads as well as private farms. One farmer reported that when her crop failed in 2013, she had to find an alternative source of income. *"During the drought in 2013, I worked as a daily labourer on an irrigation farm. Sometimes my 7-year-old daughter would work with me."*

Overall, we found that children were typically more vulnerable to water-related risks than adults and often parents were burdened with deciding how to protect their children during climate shocks. In these two cases, difficult value- and needs-based choices were made with costs and benefits of the trade-offs. In both, education was traded in favour of health in the first example and income-generation in the second.

Political Power and the Production of Water-Related Risks

Private and state-owned industrial water users were producing risks for urban and rural dwellers with pollution and by displacing communities from the land. This is strongly related to the relative power that they hold compared to rural populations. Tanneries produce wastewater that is high in salt, chromium and nutrients, among other pollutants (Chowdhury et al., 2015). Six of the seven surveyed tanneries reported undertaking primary effluent with secondary effluent treatment systems under construction. Primary effluent treatment removes primarily solids, but suspended and dissolved pollutants remain in the effluent. The two flower farms surveyed had artificial wetlands for wastewater treatment, which have been shown to have low effectiveness for nutrient removal in other areas of Africa (Mekonnen et al., 2014). Rural dwellers had negative perceptions of the effects of industrial water users on water quality in the Awash:

> *"The quality of the water in the dam is decreasing over time because of the flower farms. They dump polluted water from the farm directly into the dam. There is some change in the fish. When [the fish] are stationary in the nets for too long they start dying and decomposing. The government don't care because they are getting more money from the flower farms. The water colour becomes green like leaves, especially around [the] tannery."* (Male member of fishing community, upper basin woreda, December 2018)

Community displacement by the state-owned Tendaho sugarcane farm (downstream) has resulted in a poorer perceived quality of life by rural dwellers. Pastoralist populations had little power to participate in decision-making that ultimately put their values at risk. The displacement of pastoralists in the Awash River basin in Ethiopia is not a new phenomenon—it dates back as early to the establishment of the sugar farms in the 1950s (Lavers, 2012). A rural community member in the lower basin woreda reported insufficient provision of basic services after being displaced and a reduction in their quality of life.

> *"Our former place was better because there, we had clean water. Now we have no water. When we came to this place, the government promised that we could lead better life. However, he betrayed us and now, we have nothing."* (Male pastoralist, lower basin woreda, May 2018)

Overall, water managers with more socio-cultural, financial and political power had a greater ability to be water secure. Socio-cultural differences in the impact of water insecurity were reported in emotional well-being, physical health and children's education. The diverse negative impacts of water insecurity are often missing from the overarching narratives around water insecurity and poverty that focus on securing income-generating livelihoods and food security. For example, water policies do not include, or underemphasise values and gendered differences in lived water insecurity experiences. Moreover, uneven power relations are insufficiently engaged with by governments and practitioners developing interventions towards water security, resulting in a continued misunderstanding or inequities, meaning that they are poorly addressed.

Place

In the Awash River basin, water security is uneven in different places across the basin, between and within districts. Place is an essential element of water security as it influences exposure to differing climate conditions in the districts, the proximity of water users and managers to available water resources, the quality of those resources and exposure to risk from floods, droughts and land cover change.

Inequities of Rural Water Risks Across Scales

The risks to the water-related values of rural people varied between districts due, in part, to the proximity of water users to accessible water resources and local climate conditions. There were intra-basin differences in lived experiences of water risks between the woredas. In upstream rural areas, water resources for use at home were easily available, often on premises, due to the rich availability of shallow groundwater resources and higher average annual rainfall than downstream. In contrast to downstream areas, households did not have to travel long distances to fetch water for domestic uses. Water fetching is associated with negative health impacts (Geere et al., 2018), hence upstream there were less concerns about related physical health impacts than downstream.

In the arid downstream, rural people experienced water scarcity most of the time. In this district, women and men reported travelling up to 10 h to fetch water for domestic use at certain times of the year (usually May and June, see **Table 2**). Children were also subject to these journeys. These downstream areas experienced far greater health risks from water fetching than those upstream—reporting extreme fatigue, thirst and physical pain.

Water quality was also a risk that varied across the basin. Human health, particularly the health of children, was found to be highly valued by communities across the basin. The large quantity of shallow groundwater in the upstream woreda contained dangerously high levels of fluoride (Demelash et al., 2019); severe and debilitating health impacts are caused over time with the accumulation of fluoride in the body by consistent consumption (Kabir et al., 2019). This was not the case in the other two study woredas. In the upstream woreda, there was only one fluoride removal treatment plant providing safe drinking water for <10% of the woreda's population.

Waterborne diseases were reported in all three areas of the basin but were found to be more prevalent in the middle and lower areas. In particular, typhoid and dysentery were reported as posing a high risk, with children disproportionately affected. The World Food Programme office in the downstream woreda estimated that waterborne diseases posed the highest risk to life (WFP, 2018). While the specific relationship between water quality and ill-health varied across the basin, there were concerns reported about poor water quality and the risk to health by the majority of rural interviewees.

As well as upstream-downstream differences, water insecurity experiences varied over smaller scales, with intra-woreda differences being observed. In the middle basin, two kebeles within the same woreda had very different lived experiences of water insecurity; one area was chronically water scarce and one was flood-prone. The people living in these kebeles had shared values in terms of generating income and achieving food security through farming. These values were being put at risk in different ways—either with too much or too little water.

A person's physical location is strongly related to their experience of water insecurity. In a chronically water scarce kebele where rainfed farms were being cultivated, being water secure was highly connected to the rain—as one farmer said, *"When it starts raining, we forget our sufferings."* Conversely, in a flood-prone kebele in the same woreda, farmers were engaged in irrigated agriculture. Farms were on the banks of the Awash River with direct access to water resources for developing irrigation all year round, increasing farming output, income and food security. However, the irrigated crops were regularly destroyed by unanticipated flooding resulting in water risks.

Adaptation to Place-Mediated Rural Water Risks

Rural dwellers were maximising the protection of their values to the extent that their situation allowed. In doing so, they were making trade-offs in which risks to mitigate. In the drought-prone kebele in the middle basin woreda (agro-pastoralists), when not cultivating rainfed farms in the wet season, part of the household would migrate to a tributary of the Awash River in the dry season. This allowed access to a reliable and affordable (free) water source for people and animals as well as sufficient grazing land. Children in school and older members of the community would remain in the village.

This partial household migration allowed the protection of some of the values expressed in the area but several were still being put as risk by water insecurity. Food security, income and children's education were being protected while health and household water access remained at risk. In the village, the community had access to a single borehole that was not always functional. Those that remained in the village would have to travel long distances to access household water from a canal or a lake further afield. This was compromising the emotional well-being, physical health and increasing workload, primarily for the women and girls that were collecting water.

Insecure land rights due to an uncertain land tenure system (Ayano, 2018), and tacit barriers to migration (De Brauw et al., 2017) limit the agency of rural people to become water secure by changing their place. However, private and state-owned industries have choice as to where their farm or factory will be located. This gives industrial water users more opportunity to avoid place-mediated water insecurity, targeting good water access and less exposure to flood and drought risks.

Place-Mediated Risks From Drought, Flood and Land-Cover Change

In 2015, Ethiopia experienced the worst drought event in 50 years and food aid was requested for 10.2 million people for 2016, in anticipation of widespread food insecurity (FEWSNET, 2015). The drought was caused by an El Niño-Southern Oscillation (ENSO) event (Liou and Mulualem, 2019) that resulted in severely reduced rainfall in the belg rainfall season (March-May) and delayed and erratic kiremt (July-September) rainfall. Some areas of the country received up to 50% less than average rainfall (Singh et al., 2016). Resultantly, there were drought risks reported by different water users and managers from that most recent drought event during data collection.

In 2015/16, drought risks to three state-owned sugarcane farms varied across the basin; the severity of loss of farm production from drought risks increased further downstream. The most upstream sugarcane farm, Wenji, reported very little reduction in production. In Metehara (middle Awash), abstraction was reduced by nearly a third and in Tendaho (lower Awash) sugar production was reportedly halved due to insufficient water. Data from the Awash Basin Development Office (AwBDO) [known then as the Awash Basin Authority (AwBA)] revealed that the volume of water in the Tendaho dam in November 2016 was 23% of what it had been the previous year (Awash Basin Development Office, personal communication, May 2018). The state-owned sugarcane farms were adapting to some extent using groundwater and deficit irrigation but had no formal flood or drought management plans in place.

Intra-farm inequities in water-related risk experiences at sugarcane farms were closely connected to place. In irrigation schemes, the tail end users usually get less access to water than those at the head end (e.g., Mollinga, 2003). In Wenji (upstream), the small amount of lost production in 2015 occurred at the tail of the irrigation canal. Further downstream, the sugarcane farms' irrigation canals were shared by smallholder farmers at the tail end. In 2015, these smallholders reported insufficient irrigation water for cultivation, more severely affected by the drought than the sugarcane farm at the head of the canal. One smallholder farmer in the middle Awash reported, "*There was a shortage of water for sugarcane—we didn't get even a small amount of water at that time for irrigation.*" Smallholder farmers expressed a desire for their own irrigation canals, rather than being at the tail end of the sugarcane farm's canal. Water security of cultivators in this case is strongly connected to their place along the irrigation canal.

In addition to drought impacts, rural and urban communities were exposed to water risks from flooding and land-cover change from the expanding Lake Beseka that varied across the basin. Crop destruction from flood was occurring most commonly upstream, by flooding events every 1–2 years. In the middle basin, the expanding lake Besaka was covering land, limiting land-based livelihoods. Moreover, the lake was expanding to cover the urban water supply infrastructure for the main town in the middle basin woreda, challenging the urban water utility's ability to deliver safe and reliable water supplies. In the middle basin and downstream, crop destruction was relatively uncommon; irrigated crops had been destroyed through insufficient water availability only once in the previous seven years. These negative livelihood impacts, reported across all three districts, were contributing to sustaining poverty and putting the reported values at risk.

Overall, place inequities are shaped by climate conditions and proximal availability and quality of water resources. Place mediates exposure to a diversity of risk including health risks (related to the quality and availability of proximal water resources), livelihood risks (related to exposure and vulnerability to flood and drought shocks) and risks to agency (the ability of people to change their place). The concept of place offers insights into the dynamics and driving forces for uneven water security across multiple scales as well as the land-water connections that mediate the agency that water managers have to improve their water security.

Politics

The Awash River basin is a microcosm of Ethiopia's developmental state; the country's national development dynamics plays out at the basin scale contributing to inequities in water security. Ethiopia follows an agricultural development-led industrialisation strategy for national economic growth and institutional power lies at the federal and regional levels. It is at these higher echelons that decisions are made that favour private industry and state enterprises and disfavour rural livelihoods (Hailu et al., 2018). In this section, we unpack the governance mechanisms and institutional arrangements that influence unequal water security within the wider political economy, highlighting how the inclusion of politics is critical for studying inequities in water security as it has explanatory power for uneven manifestations of water access and water risks.

Bottlenecks to Realising Water Managers' Values

The Awash is a transregional river basin meaning that the overall responsibility for managing the river's waters is legally mandated to the federal Awash Basin Development Office (AwBDO). However, the regions have a constitutional right to develop water resources within their administrative boundaries. This is not a unique phenomenon, Suhardiman et al. (2018) argues "river basin planning as a function of power and contested arena of power struggles." Responsibility for water resources management in the Awash basin is shared by government stakeholders at the federal and regional level, as well as at the more local level.

Broadly, federal and regional water managers expressed similar values and priorities for water resources development but there were barriers to co-ordination. In interviews with the AwBDO, Oromia and Afar regional Water, Mineral and Energy Bureaus, we found that shared values include: (1) good water quality; (2) successful management of floods and droughts and (3) safe water access for urban and rural communities. In line with previous research (Mersha et al., 2016), we identified a lack of institutional clarity around roles and responsibilities for: (1) reducing industrial pollution, (2) drought management and (3) flood prevention, putting water managers' values at risk.

First, respondents communicated a strong appetite for reduced industrial pollution in the Awash but little action to decrease it. There were three key reasons reported by industrial water users that explained why they are not taking active steps to reducing their pollution: (1) Guidance: Private industries don't consider that there is sufficiently clear information from the government on what procedures and standards they should be meeting - especially foreign investors who reported difficulties in understanding their responsibilities. (2) Powerlessness: factories reported that if they improve their effluent/wastewater treatment and others don't then it will make no difference. (3) Deflected responsibility: blame was placed on other industries and agriculture, including farmers with smallholdings.

Institutionally, environmental protection laws and regulations are in place but poorly enforced. The institutional arrangements include the national pollution law and the legislation from the Oromo Environmental Protection Agency (EPA). They are not without difficulties in implementation: *"Large- and medium-scale manufacturing industries in Ethiopia have environmental protection policies. These policies are overambitious and never fully implemented… Corporate environmental protection has not been a widely accepted concept so far"* (Amare, 2019). This, within the favourable political economy, goes some way to explain how large water users are producing water-related risks for other water users despite the political action to avoid this.

Second, there is a lack of clarity around water use during a drought year and conflicting understandings of protocol. The AwBDO policy to reduce upstream irrigation in drought years aims to prevent drought risks across the basin. While state-owned sugarcane farms, who are regulated by AwBDO, reported reducing their abstraction during a drought year, private industrial water users reported not reducing their abstraction or knowing this was a policy of the AwBDO. Therefore, the values of private commercial enterprises (primarily their production processes) were not at risk during a drought year.

Efforts to prevent drought risks across the basin with pre-emptive water allocation reduction are not having the desired outcomes. The main responsibility for drought preparedness and prevention institutionally lies in the Disaster Planning and Preparedness Commission (DPPC)—the branch of the Ethiopian government responsible for disaster risk reduction across the country. The AwBDO, despite having a policy for reduced water allocation upstream during a drought year, lack the power and mandate to drive drought prevention forward.

Third and finally, there is no clear, legal mandate for who is responsible for investing in flood mitigation, hence flood management is institutionally fractured. The national water resources management policy highlights flood management as a key priority but does not say how or by whom (FDRE, 1999).

Due to the constitution/legal as well as the federal/regional disconnect, organisations feel powerless and have insufficient funding to tackle the causes of flooding by themselves. We found that this is compounded by insufficient data and a lack of trust in climate forecasts.

Equity in Water Policy

Within a political economy that favours agricultural development-led industrialisation, we have found two institutional mechanisms that specifically favour water access for farms and factories. Currently, *"there are no special institutional arrangements [in Awash] that protect the interests of the less privileged local communities."* (Hailu et al., 2019), even though drinking water has the highest national policy priority for water resources management (FDRE, 1999). We have uncovered two key policy areas that hamper more equitable outcomes in water security.

First, we have found that water allocation for irrigation, particularly for the state-owned sugarcane farms is at the centre of water allocation planning in the Awash basin. The logic behind this is intuitive—sugarcane farms are "large water users" and domestic water users are "small water users"—therefore, it is more important to manage large quantities of water rather than small quantities. However, this directly contravenes the national water policy priority of drinking water previously mentioned, reinforcing structural inequities in water security that adversely affect less powerful water users.

Second, guidelines for water pricing in the basin are highly inequitable. Industrial water users pay 3 ETB/1,000 m^3 of (untreated) water that they use[1] (0.0001 USD/m^3) whereas a rural household pays 0.5 ETB/20l of (untreated) water that they use (0.87 USD/m^3). It is important to note that, industrial water users do incur their own infrastructure development and maintenance costs. However, this does not negate that fact that rural households are paying 8,700 times more for access to water. This pricing policy contributes to inequities in water access and is likely to reproduce them overtime.

Overall, the political economy, institutional arrangements and policy frameworks are contributing to inequities in water security in the Awash River basin. Industrial pollution is on the rise and poorly regulated while responses to mitigate risks from drought and flood events are predominantly reactive rather than pro-active across all levels. Government and non-governmental organisations are insufficiently equipped to actively engage in building institutions and strategies for preventing risks from deteriorating water quality, floods and droughts.

DISCUSSION

Plural Understandings of Equity Through Embedding Values in Water Risk

Including values in the conceptualisation of risk within a hydrosocial framing of water security offers unique insights into how inequities can be understood; where values are being compromised, this offers potential indicators of degrees of inequity in water security. Equity is understood in different ways by water managers and users, strongly shaped by various water-related values, which offers insights for how we explore and understand the diversity of inequity in water security. What we found in the Awash River basin is that individuals living in rural areas were experiencing a regular inability to fulfil their values due to drought, flood or chronic scarcity of safe water provision. Conversely, private companies were usually able to fulfil their values. Therefore, inequities within and between water using groups can be assessed using a value-based framework.

Embedded values enable a diverse interpretation of water security, a grounding of its subjectivity and fosters an academic move towards local conceptual understandings (the latter called for by Sen and Kansal, 2019). There have been calls for the inclusion of diverse values in water security research and practice. Jepson et al. (2017) highlighted the importance of including *"values about water that extend beyond, or in addition to, utilitarian ones"* in hydrosocial framings of water security. Using qualitative research methods allowed research participants to identify their own values and with an analysis starting from a place of values, our case study research revealed that embedding values within ideas of water access, risk and equity enabled a diverse interpretation of water security, a grounding of its subjectivity and fosters an academic move towards local conceptual understandings.

Reconciling Competing Values

To return to where we began, Giddens (1999) argued that ameliorating risk requires managing competing values, hence a fundamentally political set of questions, which is what we have discovered to be true in the Awash River basin. Loftus (2015) noted that the mainstream water security literature fails, "*to adequately politicise the processes and relationships that reproduce water inequalities*". Our case study addressed this by directly exploring the role of politics and power in mediating the reproduction of inequities of water security over time.

The realisation of water-related values in the Awash River basin was being constrained by political factors and power relations across scales. Overall, we found that the values of private water users were being met due to their financial power (water flows to money) and ability to choose their place (premium land acquisition close to quality water resources); that the values of government managed water supply systems were constrained by a lack of financial power and that place was a key barrier for state-owned sugar farms to be able to protect their values. Therefore, we are left questioning how can the values of all water users be met and even, should they be met?

Values-based approaches to water governance are not new (Groenfeldt and Schmidt, 2013; Jiménez et al., 2020) and even considered an essential component of good governance (Schulz, 2019). These are seen to some extent already in the (FDRE, 1999) with a guiding (value-based) framework for water priorities mandating drinking water first, irrigation second, followed by industrial water users (and hydropower). In the over-allocated Awash River basin, we argue that all current water demands cannot be met; all current water-related values

[1]Additionally, it has been argued that the low water fee for irrigation water is partially contributing to low water productivity in the basin (Ayana et al., 2015).

cannot be fulfilled. The degree of inequity between rural water users and private companies in the basin is unacceptable. Reducing the water demand is required to meet values and the redistribution of water-related risk is necessary to reduce the inequity. Including ideas of inequity alongside national policy priorities in decision making can go some way towards assessing difficult trade-offs in competing water-related values for just and sustainable outcomes.

Trade-Offs in Multi-Scalar Approaches

This study offers insights for how embedding values at multiple scales can offer an operational framework for assessing trade-offs in decisions. Trade-offs in multi-scalar approaches to water security have been extensively studied in the literature and they are not easy to navigate. Koehler et al. (2018) have argued that the inclusion of water risks and values in policy is essential for achieving the sustainable development goals. This means that, to manage water security trade-offs in a way that protects the most vulnerable and marginalised, a consideration of values is essential.

The physical location of water users is a critical determinant of water security. In the Awash River basin, we found that inequities in water security were shaped by the place of a water user/manager in the basin, dictating their proximity to a volume of water resources of any quality and their exposure to water-related hazards. In turn, the ability of water users or managers to change their water security status was strongly mediated by their agency and relative power to change their place. This relationship between water security, power and place can go some way to emphasising natural systems in hydrosocial studies.

Overall, our framework, established with literature and case study evidence, sheds light on understanding inequities in water security. We have found that qualitative research methods allowed values to be embedded in risk offering nuanced and local understandings of inequity in water security. Reconciling competing values (political interests), at multiple scales, in the Awash River basin will not be straight forward, but equity must be considered for just and sustainable outcomes. Inequity is a core component of water security and it is vital to develop an evidence base for subjective understandings of the “acceptable” levels of inequity that constitute the realisation of water security.

CONCLUSIONS

In a context of global population growth, urbanisation and climate change, increasingly challenging trade-offs in water security will have to be made. Without explicit consideration of equity, risk and values in these trade-offs, the poor will continue to be marginalised and water security outcomes will remain unacceptably unequal. Water security is diverse, complex and uneven with inequities playing out at multiple scales. The diversity of water risks is often missing from water policies—not allowing holistic consideration of values and gendered differences in lived water insecurity experiences. This results from uneven power relations, the political economy and institutional arrangements, contributing to the reproduction of inequitable water security over time. Water security interventions need to include water-related values and address water equity explicitly to meet social development targets. To move towards an enabling environment for more equal water security, we call for the consideration of equity in trade-offs, that consider risk, (re)-oriented with embedded values, at multiple scales.

We find that (re-)orienting the concept of water risk from a physical towards a social science framing allows it to be embedded within a hydrosocial framing of water security. A hydrosocial framing is important for understanding how politics and power underpin inequitable water security, actively putting vulnerable and marginalised populations at the centre of water security. Lived experiences, perceptions and notions of equity in water security differ to water users and water managers and are strongly linked to risks. Considering multi-scalar inequities together rather than separately offers a more comprehensive understanding of how equity can be employed in water security trade-offs.

Building on the existing hydrosocial framing of water security, and with case study evidence, we have revealed a multidimensional, socio-natural framework for studying the production and reproduction of unequal water security. Though based solely on one study and needing application and development across contexts, we shed light of the importance of bridging the well-established concepts of equity, risk and values. This framework can be used in the water sector, and beyond, for ascertaining contextual understandings of equity, access and risk. This framework offers a sufficiently broad foundation for similar studies in different contexts, particularly those concerned with how equity can be employed in decision-making for trade-offs in water security.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Oxford Central University Research Ethics Committee. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

CG was involved in field data collection, theory development, and writing the first draft of the paper. KC was involved in theory development, and review and revision of multiple paper drafts. TA was involved in field data collection and review and revision of the final paper draft. All authors contributed to the article and approved the submitted version.

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Towards an Integrated Approach to Improve the Understanding of the Relationships Between Water-Borne Infections and Health Outcomes: Using Malaysia as a Detailed Case Study

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As in many low- and middle-income countries around the world, thousands of local communities in Southeast Asia rely on river water to sustain their livelihoods. However, poor water quality threatens the health of both humans and ecosystems. The aim of this review was to examine the available literature to investigate how health outcomes in Malaysia have been studied and reported as directly attributable to human infections from river water. Computer-aided searches from 10 electronic databases were undertaken, with searches limited to the English language and publication dates since January 2010. The literature search revealed that the predominant river water infections identified in Malaysia were bacterial (coliforms, *Salmonella* spp., typhoid, leptospirosis, melioidosis), viral (including dengue, hepatitis, enterovirus), parasitic infections including amoebiasis, giardiasis and cryptosporidiosis, helminth infections, *Blastocystis* infections and sarcocystosis. No studies were found that have attempted to evaluate the impact of water related infection on human health longitudinally. Moreover, the possibility of integrated water governance systems that could reduce infection and improve water quality, particularly for marginalized groups have not been discussed or studied. Several cross-sectional studies identified infections at a point in time, but large longitudinal data sets of water infection parameters and how they influence human health outcomes have not been reported. Using Malaysia as a demonstration case study, we suggest a number of recommendations based on using a systems approach to tackle the challenges involved in data collection and integration, which is central to the understanding, strategic planning and management of water-borne infections.

Keywords: water, health, Malaysia, infectious diseases, systems approach

INTRODUCTION

In Southeast Asia (SEA), thousands of local communities rely on river water for sustainable livelihoods; this may be through operating fisheries, coastal farming or tourism. These economic activities form an important water-food nexus, which has driven regional socioeconomic development for more than 40 years (Blancas and El-Hifnawi, 2014; Pangare et al., 2014). According to The World Health Organization (WHO), almost 10% of the Global Disease Burden could be prevented by improving water access, sanitation, hygiene and management. The WHO and United Nations International Children's Emergency Fund's (UNICEF) Joint Monitoring Programme (JMP) has reported that ∼785 million people worldwide lack access to safe water in 2019 with the majority living in rural areas of low and middle income countries (LMICs) (World Health Organization, 2017, 2019; Gomez et al., 2019).

Global burden of disease assessments over the last 25 years have allowed the influence of water accessibility, sanitation and hygiene (WASH) practices on health outcomes to be estimated (Prüss-Ustün et al., 2014). They are commonly reported in the context of communicable diseases such as diarrhoeal illnesses, nematode infections, lymphatic filariasis, trachoma, schistosomiasis, malaria and dengue (Prüss-Ustün et al., 2014; Troeger et al., 2017). However, there are several challenges involved in identifying and evaluating the direct impact of poor water sanitation and hygiene on human health, as exposure at the individual and household level is difficult and expensive to monitor. Hence, most water quality assessments are undertaken at the point of distribution. Diarrhoeal diseases are often non-specific and describe symptoms such as stomach pain and stool features rather than identifying a pathogen in every case due to difficulties in accessing the appropriate tests and laboratory services in resource limited settings. As a consequence, the burden of disease at the country level is often by inference and association with water sources, such as river water, rather than a well-documented pathway from exposure at the river to disease development.

A fundamental goal of applied epidemiology is to determine a relationship between the two factors (in this case exposure to unclean water causing diarrhea illness) removing confounders, mediators or modifying factors. Unfortunately, most of the time, because data is collected based on a historic event, it is prone to recall and interviewer bias, along with sample and detection bias as only severe cases tend to get reported. When symptoms rather than objective evidence of a specific microorganism are used as surrogate markers of an infection, data will likely be skewed showing a large number of false positives (Aiello and Larson, 2002). The United Nations Sustainable Development Goals (SDGs); SDG3 (Good health and wellbeing), SDG6 (Clean water and sanitation), SDG12 (Responsible consumption and production), SDG13 (Climate action), SDG14 (Life below water) and SDG15 (Life on land), all directly affect or are influenced by water accessibility and quality. There is a huge disparity in provision of WASH between countries and LMICs are beginning to develop national policies to implement the WASH requirements warranting an evaluation of the impact of water on health in emerging countries.

Here, in this review, we initially evaluate the impact of water sanitation and hygiene on human health in an upper middle-income country, Malaysia. In 2017, Malaysia had a population of 30.6 million with a life expectancy for women of 77.3 years and men, 72.4 years with the greatest number of deaths, from ischaemic heart disease, lower respiratory tract infections, stroke and road traffic injuries. Drowning comprised 0.52% deaths in <5-year-olds, but 8.6% total deaths in 5- to 14-year-olds. Diarrhoeal illnesses caused 1.46% total deaths in <5-year-olds and 0.98% total deaths in 5–14-year-olds. In Malaysia, residential, agricultural and industrial wastes are the three main sources of river pollution. In the 1920's, Malaysia introduced pollution-related legislation to control river pollution through the "Waters Act 1920." This has been amended and improved several times over the years to regulate environmental issues, pertaining to drinking water, household water and water used for industrial purposes and recreation. The impact of water-borne infections on human health in Malaysia has been reported and they are sporadically reviewed. However, there is currently no systematic review that has comprehensively evaluated the evidence that connects water-borne infections to health. The aims of this review were firstly to examine river water and health related articles from 2010 in Malaysia, assessing the types of water-borne infection and the challenges involved in their management, and secondarily to use this data to make recommendations for future data collection in order to facilitate the development of integrated, water-borne infection management strategies using systems approach in Malaysia for the future.

METHODS

In this study, computer-aided searches of the following electronic databases were undertaken, limiting searches to English Language and publication since January 2010: PubMed, Medline, Ovid, ProQuest databases, Scopus, Web of Science, JSTOR, EBSCO, Compendex and Google Scholar. The keywords and combinations of keywords are listed in **Supplementary Table 1**. The types of studies included in the review comprised: randomized (including cluster randomized) controlled trials, quasi randomized and non-randomized controlled trials, case control and cohort studies related to an event or intervention, observational studies and time series or interrupted time series design studies related only to humans. Titles and abstracts were screened by a single reviewer, and data extraction were carried out by two independent reviewers, using a structured and piloted form. Differences between reviewers over data extraction and quality assessment were reconciled with the intervention of a third assessor, where required.

A second search was performed using various database as listed in **Supplementary Table 2**, as these diseases were either endemic, neglected tropical diseases, or having occasional outbreak that involved not only local citizens but also overseas travelers. The same inclusion and exclusion criteria listed in **Table 1** were followed for this second search. Reference lists of

TABLE 1 | Studies were selected or excluded based on the criteria.

Criteria	Inclusion	Exclusion
Publication date	2010–2020	Prior to 2010
Language	English	Other languages
Geographical location	Malaysia (including Peninsular Malaysia and East Malaysia)	Out of Malaysia
Type of publication	Research articles	Reviews, books, journals, theses, systematic review, case report, articles with no full text available, news, government reports
Participants	Mainly human, if the disease is related to zoonosis, study on reservoir animals may be included	Animals or vectors, bacteria (genome analysis, antimicrobial susceptibility), case study reporting clinical features
Diseases	Infectious diseases	Other diseases (non-communicable diseases)
Other	Related to WASH, public health, river or environmental pollution (with microorganisms or others)	Method development for diagnosis and detection, qualitative studies

articles were also screened to supplement the above searches. Searches were cross-checked to avoid duplication.

The following data from selected papers were extracted from each paper for data analysis: (i) study authors; (ii) study design; (iii) sample size; (iv) sample demographics; (v) location: urban or rural; (vi) sample demographics; (vii) time of exposure or intervention and length of monitoring period; and (viii) measurement outcomes. Data were analyzed descriptively due to the limited number of searches within each section.

RESULTS

Most water pollution in Malaysia is caused by human activities such as surface water pollution from point sources such as industrial effluents, leachate from unsanitary landfills, sub-standard sewage effluents and pollution at non-point sources from pesticides and herbicides used in agriculture activities. In a monsoon climate, pollution from pluvial flooding causing flash floods and surface water flooding is common but relatively predictable and preventable at least in part with some basic preparatory measures; for example, to ensure adequate drainage and run off from fields and in urban areas, ensure clean drains, separate storm drainage from sewer systems, landscaping to store or direct pluvial flood water to drains (Huang et al., 2020). This review focuses on understanding the prevalence and the impact of infections on humans related to water in various parts of Malaysia in the last 10 years. The number of articles that met our minimum inclusion criteria mentioned in the methods are screened manually and incorporated in the review (**Figure 1**). The results section was separated into bacterial, viral and parasitic infections based on major water-borne diseases reported in Malaysia and the number of articles included in the review from each of the states in Malaysia were also reported (**Figure 2**). Rare water-borne human infections in Malaysia were not covered in this review.

Bacterial Infections

In this section, we discuss various studies that report major water-borne bacterial infectious diseases such as melioidosis, leptospirosis, typhoid, *Enterococcus, Aeromonas spp., Helicobacter pylori,* coliforms and *Escherichia coli* reported in humans in Malaysia.

Melioidosis

Melioidosis, a life-threatening infection is caused by Gram negative environmental bacteria, *Burkholderia pseudomallei* found in contaminated water and soil. The recent modeling studies suggest that 165,000 cases of melioidosis result in 89,000 deaths worldwide per year. Around 47% (42,000 cases of 89,000 cases worldwide) of deaths were estimated to be caused by melioidosis in South Asia indicating the endemic status of the disease (Limmathurotsakul et al., 2016). Melioidosis is not, however, considered a neglected tropical disease (NTD) in the WHO's list of NTD (World Health Organization, 2020), this should be re-considered as the disease burden in the Southeast Asian tropical and subtropical regions is high (Wiersinga et al., 2018; Birnie et al., 2019).

Melioidosis can have a wide array of atypical clinical presentations, such as deep organ abscess, bacteraemia, septic shock, and multiple organ involvement, with different severity and chronicity. Lungs were generally considered as the most frequently infected organs (Wu et al., 2012; Zueter et al., 2016; Mohan et al., 2017; Yazid et al., 2017), which could be misdiagnosed as tuberculosis (Mohapatra et al., 2019). Melioidosis can also cause fetal loss although the underlying cause remains unclear (Chang et al., 2020). Other less common symptoms include endophthalmitis and seizures (Feng et al., 2018).

A study by Musa et al. (2016) showed the detection of *B. pseudomallei* in soil from 32 out of 60 ruminant farms spread throughout Negeri Sembilan, Pahang, Perak and Selangor (Musa et al., 2016). In this unmatched case-control study, the presence of river, stream, as well as flooding or water logging were cited as significant risk factors that contributed to the occurrence of melioidosis in the ruminant farms (Musa et al., 2015). Later in 2018, a separate study also detected *B. pseudomallei* in water samples, from boreholes, river, tap water and well water, in the ruminant farms (Musa et al., 2018).

Very few retrospective studies have been undertaken on patients admitted to hospital in Malaysia with melioidosis although the majority of individuals who were infected by melioidosis worked in agricultural, farming and fishing sectors (Hassan et al., 2010; Abu Hassan et al., 2019; Tang et al., 2019). Diabetes mellitus in several studies appears to be a major underlying risk factor in diagnosed melioidosis cases (Hassan et al., 2010; Zueter et al., 2016; Yazid et al., 2017; Abu Hassan et al., 2019). However, it should be noted that the related immune suppression in poorly controlled diabetics may have accelerated disease development, producing symptoms that forced infected individuals to seek medical help. Detection bias

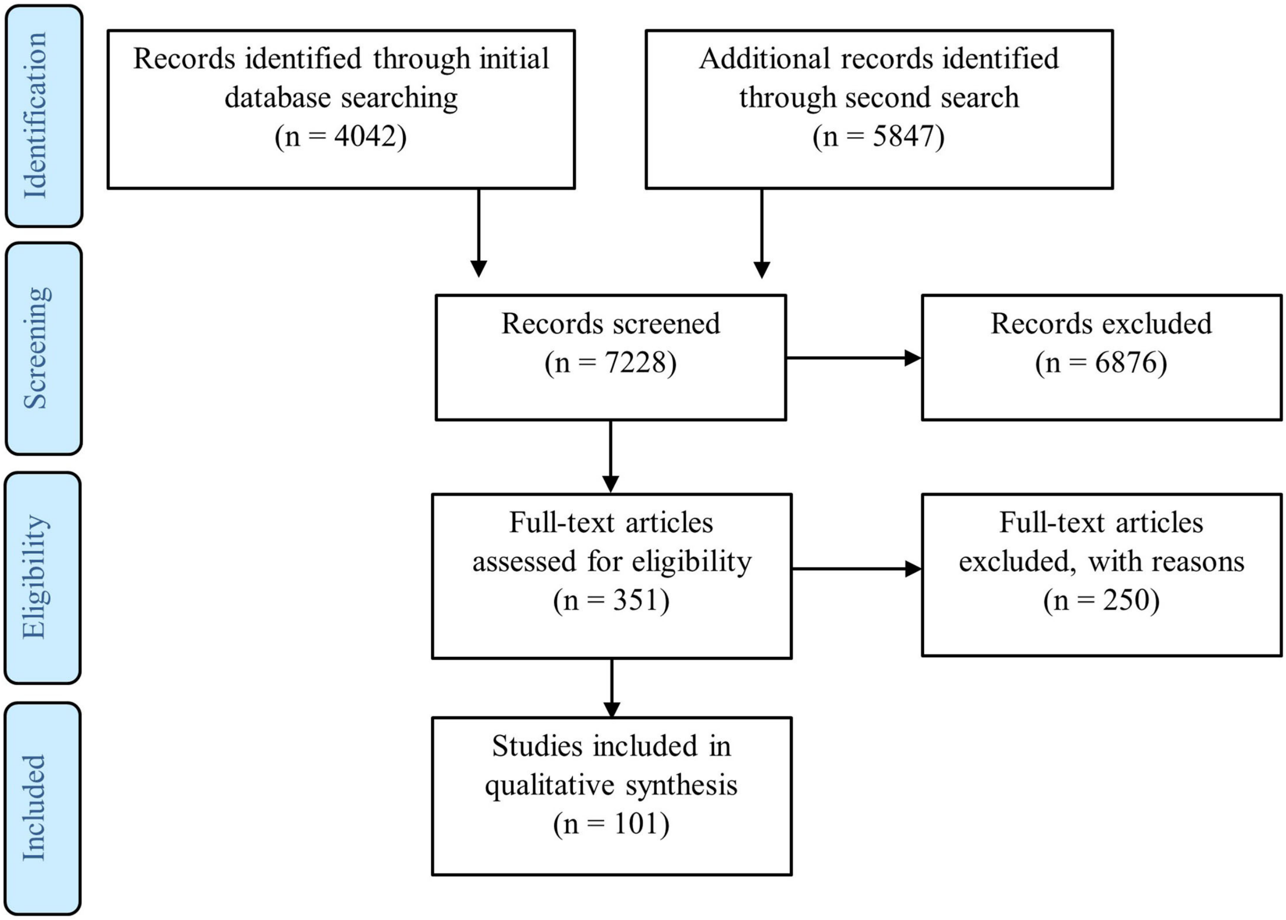

FIGURE 1 | PRISMA statement showing flow of information through the different phases of a systematic review (Moher et al., 2009). This PRISMA diagram contains public sector information licensed under the Open Government Licence v3.0. Adapted from Moher et al. (2009).

may underestimate prevalence statistics in affected communities where people with minor symptoms fail to seek medical help and achieve an objective, formal diagnosis of melioidosis. There was also a report of a diabetic patient who worked as a palm oil worker in Perak, being infected with melioidosis, tuberculosis and *Salmonella* at the same time, suggesting diabetes as a predisposing factor to multiple infections (Sulaiman et al., 2013). Recorded risk factors for melioidosis include co-morbidities, immune-compromission, cystic fibrosis (Mariappan et al., 2018), thalassemia, kwashiorkor, albinism and patent ductus arteriosus (Fong et al., 2015). Residing areas also play an important role in acquiring melioidosis, Abu Hassan et al. (2019) showed that living in areas with large-scale irrigation-based agriculture and mixed agriculture/pastoral environments had a higher prevalence rate of melioidosis (Abu Hassan et al., 2019).

In 2010, there was an outbreak of melioidosis and leptospirosis co-infection after a rescue operation in Pahang, Malaysia (Sapian et al., 2012) where 153 people were exposed to the outbreak. Overall, the fatality rate in this outbreak was 38.1% (8 out of 21), where all eight individuals with diabetes mellitus, four had melioidosis alone and three had a co-infection of melioidosis and leptospirosis. In this study also, the water samples were collected from the riverbank at the outbreak site, which confirmed the presence of *Leptospira* as well as *B. pseudomallei* indicating a likely environmental source of the infectious agent.

Pediatric melioidosis accounts for 5–15% of all melioidosis cases worldwide (Sanderson and Currie, 2014), however, there are not many childhood melioidosis studies reported from Malaysia. In 2017, a study from Sarawak reported an overall average annual incidence rate of 4.1 per 100,000 children (<15-years-old) (Mohan et al., 2017). In this region, most of the children (80%) resided in rural areas and had used untreated water sources for recreation and consumption; some of the children (32%) also had poor nutritional status. It is interesting to note that the *B. pseudomallei* isolates in this study were susceptible to gentamicin (Mohan et al., 2017), a finding which is similar to a previous study in Sarawak (Podin et al., 2014). Of note, *B. pseudomallei* is known to be intrinsically resistant to aminoglycosides (McEniry et al., 1988). In summary, there were several sporadic melioidosis outbreaks reported from various states of Malaysia (Sapian et al., 2012; Mohan et al., 2017) (**Figure 2**). However, it is difficult to assess the real disease burden

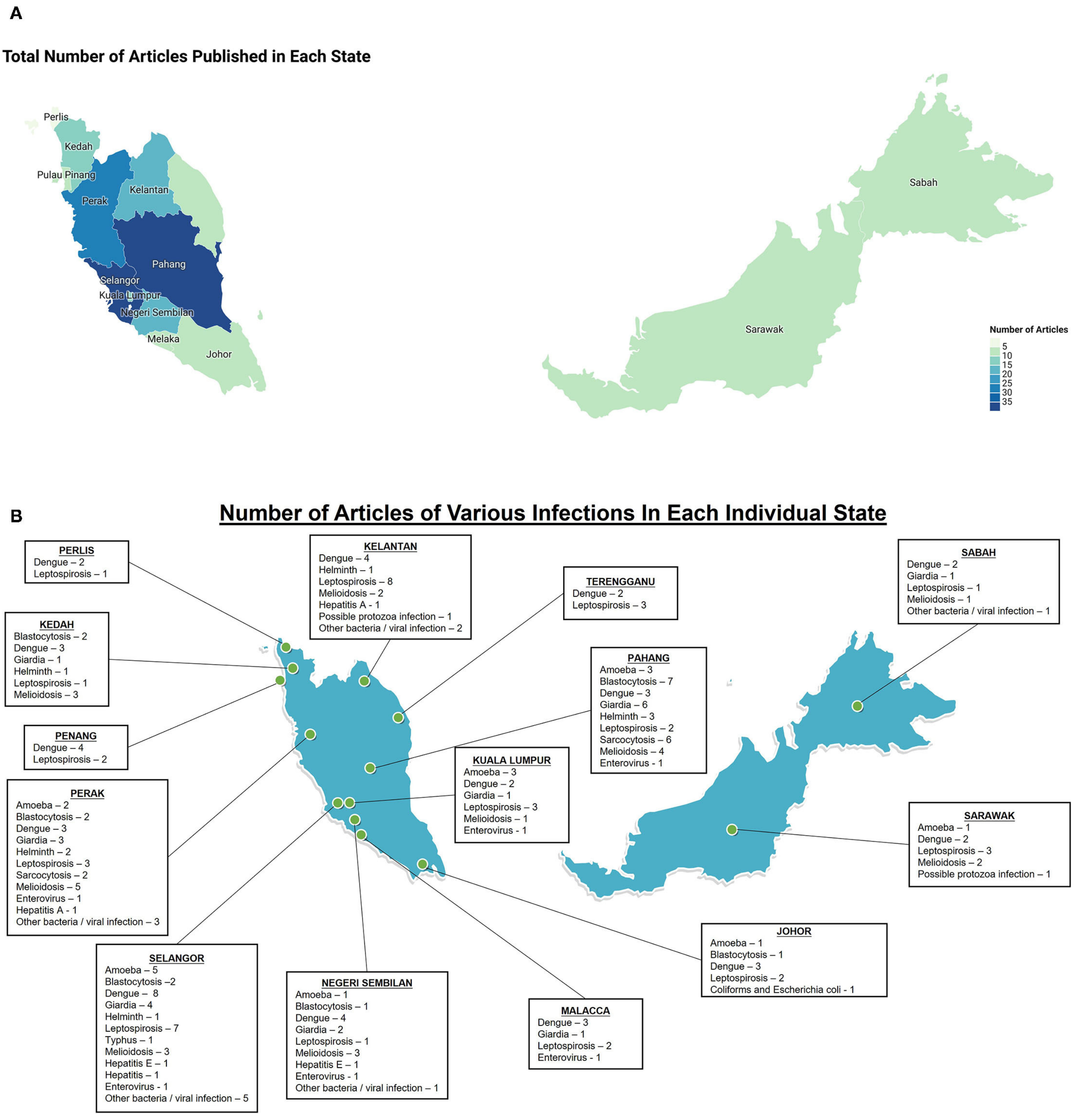

FIGURE 2 | Elucidation of number of articles included in this review in Malaysia, mainly focus on infectious diseases related to human, however if the disease is related to zoonosis, studies on reservoir animals may be included. **(A)** Total number of articles that were included in each state, the color intensities are proportional to the number of articles; **(B)** Number of articles for each disease that were included in each state.

as the source of infection in each study were not established. Furthermore, there is a lack of systematic disease monitoring using specific nation-wide diagnosis for melioidosis.

Leptospirosis

Leptospirosis is a bacterial disease that causes high levels of morbidity and mortalities in tropical climates. In such countries, flooding is a common cause of leptospirosis outbreak, as incidences often increase significantly during floods. Leptospirosis outbreaks are generally associated with rises in temperature, humidity, rainfall, flooding and raised river levels (Mohd Radi et al., 2018). Rodents and domestic animals serve as a reservoir and host for infection *Leptospira* as they transmit the disease via urine (World Health Organization, 2003). While the worldwide prevalence is not known, incidences are higher in humid tropical regions, like Southeast Asia (World Health Organization, 2003; Pappas et al., 2008).

The clinical manifestations of leptospirosis infection ranges from a mild, self-limited febrile illness to life-threatening illness; patients usually present with sudden onset of fever, chills, headache, cough and gastrointestinal symptoms. Since leptospirosis shares a number of non-specific symptoms with conditions like influenza or dengue and co-infection is not uncommon, therefore the actual prevalence rate may be significantly higher than reported (Kishimoto et al., 2004; Leung et al., 2011). Indeed, there were several reports that include leptospirosis co-infection with dengue (Suppiah et al., 2017; Philip et al., 2020), where males had a higher preponderance for co-infection and shock was a common symptom in those patients (Suppiah et al., 2017).

In Malaysia, a study reported a total of 3,604 cases and 47 cases of death in Ministry of Health hospitals in Malaysia in 2012 (Benacer et al., 2016b). Several cross-sectional studies reported the seroprevalence of leptospirosis from various states. When the seroprevalence of leptospirosis in municipal service workers from Kelantan (2012) and Selangor (2015) were investigated, they found an overall seroprevalence of 4.7 and 34.8%, respectively (Shafei et al., 2012; Samsudin et al., 2015). However, a lower seroprevalence of 9.4% was found in urban service workers from Sabah in Borneo (Atil et al., 2020). Rahman et al. (2018) screened 232 local wet market workers in Kelantan and found 78 of the respondents (33.6%) were seropositive for leptospirosis with the highest seroprevalence detected in those who sold processed food, fresh meat and fish, fruits and vegetables (Rahman et al., 2018). A screening study on a community near Rejang river basin, Sarawak in 2016 (Suut et al., 2016) revealed that the community with 86% Iban ethnicity had 37.4% seroprevalence for leptospirosis, but not all individuals were symptomatic as is often the case despite the detection of seropositive antibodies. In the same year, an outbreak of leptospirosis occurred among military reserve recruits in Kuala Lumpur following a survival exercise (Neela et al., 2019). Since not all recruits were interviewed, the study was prone to selection bias in terms of identifying risk factors. In an effort to establish a source of infection, water and soil samples were analyzed along with rat urine. This study identified *L. kmetyi* and *L. wolffii* in the environmental samples and *L. interrogans* and *L. borgpetersenii* in some of the kidneys of rodents. This study clearly suggested that exposure to an environment contaminated from rodents' excrements were a likely risk factor human leptospirosis infection.

Other studies reported detection of *Leptospira* in the environment (using water and soil samples) particularly from the National Service Training Center (Ridzlan et al., 2010), and residential areas with leptospirosis patients (Mohd Ali et al., 2018). The water and soil samples with *Leptospira* were (Benacer et al., 2013; Azali et al., 2016) identified, but it has not caused symptomatic disease in all exposed individuals. Other studies have identified *Leptospira* in rat populations in Peninsular Malaysia (Benacer et al., 2013, 2016a; Mohamad Ikbal et al., 2019) and Sarawak (Pui et al., 2017; Blasdell et al., 2019) as rats serve as a reservoir for the disease. A cross-sectional study by Daud et al. (2018) showed that, among cattle farmers, the seroprevalence of leptospiral antibodies was 72.5% and pathogenic *Leptospira* originated from the waste dump at the farm (Daud et al., 2018). In short, studies that reported leptospirosis from Malaysia mostly identify the contaminated sources that cause the outbreaks, but it is difficult to assess the prevalence rates and to understand the significance of variations in the seroprevalence reported from various communities.

Typhoid

Typhoid fever is a human systemic infection caused by *Salmonella enterica* serovar Typhimurium (*S. typhi*). It is a highly adapted human pathogen that is transmitted *via* the fecal-oral route (Yap et al., 2014). In the year 2010, there were 21.7 million typhoid infection cases and about 217,000 deaths reported worldwide (Crump and Mintz, 2010). The main reservoir of *S. typhi* transmission is from human carriers and food. It is spread mainly by contaminated food, water, and close contact to infected patients (Antillón et al., 2017). Among the 13 states of Malaysia, Kelantan has the highest incidence of typhoid fever (Yap et al., 2014). Typhoid fever is common among children aged more than 2 years old and teenagers in Malaysia (Ministry of Health Malaysia, 2017a). Other symptoms, such as headache, malaise, coughing and loss of appetite, were reported as early signs but the most common symptom for this disease is prolonged fever (Laishram and Singh, 2016; Roy et al., 2016; Ministry of Health Malaysia, 2017a; Singh and Sundar, 2019). Abdominal symptoms ranging from discomfort, pain, constipations, and diarrhea have been reported as well (Rasul et al., 2017; N'Cho et al., 2019; Muhammad et al., 2020). Rose spots are usually observed on the body of patients with fair skin (Rasul et al., 2017; Muhammad et al., 2020).

A case-control study was undertaken by Anita et al. (2012) to identify the risk factors for an outbreak of typhoid infection in Selangor. In this study eleven water samples were taken from different sampling sites of Congkak River (*Sungai*) in Selangor for microbiological analyses. No *S. typhi* was isolated from the water samples indicating that the river water was not the vehicle for transmission but there was evidence for sewage contamination in the river (Anita et al., 2012).

There are two types of typhoid vaccination available in Malaysia, which are Typhim Vi (Vi CPS) and Ty21a (Ministry of Health Malaysia, 2017a). Both type of vaccinations requires a booster dose every 3 years. For the general public, typhoid vaccination is voluntary. Only certain groups of people, such as food handlers, health officers, sewage and sewerage sanitation workers, workers involved in water supply operation and maintenance, and travelers to places identified as high-risk exposure toward *S. typhi* are advised to take the vaccination.

Enterococcus, Aeromonas spp. and *Helicobacter pylori*

Several reports have described water-borne bacteria that can cause gastrointestinal diseases, including *Helicobacter pylori* and *Enterococcus* spp. Common symptom of *H. pylori* infection is burning pain or discomfort ranging from abdomen to the chest, also known as epigastric pain (Ministry of Health Malaysia, 2016). The discomfort, usually caused by ulcers, may last from a few minutes to hours, and usually occurs at night, which may lead to sleep disturbance. Other symptoms may include nausea or vomiting, bloody or blackish stools, bloating and weight loss. Known for its carcinogenic properties, *H. pylori* infection also increases the risk of gastric cancer by 6 times if untreated.

Aeromanas spp. (Batra et al., 2016) and *Enterococcus faecalis* (Golob et al., 2019) both recognized as nosocomial pathogens, are known for their role in contributing toward urinary tract infections. Both infections share similar symptoms like: abdominal cramps, nausea, vomiting and fever (Drancourt, 2010). *Aeromonas* infection may also cause acute diarrhea (Drancourt, 2010). *E. faecalis* infection can be exceptionally difficult to treat due to its resistance toward many drugs (Kau et al., 2005). There are some reports describing detection and characterization of these pathogenic bacteria in various water bodies in Malaysia. Khor et al. (2015) reported the presence of *Aeromonas* spp. that carried virulence genes in five recreational lakes in Selangor (Khor et al., 2015). In Selangor, isolates harboring enterotoxin gene from *Clostridium perfringens,* a gastrointestinal commensal bacteria known to cause food poisoning and antibiotic-associated diarrhea (Florence et al., 2011), were also reported from the rivers.

Two case-control studies have described the prevalence and predictors of *H. pylori* infection among Malays (Lee et al., 2012) and indigenous (Rahim et al., 2010) ethnic groups residing in Kelantan, northeast of Peninsular Malaysia. Both reports stated a remarkably low prevalence of *H. pylori* in those living in the north-eastern region, particularly the Malays. Rahim et al. (2010) mentioned that the increased prevalence of *H. pylori* infection among the Malays might be associated with the use of well water and pit latrines, less frequent boiling of drinking water, and infrequent hand washing practice, but it is difficult to directly attribute these factors to *H. pylori* infections when so many confounders were not controlled for, it is purely anecdotal and an observational finding.

Enterococcus faecalis can be found in a variety of environments including soil and water. It is usually gastrointestinal tract commensal bacteria but can become an opportunistic pathogen in immunocompromised humans. *E. faecalis* is also known to acquire antibiotic resistance and is prevalent in nosocomial infections. As far as environmental sources are concerned, Daniel et al. (2017) was able to isolate virulent and multidrug resistant forms of *E. faecalis* from animal farms, patient samples, and also wastewater and river water samples (Daniel et al., 2017) but there is no data presented to demonstrate the impact of these bacteria on humans. Similarly, Dada et al. (2013) also reported high frequencies of *E. faecalis, E. faecium* as well as multi-antibiotic resistant isolates at two recreational beaches, indicating fecal contamination of sea water (Dada et al., 2013).

Coliforms and *Escherichia coli*

Escherichia coli and fecal coliforms levels are the standard indicators of microbial contamination in water and food. Total coliforms and *E. coli* levels were studied in Semenyih River, Selangor (Al-Badaii and Shuhaimi-Othman, 2015), Matang mangrove estuary, Perak (Ghaderpour et al., 2014) and Melayu River, Johor (Ho et al., 2021). Total coliforms, *E. coli* (Al-Badaii and Shuhaimi-Othman, 2015), specifically *Klebsiella pneumoniae* (Barati et al., 2016) were found to have high resistance to multiple antibiotics in Semenyih as well as Matang mangrove estuary. At Melayu River, extended spectrum β-lactamase (ESBL)-producing and multidrug-resistant *Enterobacteriaceae* (*Enterobacter cloacae*, *E. coli*, *K. pneumoniae*) were detected (Ho et al., 2021). Data on the prevalence of human infections due to declining river water quality in Malaysia is scarce. Nevertheless, the presence of such pathogenic and antibiotic resistant bacterial strains in areas of high human activity should prompt further action particularly in monitoring water quality and educating the general public.

In conclusion, the occasional outbreaks of melioidosis, and leptospirosis and the water sources that causing these infections have been reported in Malaysia. While *S. typhi*, *Enterococcus* spp., *Aeromonas* spp., *H. pylori*, coliforms and *E. coli* mostly detected in rivers were reported, the systematic investigations that define the disease prevalence or the impact of such infections on human health remain unknown.

Viral Infections

Viral infections that are commonly reported in humans in Malaysia include dengue, hepatitis and enterovirus. Here, we reviewed published articles on water-related viral infections in Malaysia.

Dengue

Dengue fever is caused by RNA virus from the Flaviviridae family and is transmitted through mosquito vectors commonly *Aedes aegypti* and *Aedes albopictus* (Kyle and Harris, 2008). The WHO has classified dengue fever as a water-related disease as *Aedes* mosquitoes breed in areas where there is stagnant water such as flowerpots, water containers, discarded tires and mud pots (Ferede et al., 2018; World Health Organization, 2021a). The Global Burden of Disease Study 2013 reported that dengue fever is highly prevalent in the Southeast Asian region (Stanaway et al., 2016). In Malaysia, dengue remains endemic since its outbreak in the 1980's with its highest concentration of cases in the state of Selangor. A 61.4% increase in dengue cases were reported in 2019 compared to 2018 in Malaysia, with Selangor state accounting for the highest number of reported cases (n = 72,543) [Crisis Preparedness and Response Centre (CPRC), 2020]. The symptoms of dengue fever are flu-like, however a severe infection may lead to dengue haemorrhagic fever or dengue shock syndrome (Hasan et al., 2016). Practices such as improving household environmental sanitation and eliminating *Aedes* breeding sites have shown to be effective methods of controlling and preventing dengue (Chandren et al., 2015).

Since 2010, there have been few published cross-sectional studies evaluating the general public's knowledge, attitude, and practices (KAP) on dengue prevention (Naing et al., 2011; Mohamad et al., 2014; Wong et al., 2014, 2015; Chandren et al., 2015; Wan Rosli et al., 2018; Yeo and Shafie, 2018). Three articles reported the association of health beliefs and knowledge toward dengue prevention practices among Orang

Asli (indigenous) communities (Chandren et al., 2015) and the nationwide population (Wong et al., 2014, 2015). Another two studies, Naing et al. (2011) and Mohamad et al. (2014) reported the level of knowledge and practice of dengue control and factors affecting these practices in a semi-urban town in Mantin, Seremban (Naing et al., 2011) and in a dengue outbreak-prone area in Selangor (Mohamad et al., 2014). In 2018, there are two cross-sectional studies that investigated the willingness among people to pay for vaccinations (Yeo and Shafie, 2018) and the impact of educational intervention on the levels of knowledge, attitude, and practice toward dengue prevention among university students (Wan Rosli et al., 2018).

The aforementioned cross-sectional studies used self-administered questionnaires (Wan Rosli et al., 2018), a computer assisted telephone survey (Wong et al., 2014, 2015) or interviewer administered survey (Naing et al., 2011; Mohamad et al., 2014; Chandren et al., 2015; Yeo and Shafie, 2018). The questionnaire in all seven studies included a section on self-reported preventive practices that are undertaken to combat the spread of dengue. In the context of WASH practices involving safe use of water for combating dengue, there were several recurrent concerns found among the aforementioned reports. Firstly, dengue prevention practices were found to be inadequate in some study populations. For example, just over half of the indigenous participants ($n = 280$, 55.4%) showed good prevention practices but only 52.1% of the study population would examine for *Aedes* larvae in their water containers (Chandren et al., 2015). Even in the semi-urban population of Mantin, Seremban, it was reported that only 44.5% of the study population had covered their stored water properly (Naing et al., 2011). Thus, these studies demonstrate the KAP of general public on dengue prevention and the need for improving awareness around WASH practices in Malaysia.

In the same theme of evaluating the health related perceptions and behavior in the context of dengue, two studies, that adopted the Health Belief Model (HBM), which is recognized for its ability to predict health behavior by looking at four main elements: perceived susceptibility of the disease, perceived seriousness of the disease, perceived benefits of an action and perceived barriers carrying out said action, were reported (Hayden, 2019). These two studies found that participants with lower knowledge and lower perceived susceptibility were less likely to perform dengue prevention practices. In contrast, participants with lower perceived barriers to perform dengue prevention practices were more likely to perform dengue prevention practices (Wong et al., 2014; Chandren et al., 2015). Another recurrent concern that was identified from these studies are the lack of use of Abate or chemicals in stored water to prevent mosquito breeding, which is key toward dengue prevention (Mohamad et al., 2014; Chandren et al., 2015; Wong et al., 2015; Wan Rosli et al., 2018). This is likely due to the misconception that Abate is harmful to humans or *Aedes* can breed in dirty/contaminated water only (Naing et al., 2011; Chandren et al., 2015; Yeo and Shafie, 2018), suggesting a lack of awareness on the life cycle of *Aedes* mosquitoes and their preferred breeding environments. It is important to note that participants with good knowledge scores of dengue tend to have better prevention practices score (Chandren et al., 2015; Wong et al., 2015), although this is not the case among the university students (Wan Rosli et al., 2018). In general, high dengue prevention practice scores were associated with factors such as a high density of mosquitoes in neighborhood, lower income (Wong et al., 2015), younger age with higher level of education (Naing et al., 2011), and attendance to health campaigns (Mohamad et al., 2014).

Besides studying human behavior toward dengue and dengue prevention, we also found reports that described other factors such as environment, land use, climate and weather (Dieng et al., 2012; Dickin et al., 2013; Dom et al., 2013; Roslan et al., 2013; Aziz et al., 2014; Cheong et al., 2014; Mallhi et al., 2015; Lau et al., 2017). Dengue incidence was found to be significantly associated with land areas that had water bodies (Cheong et al., 2014). Aziz et al. (2014) and Roslan et al. (2013) described the spatial density of *Aedes* distribution in urban areas situated in Kuala Lumpur and its positive association with monthly rainfall (Roslan et al., 2013; Aziz et al., 2014).

Indeed, a study that investigated the impact of environmental factors on dengue incidence found that high temperature and rainfall led to increased incidence of dengue (Dom et al., 2013). Mallhi et al. (2015) studied the clinic-laboratory spectrum of dengue viral infection and the associated risk factors such as heavy rainfall and exposure to stagnant water resources (Mallhi et al., 2015). Similarly, Lau et al. (2017) reported that a rise in dengue cases positively correlate to heavy downpour (Lau et al., 2017). Interestingly, they also found that *Aedes aegypti* could breed in water tanks on the rooftop of high-rise buildings. A similar finding was previously reported by Dieng et al. (2012) where *Aedes* were found to breed in water tanks and even in water bowls used for pets (Dieng et al., 2012). Although many water sources harbor and breed *Aedes aegypti*, higher susceptibility and vulnerability to dengue was reported in areas of higher use of pour-flush toilets (Dickin et al., 2013). Despite these useful observations, several limitations to these studies including selection bias around convenience sampling of residents accessible by land transport, recall bias from questionnaires, bias in selecting socially desired behaviors when answering survey questions and lack of correlation of timing of survey distribution with Dengue outbreaks may impact the findings.

In summary, these recent studies focus on defining the various environmental factors and water sources that contribute to the spreading of the disease and the perceptions and practices that influence the implementation of the prevention measures. Education intervention through health campaigns by government representatives implemented throughout Malaysia with emphasis on the common rural population practice could be implemented (Wong et al., 2014; Wan Rosli et al., 2018) highlighting the need to increase awareness of dengue and dengue prevention through social media or other visual aids (posters/billboards).

Hepatitis and Enterovirus

Hepatitis is a form of liver inflammation (Centers for Disease Control Prevention, 2020) that affects liver functions acutely or chronically. Overconsumption of alcohols, toxins, certain medications and medical conditions may cause hepatitis. The most common cause of hepatitis is due to hepatitis viruses A, B, C, D, and E exposure. Viral hepatitis may lead to complications such as: fibrosis, cirrhosis and liver cancer (Ministry of Health Malaysia, 2019, 2020). Patients with viral hepatitis may experience fever, fatigue, loss of appetite, nausea and vomiting, abdominal pain, jaundice and dark urine. Certain patients with chronic Hepatitis B or Hepatitis C may not show any symptoms at all (Ministry of Health Malaysia, 2020).

In Malaysia, the most common types of viral hepatitis are: Hepatitis A, Hepatitis B and Hepatitis C (Ministry of Health Malaysia, 2020). The Ministry of Health Malaysia highlighted that it is compulsory to notify viral hepatitis infections under the First Schedule of Control and Prevention of Communicable Disease Act 1988 (Ministry of Health Malaysia, 2019). Hepatitis A virus (HAV) infection is usually acute and transmitted through food and water, but it is much easier to control through good personal hygiene and sanitation practices. On the other hand, Hepatitis B (HBV) and Hepatitis C viral (HCV) infection are more serious in Malaysia, where both viruses are spread through sex, exposure to contaminated blood and mother-to-child transmission. Most patients with HBV or HCV infection are diagnosed until chronic stages, as they are often asymptomatic in early infection (Ministry of Health Malaysia, 2020). Currently, three doses of vaccination for Hepatitis B have been mandatory to new-born babies and booster given in the 1st and 6th months after birth since 1989, but not for Hepatitis C. Hepatitis A is suggested for immunization but is currently not listed in the National Immunization Program (Yeong, 2015). For Hepatitis E (HEV), a vaccine has been developed and is licensed in China, but is not yet available elsewhere (World Health Organization, 2021b).

There were a few reported outbreaks of Hepatitis A infection in Malaysia since 2010. In 2011, three villages in Hulu Terengganu, Terengganu had an outbreak of HAV infection where their water source was contaminated affecting Orang Asli settlement and two other villages (Zolkepli, 2011). In 2012, there were 78 confirmed cases of HAV infection in Manjung district, Perak identifying unhygienic toddy processing places, procedures and contaminated well water as potential sources of the outbreak (Yusoff et al., 2015).

In 2011, Ahmad et al. enrolled 119 patients with viral origin chronic liver disease (CLD) between July and September 2009 in Kelantan to determine the seroprevalence of anti-HAV antibodies (Ahmad et al., 2011). 80.7% (96) patients were with HBV infection and 19.3% (23) patients were with HCV infection while the overall prevalence of anti-HAV was 88.2% (105/119). The seroprevalence rate of HAV was higher in the age group of more than 30 years, and all 17 patients with liver cirrhosis were anti-HAV positive and were in the older age group of mean age 52.4 years. The authors suggested that patients with CLD who are younger than 30 years old will benefit from Hepatitis A vaccination.

From April 2011 to February 2013, Wong et al. (2020) collected 207 blood samples from healthy aboriginal communities and analyzed for anti-HEV IgG and IgM in 2018 and conducted semi-structured interviews through a cross-sectional study. Usage of river water for daily washing and recreational swimming occasionally or when clean water sources was not available, seems to be one of the major reasons causing HEV infection in the aboriginal villages at Negeri Sembilan and Selangor. Participants also claimed that outbreaks of HEV were not uncommon, this could imply that WASH practices and surveillance in the aboriginal communities need to be improved to prevent transmission of HEV (Wong et al., 2020). A cross-sectional study was conducted on 120 university students in Klang Valley to evaluate KAP, which is important to reduce the risk of viral hepatitis infection. The mean total scores of KAP regarding viral hepatitis were significantly higher in medical students as compared to non-medical science-based participants (Mohd Nazri et al., 2019).

Hepatitis A and Enterovirus (EV) are both Picornaviruses in the family of picornaviridae. EV are classified into 13 species, EV-A to D are the most commonly known species; where poliovirus is EV-C species. Non-polio enteroviruses (NPEVs) include coxsackieviruses, echoviruses, numbered enteroviruses and rhinoviruses. The infection usually causes mild illness including fever, runny nose, sneezing, cough, skin rash, mouth blisters, body and muscle aches. EVs are also associated with outbreaks of more serious diseases, such as hand, foot, and mouth disease (HFMD). Enteroviruses spread either through the fecal–oral route or via respiratory transmission. Enterovirus A71 (EV-A71) is one of the major causes of HFMD together with coxsackievirus A16 (CVA-16) and coxsackievirus A6 (CVA-6) (Xing et al., 2014). EV-A71 can cause a wide range of disorders with varying presentation and severity, most often in infants, young children and immunocompromised individuals (Baggen et al., 2018).

NikNadia et al. (2016) conducted a study to compare the seroepidemiology of EV-A71 among rural Orang Asli and urban Kuala Lumpur populations, and determined the risk factors associated with EV-A71 seropositivity in rural Orang Asli (NikNadia et al., 2016). They collected 460 serum samples from Diagnostic Virology Laboratory, University of Malaya Medical Center, in Kuala Lumpur and 298 samples previously collected from aboriginal communities in Selangor, Pahang, Perak, Malacca, and Negeri Sembilan between 2010 and 2012. The seropositivity rates of Orang Asli children $\leq$12 years were significantly higher than children living in urban area. Using untreated water (e.g., river, well and rainwater) and age $\leq$12 years were important risk factors for EV-A71 seropositivity among Orang Asli confirmed by univariate and multivariate analysis and this could be due to poor hygiene and sanitation practices.

Parasitic Infections

In this section, we reviewed the articles of major parasitic human infections in Malaysia, including free-living amoeba, amoebiasis, giardiasis, cryptosporidiosis, helminths, *Blastocystis* sp. and sarcocystosis.

Free-Living Amoeba and Amoebiasis

Free-living amoeba (FLA) that cause human disease include *Acanthamoeba* spp, *Naegleria fowleri, Balamuthia mandrillaris,* and *Sappinia diploidea* (Visvesvara et al., 2007). *Acanthamoeba* spp. are opportunistic pathogens known to cause granulomatous amoebic encephalitis (GAE) and more commonly severe keratitis among contact lens wearers. *N. fowleri*, on the other hand, causes primary amoebic meningoencephalitis (PAM), which is an acute and potentially lethal disease of the central nervous system. These FLAs are present ubiquitously in the environment including soil and water bodies, and hence poses a serious health risk to humans.

While human diseases caused by *Acanthamoeba* spp. and *Naegleria* spp. are rarely reported in Malaysia, several reports showing the presence of these FLAs in water bodies have been published. A report in 2010 by Init and colleagues described the detection of *Acanthamoeba* spp. and *Naegleria* spp. in 14 swimming pools around urban cities of Petaling Jaya and Kuala Lumpur (Init et al., 2010). They reported that *Acanthamoeba* spp. was more widespread than *Naegleria* spp. and that *Acanthamoeba* spp. is resistant to dry-hot areas and chlorinated water, but no confirmation of FLA species was performed. However, a study in 2018 by Basher et al. found that *Acanthamoeba* spp. was indeed widespread as it was detected in all water samples from 15 recreational rivers around urban Selangor and Kuala Lumpur (Basher et al., 2018). In fact, the detected *Acanthamoeba* spp. strains have been previously associated with GAE and severe keratitis. Similarly, water-borne parasites including *Acanthamoeba* spp. and *Naegleria* spp. were detected in various processing sites of two drinking water treatment plants in Sarawak (Richard et al., 2016). The detection of *Naegleria* spp. in swimming pools, recreational lakes and rivers, and water tanks in mosques around Selangor and Kuala Lumpur was also reported (Ithoi et al., 2011a) but none of them included any pathogenic strains. Collectively, reports on FLA stress the importance of proper monitoring of drinking water treatment plants and recreational sites such as rivers, streams, and swimming pools.

Unlike studies on the aforementioned FLAs that were mostly conducted in waters from urban areas, studies on *Entamoeba* infections focused on indigenous ethnic groups in rural areas (Anuar et al., 2012a; Ngui et al., 2012; Lau et al., 2013). The genus *Entamoeba* includes many species but only *E. histolytica* is a confirmed human pathogen that causes intestinal disease. *E. histolytica* is commonly observed in tropical regions and is transmitted *via* contaminated water or food. In Malaysia, *Entamoeba* infection is sporadically observed in rural areas particularly among indigenous ethic groups where access to clean water and hygiene practices are still subpar (Tengku and Norhayati, 2011). Although common in Malaysia, most studies on the prevalence of *Entamoeba* infection relied on data from microscopic analysis of stool samples. As such, the true prevalence of *E. histolytica* remains unknown especially since *E. histolytica, E. dispar and E. moshkovskii* cannot be distinguished under the microscope.

Our search that was limited to recent years resulted in three reports that aim to study the true prevalence of *Entamoeba* species using the molecular method, PCR (Anuar et al., 2012a; Ngui et al., 2012; Lau et al., 2013). Anuar et al. (2012a) studied the risk factors of *Entamoeba* infection, i.e., behavioral risks (personal hygiene and food consumption), environmental sanitation and characteristics of living conditions. The overall prevalence of *Entamoeba* infection among the indigenous ethnic group determined by microscopy ranges between 17.6 and 19.5%. Lau et al. (2013) reported that the most common infection was either a single *E. histolytica* infection or mixed *E. histolytica* and *E. dispar* (Lau et al., 2013). Similarly, Ngui et al. (2012) reported that *E. histolytica* was the most common *Entamoeba* infection among indigenous people (Ngui et al., 2012), but Anuar et al. on the other hand found that *E. dispar* was most common followed by *E. histolytica* (Anuar et al., 2012a). A recurring observation that was reported in all three studies was the lack of hygienic practices.

Although none of the three reports have studied water samples specifically, current WASH practices suggest that *Entamoeba* infection among the native Orang Asli may have been acquired through contaminated water sources. Therefore, educational intervention is very much needed to improve their knowledge, attitude, and practice toward *Entamoeba* infection prevention and the safe use of water. Besides that, the true incidence of pathogenic *Entamoeba* species among the population as well as its pathogenicity must be investigated. Since *Entamoeba* can be found in aquatic environment and water bodies, it also remains to be elucidated whether other factors such as environment, climate and weather have an effect on *Entamoeba* survival in the environment.

Giardiasis and Cryptosporidiosis

Giardiasis and cryptosporidiosis are protozoan parasitic intestinal infections, in which the transmission route could be water-borne, through ingestion of drinking water or recreational water or contaminated food. *Giardia*, together with *Cryptosporidium* are mentioned in the WHO's "Neglected Diseases Initiative" in 2004, which exhibit an increasing global burden (Savioli et al., 2006). The prevalence of *Giardia* in developed countries is nearly 2% for adults and 8% for children, while the estimation in developing countries is almost 33% (Dunn N, 2020). In the European Union (EU), there were 5.4 confirmed cases per 100,000 population in the year 2014 (European Centre for Disease Prevention Control, 2016). On the other hand, the prevalence in Malaysia varies and has been increased, where it was 1.4–11% in 1992 (Shekhar et al., 1996).

Patients with parasitic intestinal infections share similar signs and symptoms. Ministry of Health Malaysia listed patients with cryptosporidiosis may suffer diarrhea, stomach cramps/pain, nausea, vomiting, fever, headache and loss of appetite (Ministry of Health Malaysia, 2017b). Meanwhile, for acute cases of *Giardia* infection, CDC included symptoms like diarrhea, abdominal pain, bloating, nausea and vomiting (Centers for Disease Control Prevention, 2017). Less common symptoms like fever, itchy skin, hives, swelling of the eyes and joints has been reported as well (Centers for Disease Control Prevention, 2021). Patients with chronic *Giardia* infections might suffer from fatigue and weight loss (Centers for Disease Control Prevention, 2017; Wang et al., 2019). However, Dixon (2021) highlighted that there is an ongoing debate that challenges the link between diarrhea and *Giardia* infection, due to the increased reporting of asymptomatic infection (Dixon, 2021).

There are several articles that report infections from intestinal parasite species, prevalence of polyparasitism and mixed infections with one or more parasite species in Malaysia. From 2010 to 2012, Lee et al. carried out a study in five indigenous villages located in Selangor, Pahang and Perak using One Health (Mackenzie and Jeggo, 2019) approach to investigate occurrence of *Giardia* in humans, animals and river water (Lee et al., 2014b, 2017). The overall prevalence of *Giardia* infection (*G. duodenalis*) among humans was 6.7% (18 out of 269) and some participants were co-infected with other protozoa and helminths. Fecal samples from free roaming and companion animals, such as dogs, chickens, ducks, birds, rodents, otters and cows were also tested but only dogs and cats harbored *Giardia* infection at 4.7% (Lee et al., 2017). When the river water at same locations were tested, 51.3% of the samples had *Giardia* cysts and 23.1% samples had *Cryptosporidium* (oo)cysts (Lee et al., 2014b).

The co-infection in children have been reported by another study in Pahang where 374 children aged 7–12 were enrolled to investigate the burden of giardiasis and its effect on the growth of the children in rural, indigenous community (Al-Mekhlafi et al., 2013). Among these children, 22.2% had *Giardia* infection and 60% of the children with giardiasis had co-infection with other parasites. The children in these communities were found to be malnourished including 28.3% severely underweight, 23.8% severely stunting and 21.0% severely wasting. Lower weight was significantly associated with *Giardia* infection compared to their counterparts and treatment with albendazole improved the children's weight and height at 6 months assessment.

Another study of 498 children in Pahang also highlighted the polyparasitism and found 98.4% (490 of 498) infected with at least one intestinal parasite species (between January and April 2012), with higher prevalence of *Trichuris trichiura* at 95.6% (Al-Delaimy et al., 2014). Giardiasis was prevalent in 28.3% of the study sample and *Cryptosporidium* infection had 5.2% prevalence. Polyparasitism was however common and present in 71.4% study participants. Children <10-year-old, those living in houses without a toilet, those using unsafe sources (river) for drinking water, not washing hands before eating and presence of infected family members had higher prevalence of polyparasitism.

When the prevalence and risk factors of giardiasis in three indigenous communities in Perak, Pahang and Negeri Sembilan (Anuar et al., 2012b) were investigated, the prevalence of giardiasis was 20% (100 of 500) in those populations. Drinking untreated water, bathing and washing in the river were identified as significant risk factors in two of the tribes, but this was not confirmed in a multivariate model. Presence of other family members infected with giardiasis was the variable confirmed by logistic regression as the most significant predictor of giardiasis among all the tested tribal communities.

Choy et al. (2014) undertook a larger study on aboriginal communities from 28 villages distributed in Pahang, Selangor, Negeri Sembilan, Kelantan, Kedah, Malacca and Sabah where 1,330 participants were screened for prevalence of *Giardia* infection (Choy et al., 2014). The majority of participants were aged <12 years (69.9%) and had acquired a significantly higher prevalence of *Giardia* infection than older children. The overall prevalence of *Giardia* in this study was 11.6% (154/1,330) yet some participants had co-infections of other intestinal parasitic infections where about two thirds of (104/154) were mixed infections with one or more parasite species (*Trichuris*, *Ascaris*, *Entamoeba*) while one third were Giardia single infections (50/154). In contrast to the study by Anuar et al. (2012b) but similar to the study by Al-Delaimy et al. (2014), in both univariate and multivariate analyses, no toilet in the house, not boiling water before consumption, bathing in river and not washing hands before eating were significantly associated with increased levels of *Giardia* infection which manifested with symptoms of diarrhea, abdominal pain and vomiting.

A 6-month long survey of the river water in Sungai Lopo, Hulu langat was carried out by Lim and Aahmad (2004) to study the occurrence of *Giardia* cysts and *Cryptosporidium* oocysts in the Temuan Orang Asli river system (Lim and Aahmad, 2004). The findings showed that while Giardia cysts and fecal coliform was detected in all the water samples collected, *Cryptosporidium* oocysts were detected only in one water sample which was collected downstream. Overall, the results implied that the river is contaminated with fecal-oral transmitted parasites, indicating a possible route for *Giardia* and *Cryptosporidium* transmission through open defecation to the river at this location. Similarly, a study by Bilung et al. (2017) revealed that higher concentrations of *Cryptosporidium* and cyclospora in environmental water used for abstraction of drinking water treatment plant (Sungai Sarawak Kanan and Sungai Sarawak Kiri) and recreational activities (Ranchan recreational park and UNIMAS lake) in Sarawak (Bilung et al., 2017). However, the study had a small sample size at a specific point in time and hence it is difficult to draw any general conclusions from this study.

When the water quality of the two main rivers in Kuantan, Pahang, namely Sungai Kuantan and Sungai Balok were investigated by studying the levels of *Cryptosporidium* oocysts, the physicochemical and heavy metal parameters, the Sungai Kuantan and Sungai Balok were reported as major risks for *Cryptosporidium* infection (Zainutdin et al., 2017). This may be due improper waste management and poor hygiene practices among the population near the two rivers but there was no direct evidence provided in the study (Zainutdin et al., 2017). Further, a cross-sectional study of 25 eligible water treatment plants (WTPs) across 11 administrative divisions in Sarawak, Malaysia (Ting Lo et al., 2018) also suffered lack of direct evidence and insufficient participation as only eight of the 25 WTPs in Sarawak and one WTP in Peninsular Malaysia participated. Thus, the data collectively indicate the impact of unhygienic WASH practices and river/drinking water contamination as major risk factors of Giardiasis and cryptosporidiosis intestinal infection in various parts of Malaysia. Regular monitoring of the rivers and water treatment plants along with awareness programs that educate the local communities on proper sanitation and proper waste disposal are necessary to combat these parasitic infections.

Helminths

Soil-transmitted helminth (STH) infections are caused by mainly 3 types of STH species: *Ascaris lumbricoides, Trichuris trichuria*, and hookworms (*Ancylostoma duodenale* and *Necator americanus*). As these worms feed on host tissues, the host develops protein-energy malnutrition, iron-deficiency anemia, and vitamin A deficiency (American International Medical University, 2017), causing symptoms to arise including abdominal pain, nausea, diarrhea, bloody stools, worm in stools, and weight loss. As one of the NTD, STH has infected approximately 2 billion people globally by 2012 (World Health Organization, 2012), resulting in about 135,000 deaths annually (Pasaribu et al., 2019), and has been exclusively prevalent in the lower income developing countries. In Malaysia, STH prevalence varies across different geographical locations/populations, mainly affecting the aboriginal Orang Asli tribes and the rural Malay, mostly located in Perak, Kedah, Kelantan, and Pahang (Northern Peninsular Malaysia). Factors that contribute to this are poor sanitation systems, lack of deworming programmes, preventive health education and in some cases inadequate personal hygiene practices (Nasr et al., 2013a).

Nasr et al. (2013a,b) carried out a two-part cross-sectional study among 484 Orang Asli children aged ≤ 15 years belonging to 215 households from 13 villages in Lipis district, Pahang, Malaysia. The study showed a high prevalence of STH in these children and key factors were using unsafe drinking water supply, absence of a toilet in the house, large family size (≥ 7 members), as well as not washing hands before eating, and after defecation (Nasr et al., 2013a). The second part of the study shows that the KAP on STH infections among the participants were inadequate (Nasr et al., 2013b). Overall, the entire study exposed the need for school-based deworming programmes, proper sanitation, treated drinking water supply, proper health education on personal hygiene and transmission & prevention of STH; as a more holistic STH prevention and elimination strategy. In the same way, Lee et al. (2014a) reported a cross sectional study of 269 people from two different subtribes of indigenous communities: the Temuan and Temiar subtribes (Lee et al., 2014a). They discovered that overall STH infections were higher in the Temuan subtribe, with *Trichuris trichiura* (46.2%) as the most prevalent parasite, followed by *Ascaris* spp. (25.7%) and hookworm (4.1%). Comparatively, *Ascaris* spp. (39.8%) was more prevalent among the Temiar subtribe, preceded by *T. trichiura* (35.7%) and finally hookworm (8.3%). Co-infections of helminthiasis and intestinal protozoa were three times higher among the tribes Temiar compared to Temuan. This study takes into account the variations in infections and also cultural practices in each subtribe of the indigenous population, rather than considering the indigenous communities as a homogenous group, and this enables more customisable control measures (Lee et al., 2014a).

Another cross-sectional survey from May 2016 to April 2017, in eight villages comprising all six Negrito indigenous sub-tribes located in the northern states of Peninsular Malaysia (Muslim et al., 2019). The survey aimed to compare STH infections in 416 participants who were grouped into two categories of communities based on location; Inland Jungle Villages (IJV); and Resettlement Plan Scheme (RPS). Their findings proved that prevalence of STH was significantly higher in IJV than in RPS. The prevalence of moderate to severe hookworm infections and other intestinal parasitic infections (e.g., *Entamoeba* sp., *Blastocystis* sp. and flukes) were also higher in IJV than in RPS. However, the percentage of individuals with severe *T. trichiura* infections and severe *Ascaris lumbricoides* infection were significantly higher in the RPS compared to IJV. Therefore, all these suggested that the development plan by RPS does not result in a great impact in terms of STH reduction among the indigenous communities. A biannual mass albendazole intervention, community empowerment to both communities, and also recruitment of more Orang Asli individuals in the health-care taskforce were suggested as a long-term strategy (Muslim et al., 2019).

In these studies, *Ascaris* spp., *T. trichiura*, and hookworm infections are the most prevalent parasites causing STH infections in Malaysia. Although Lee et al. (2014b) isolates different subtribes of the indigenous population, all the studies were conducted in few villages with limited number of sampling sites (Lee et al., 2014a). Furthermore, demarginalisations and resettlements *per se* will not bring about impactful outcomes in STH elimination. More holistic approaches in the health-care taskforce, raising awareness and education about STH transmission and prevention, water quality monitoring and drinking water treatment, and proper sanitation are required to eliminate helminth infections.

Blastocystis sp.

Blastocystis sp. is also an enteric parasite, and is found to be more prevalent than other intestinal protozoan parasites (Wawrzyniak et al., 2013). Although the prevalence varies widely from country to country, higher prevalence in developing countries appears in univariate and multivariate models to be due to poor hygiene, exposure to animals, and consumption of contaminated food or water (Tan, 2008; Wawrzyniak et al., 2013). Different subtypes of *Blastocystis* are found worldwide with nine subtypes detected in humans to date (Tan, 2008; Alfellani et al., 2013). Ministry of Health Malaysia (2020) stated that infection with *Blastocystis* can lead to symptoms like watery or loose stools, diarrhea, abdominal pain, anal itching, weight loss and constipation, although asymptomatic infections were reported. Abdullah et al. (2017a) reported that *Blastocystis* infection can cause other gastrointestinal symptoms like nausea, vomiting, anorexia pruritus as well as tenesmus (Abdullah et al., 2017b).

A study carried out among 300 primary school children (aged 6–12 years) living in rural communities of Pahang reported a 25.7% (77/300) overall prevalence of *Blastocystis* (Abdulsalam et al., 2012). Other infections were also reported among these children including *G. duodenalis* (15.3%), co-infection of *Blastocystis* and giardiasis (2.3%), helminth *T. trichiura* (47.0%) and *Entamoeba histolytica/dispar* (4.3%). Univariate analysis and logistic regression analysis confirmed that absence of piped water supply was significantly associated with the occurrence of *Blastocystis* infection and those children who do not have a tap water supply were three times more likely to get *Blastocystis* infection.

Similarly, when the prevalence of *Blastocystis* infection among aboriginal communities in Pahang was investigated during dry and wet season (Abdullah et al., 2017b), the overall prevalence of *Blastocystis* infection was 40.4% and was not statistically significant different between wet and dry seasons. Among the subtypes, ST1 significantly had greater prevalence during the wet season while ST2, ST3 and ST4 had no significant difference between two seasons. More than half of the participants used untreated tap water supply (63.6%) and river water (50.5%) for their daily use. 43.3% of the people do not have proper latrine systems and practice defecation in the river and bushes. Univariate analysis revealed that use of untreated tap water supply, use of untreated tap water for washing, use of stored river water for domestic use and the absence of latrine system during the wet season, while use of stored river water in containers for domestic use during the dry season was significantly associated with *Blastocystis* infection. In logistic regression analysis, presence of other family members infected and use of river water stored in containers for domestic activities were significant risk factors during dry and wet seasons.

Two further studies tested the occurrence of *Blastocystis* and fecal coliforms in river water samples from indigenous community settlements (Abdullah et al., 2017a) in both wet and dry seasons (Abdullah et al., 2016) at Sungai Krau and Sungai Lompat and reported significant association between the infection and concentration of fecal coliforms (Abdullah et al., 2017a). *Blastocystis sp.* subtype ST3 were detected at all sampling points during dry and wet season (Abdullah et al., 2016). High concentration of fecal coliform was also detected in both the rivers during both seasons, although only occurrence of *Blastocystis sp.* subtype ST2 was significantly associated with fecal coliform (Abdullah et al., 2016). Similar results were demonstrated by a study done earlier in 2004 to 2005 where they detected *Blastocystis* sp. in river water of recreational areas (Ithoi et al., 2011b). It was detected at the rate of 33.3% (Sungai Congkak) and 22.1% (Sungai Batu) where the highest concentration was at the downstream of both rivers. The significant correlation between fecal coliforms and *Blastocystis* was also evident in both rivers. Both the studies raise the potential health risk to the indigenous community if they use river water as drinking water or other purposes and the need of river water monitoring. The study did not evaluate presence of symptoms or human health impact with the presence of fecal coliforms or *Blastocystis sp.*

In selected villages at Negeri Sembilan, Perak and Pahang, Peninsular Malaysia indigenous communities, the overall prevalence of *Blastocystis* infection was reported as 20.4% (102 of 500) where most of the infected individuals were <15 years old (Anuar et al., 2013). Of all the samples with *Blastocystis*, 82.4% had co-infection with one or more other parasites such as *T. trichiura* (53.9%), *E. histolytica/dispar/moshkovskii* (26.5%), *E. hartmanni* (22.6%), *E. coli* (20.6%), *G. intestinalis* (17.7%) and others. Like other studies, univariate analysis and logistic regression analysis showed that drinking untreated water and presence of other infected family members significantly associated with presence and higher numbers of *Blastocystis* infection among the study population. Further, a focused study on school children aged 7–12 years that tested the prevalence of intestinal parasitic infection (IPI) (Nithyamathi et al., 2016) found that 13.3% of the school children had IPI, with 10.6% ($n = 186$) of children had *Blastocystis* sp. detected in both rural (13.7%) and urban (7.2%) area. Other parasites such as *Giardia* sp. and *T. trichiura* were found only in rural areas. There were higher number of ST1 (22.6%) infecting these school children detected in both urban and rural areas compared to other subtypes.

In contrast to the studies in children, where children had higher prevalence, study by Mohammad et al. (2017) showed those aged 15 years or above having significantly higher prevalence of *Blastocystis* infection. Among the 253 participants, 40.7% of 253 participants had *Blastocystis* infection (Mohammad et al., 2017). Drinking untreated water was significantly associated with occurrence of *Blastocystis* infection in univariate analysis but not multivariate analysis. Presence of other family members with *Blastocystis* infection was a significant risk factor shown by both univariate and multivariate analysis, which is consistently reported in all the studies. Together, these reports highlight the various risk factors, coinfections and the significance of water quality monitoring of rivers, drinking water and need for WASH practice awareness in rural communities.

Sarcocystosis

Sarcocystis spp. being the causing agent of sarcocystosis, is a parasite that could infect intestine or muscles which could be transmitted through food or water. This is due to the fact that swine and cow might serve as an intermediate host of *Sarcocystis*, thus infecting human through undercooked meat (Fayer et al., 2015). Depending on the site of infection, different clinical presentations were observed, ranging from diarrhea, vomiting for intestinal sarcocystosis, to muscle weakness and myalgia for muscular sarcocystosis (Latif and Muslim, 2016). The prevalence of *Sarcocystis* infection was relatively unknown, but there is <100 humans infected with muscular sarcocystosis reported in the literature and intestinal sarcocystosis was more prevalent in Europe (Fayer, 2004). It was found in a seroepidemiological survey that almost 20% of 243 participants had antibodies to *Sarcocystis* (Thomas and Dissanaike, 1978).

Sarcocystosis were only reported by travelers who returned from vacation in Tioman Island from 2011 to 2013 (Maizura et al., 2012; Tappe et al., 2013; Esposito et al., 2014). Some of the patients had prolonged symptoms of >6 months (Slesak et al., 2014). Another wave of muscular sarcocystosis outbreak was suspected in May 2014 involving six patients after returning from Tioman Island, although no muscle biopsies were taken (Tappe et al., 2014). An outbreak of muscular sarcocystosis occurred after a retreat at Pangkor Island in 2012 involving 89 students and teachers (Italiano et al., 2014). A subsequent study on two symptomatic patients also detected sarcocysts in the skeletal muscle biopsy and the species was identified as *S. nesbitti* (Lau et al., 2014). Thereafter, Shahari et al. collected sediment samples (indirect screening of water samples) from rivers, water tanks, wells and seawater in 2015 at Tioman Island, the hotspot of sarcocystosis outbreak (Shahari et al., 2016). Of the 157 samples, 19 samples tested positive of sarcocysts.

The same searches were performed in PubMed on fungal infections related to water in Malaysia. However, to the best of our knowledge, no articles were published between 2010 and 2021.

DISCUSSION

According to the data from Ministry of Health Malaysia in 2018, dengue has the highest incidence rate per 100,000 population, leptospirosis recorded 15.39 incidence rate with a mortality rate of 0.11 per 100,000 population and typhoid and paratyphoid fever recorded 0.53 incidence rate with a mortality rate of 0.02 per 100,000 population (Ministry of Health Malaysia, 2018). While there are reports of occasional outbreaks and patients admitted to hospital in Malaysia, the burden of melioidosis in Malaysia, as other places in the world, is unknown and most probably under-reported (Limmathurotsakul et al., 2016). Leptospirosis also had a significantly higher incidence rate and death rate among the infectious diseases and can be co-infected with other diseases, hence more precautions are needed especially in Southeast Asia countries, including Malaysia, where the climate is humid and flooding is relatively common (Pappas et al., 2008; Mohd Radi et al., 2018). Studies proved that seroprevalence toward leptospirosis was high, for example, among municipal service and wet market workers, indicating work exposure is one of the important exposure routes. There are not many reports about *S. typhi* infection or determination of *S. typhi* concentration in the water environment. Other than that, *H. pylori* infection is associated with clean water and sanitation as contaminated water could be a source (Bahrami et al., 2013; Aziz et al., 2015) and with the improved facilities in Malaysia, the prevalence is relatively low as concluded by Rahim et al. (2010). Most of the studies carried out in the indigenous communities' settlements concluded that some of the settlements do not have toilet facilities or piped-water supply, instead they might use untreated water from nearby river and/or defecate indiscriminately. Consequently, the indigenous communities were more prone to amoeba (Tengku and Norhayati, 2011; Anuar et al., 2012a, 2013; Ngui et al., 2012; Lau et al., 2013), giardiasis and/or cryptosporidiosis (Lim et al., 2011; Anuar et al., 2012b, 2013; Al-Mekhlafi et al., 2013; Al-Delaimy et al., 2014; Choy et al., 2014; Lee et al., 2017), helminth and hookworm (Anuar et al., 2013; Nasr et al., 2013a; Lee et al., 2014a; Muslim et al., 2019), *Blastocystis* sp. infection (Anuar et al., 2013; Abdullah et al., 2017b) and even co-infections. Safely managed water, sanitation and hygiene (WASH) is essential but remain a major challenge in low-and-middle income countries (World Health Organization Regional Office for the Western Pacific, 2018).

Data Collection and Analysis

From the findings of this study, it is apparent that there is no standardized methodology for examining the relationship between microorganisms and health in Malaysia. This is a common finding in many countries where water sampling for health-related issues is only undertaken after an event has come to light, by which point it is difficult to directly attribute symptoms and health outcomes to a specific organism, time point or location and identify causality (Hill, 1965). When sites are selected for water sampling, it is important to also think about the sources of infection that cause disease and the route of the infection. For example, food, latrines and other sources can transmit similar microorganisms to water bodies. In the reviewed papers, there has been little or no attempt to identify other sources of infection that may have confounded the findings of those studies. For most microorganisms, there is little or no baseline data and in Malaysia, only *E. coli* and dengue are regularly measured at specific locations decided in the government sector and these are often the same locations chosen for research projects; whereas this increases the frequency of sampling, it does not improve the general understanding of a basin. Sharing and making access to data easier, alongside more strategically designed sampling campaigns, would help pinpoint infection sources and make source tracking studies more feasible. Multivariate predictive models could use existing data to predict optimum sites for future sampling and inform regularity of sampling in relation to environmental, physical and hydro-climatic related variables. A multi or transdisciplinary systems approach to disease modeling incorporating environmental and health data would improve existing models and enable health practitioners and environmental bodies to work together in tackling water quality issues affecting health of vulnerable populations. Such a model could involve citizen scientists in data collection, which would increase public awareness and input into maintaining water security locally (Siew et al., 2016; Nardi et al., 2020).

Disease Reporting

When infectious diseases as described above are symptomatic in communities, reporting of cases largely falls on general practitioners in family medicine clinics, but only when a symptomatic individual presents themselves for treatment. To report a case formally, an objective diagnosis, for example, from a stool sample is required. Without this, cases will not get reported to the center for disease control. It is therefore likely that many cases are unreported, and the scale of water related infection in communities residing by lakes, ponds and rivers, for example, is considerably higher than official data shows. In most studies, controls are not evaluated for presence of microorganisms, studies are affected by recall bias as interviewing is typically days to weeks after an outbreak and there is no long term follow up. In many cases, the number, site and frequency of samplings undertaken for water quality studies is not justified rather, simply determined by funding and existing practice. Since symptoms of diarrhoeal disease from any source are similar, it is likely that such symptoms are normalized, and specific infections are not ever identified. Those living with these conditions may consider them common and minor, as such, do not seek medical assistance, hence cases will not be identified and recorded. There is little information in the articles reviewed in this paper on recording pre-existing immunocompromised in infected individuals. With the exception of diabetes mellitus, few other conditions are asked about and severity of diabetes mellitus is not recorded or measured. As such, it is difficult to know the impact diabetes mellitus had on infection outcomes in those patients. Informing citizens of symptoms to watch out for might alert vulnerable populations including poorly controlled diabetics to seek medical help and gain formal diagnoses rather than staying home with manageable symptoms typically lasting only a few days. Without more accurate data to demonstrate a causal relationship between presence of microorganisms and disease (Hill, 1965) it is difficult to evidence base a policy change or health initiative to improve existing situations.

Extreme Events

It is important to note that in a natural disaster such as a flooding episode, other issues may be considered more than acute emergency priorities, such as trauma, mobilizing communities and, preventing hypothermia. As such, water sampling may be a later event that only commences when symptomatic disease becomes more widespread. By the time, conditions are sufficiently settled to sample water and focus on health outcomes, sites of infection will have altered and point sources of infection will have changed or moved (Watkins et al., 2012; Johanning et al., 2014). Such a situation can occur with sewage overflow following pluvial flooding, but remedying the situation is difficult in the short term as it requires structural changes at some expense to existing drainage systems, which may not be a priority for emergency task forces and future planning where maintaining transport links to schools and businesses and supply chains are priorities (Patterson and Jeffrey, 2011).

During the COVID-19 pandemic, regular collecting of baseline data has not been possible in many countries, with lockdowns, lack of access to laboratory facilities and suchlike. It has been shown however, that drinking water pollutants may affect response to COVID-19 in susceptible individuals (Quinete and Hauser-Davis, 2021). Environmental hazards such as monsoon flooding however continues compounding difficulties for inhabitants of river basins and those living near water bodies.

Key Recommendations

A strategic approach to better understand and manage the relationship between water quality and health is needed. This is particularly important as the latest IPCC report (IPCC, 2021) provide clear evidence that climate change is intensifying the water cycle, with changing rainfall patterns and intensities affecting flood and drought risk. Taking into account whole system interdisciplinary understanding of basins, this strategic approach should consider and include:

- Identification of point and diffuse sources of infection and transport/transmission routes, this requires an integrated understanding of the basin hydrology;
- Standardized data collection protocols and sharing mechanisms amongst the relevant authorities and decision makers;
- Procedures for data analysis and interpretation that could inform predictive models, improve understanding of health-related challenges and in turn iteratively design data collection strategies;
- Empowering citizens and communities to collect their own data, understand and identify problems, promote behavior change and provide more frequent data points;
- Protocols that prioritize sampling during extreme flood events, which have shown to cause more widespread disease; although not identified in this review, there is growing evidence of links between experiencing flooding and mental health (e.g., Fernandez et al., 2015; French et al., 2019);
- Exploration for data proxies or alternative mechanisms to collect samples e.g., using drones during periods of inaccessibility.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

JH, AL, and DK conducted data collection and analysis, prepared figures, and wrote the manuscript. CL wrote the manuscript. AR conducted data collection and analysis. CW, MG, and JE provided resources, suggestions, conceptualized the ideas and methodology, managed the overall project administration and coordinated the data analysis, wrote original draft, reviewed, and edited the manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2022.779860/full#supplementary-material

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A Synthesis of Surface Water Quality in Awash Basin, Ethiopia

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Developing countries like Ethiopia are grabbling with rapid population growth, urbanization, agricultural intensification, and climate change which put intense pressure on the availability and quality of water resources. The surface water quality degradation is exacerbating due to increasing urbanization and agricultural activities. The average annual fertilizer use in Ethiopia increased from 132,522 metric tons (mt) in 1996 to 858,825 mt in 2015. Pesticide use also increases significantly from 3,327.7 mt/y in 2006 to 4,211.5 mt/y in 2010. The Awash river is one of the most affected rivers by intensified irrigation schemes, industrial, and urbanization pollution. The Awash river and its tributaries are used for domestic, irrigation, industrial, and recreational purposes. However, as per Canadian water quality indices for the drinking and irrigation water quality, the upper Awash basin scored 34.79, and 46.39, respectively, in the poor and marginal categories; whereas the middle/lower basin indicated 32.25 and 62.78 in poor and marginal ranges, respectively. Dissolved phosphorous in the headwater tributaries is about 0.51 mg/l which is beyond the threshold (0.15 mg/l). The surface water quality impairment is severe in the upper Awash basin where more than 90% of Addis Ababa's industries discharge their waste into nearby waterways without treatment; about 30% of the population lacks access to a liquid waste disposal and treatment facility; only 16% of the population is connected to sewage system, and 25% of the total waste generated enters freshwater systems without treatment. Many studies on surface water quality are reviewed and many of them are inconclusive for a number of reasons. For example, no comprehensive surface water quality research, lack of detailed combined spatial and temporal surface water quality data, and analysis to show the overall picture of the basin are a few of them. Despite the existence of the policy and legal tools, enforcement is lacking. Improving the ecological health of rivers necessitates policy revision as well as increased knowledge and engagement among implementers.

Keywords: pollution, water quality, water quality monitoring, point source, non-point source, Awash basin, Ethiopia

INTRODUCTION

Water is an essential requirement for all living forms on Earth, as well as the most crucial irreplaceable natural resource on which a country's socio-economic growth and long-term development are heavily reliant. Despite its importance to humans, water is the world's most poorly managed resource, particularly in developing countries, and is under serious threat from a wide range of anthropogenic activities (Kumar et al., 2021). The water quality degradation is exacerbating in Ethiopia due to increasing urbanization, and agricultural intensification. Poor urban water quality remains a concern, especially with rising population, the presence of new and uncontrolled substances, a higher value attributed to ecosystem services, and uncertainty about the effects of climate change on controlling factors of water quality such as temperature and environmental flows (Miller and Hutchins, 2017). The effects of urbanization on water quality vary widely, depending on a variety of factors such as the age/type of urbanization (existing urban center vs. suburban development), the existence of wastewater treatment, storm water infrastructure, legacy land use, vegetation, and hydrologic regime (O'Driscoll et al., 2010). Urbanization degrades water quality in three ways: point source pollution discharge, diffuse source pollution mobilization, flow changes, and temperature changes in receiving watercourses. Each of these will be determined by the shape and function of future urbanization, as well as the controls and management of potential pollutant discharges (Miller and Hutchins, 2017). For example: the population and built up area of Addis Ababa is rapidly expanding as a result of urbanization. The area downstream of the city that is affected by industrial and domestic pollution seems to be growing as well (Mekonnen et al., 2020).

Land and surface water quality degradation in Ethiopia was minimal before the last 30 years due to the low population density that practices slash and burn agriculture with minimum agricultural inputs (Ligdi et al., 2010). However, due to natural and anthropogenic sources, Ethiopia's land and surface water quality has recently been vulnerable to a wide range of pollution, including organic matter, salts, nutrients, sediments, heavy metals, and so on. Recent increases in sedimentation biodiversity loss in Ethiopia have been driven by rapid ecosystem loss and land use change, which is partly attributable to agricultural intensification (Moges et al., 2017). Although the United Nations General Assembly resolution 45/94 (1990), which reaffirmed the Stockholm declaration, advises that "all individuals are entitled to live in an environment adequate for their health and well-being," most of the Ethiopian people could not have access to clean water due to increasing environmental degradation. The right to have clean water and a healthy environment for all is also included as part of the Federal Democratic Republic of Ethiopia (FDRE's) constitution [Article 44(1)]. Accordingly, developing countries like Ethiopia have policies, laws, and formal administrative mechanisms in place to monitor and manage pollution, they fail to put them into practice and enforce them to safeguard the environment (Awoke et al., 2016). Likewise, the Ethiopian Public Health Proclamation (EFDR, 2000) prohibited the discharge of untreated waste generated from domestic and industries into freshwater bodies. Although the freshwater policies are in place, the enforcement was weak and freshwater pollution has been predominant in Ethiopia (Berg et al., 2019). Despite the severity, there is no systematic and comprehensive surface water quality assessment in Ethiopia that clearly presents the surface water quality challenges to policy makers and practitioners.

Agriculture releases non-point source pollutants causing significant pollution to the aquatic ecosystems (Awoke et al., 2016). The main source of pollution in agricultural fields are increased use of fertilizer, and pesticides that are aimed to improve agricultural production (Wondie et al., 2007; Emama et al., 2010). The average annual fertilizer uses in Ethiopia increased from 2.5 million decitonnes in 2003/4 to about 8.5 decitonnes in 2015/6 (Legesse et al., 2019), which is fivefold increase in a period of less than 10 years. Subsequent demand for pesticides in the agriculture and flower sectors, pesticide use also increases significantly [3,327.7 metric tons per year (mt/y) from 2006 to 4,211.5 mt/y in 2010] in which the country imports more than 3,346.32 mt annually (Begna, 2014). There is also an increase in land use conversion to agricultural land (from natural or native vegetation) which is reducing biodiversity in the landscape that undermines other ecosystem services such as pollination, medicinal plants, etc.

Growing number of evidences showed the severity of non-point source pollution in Ethiopia (Tafesse et al., 2015; Moges et al., 2016). Tafesse et al. (2015) showed that the contribution of overland flow to dissolved phosphorus is high in most of Lake Tana Basin catchments mainly due to fertilizer application in agricultural fields. Similarly, Moges et al. (2016) reported substantial amounts of available phosphorus in the Awramba watershed in the Lake Tana basin, which was related to use of DAP fertilizer use. Alemu et al. (2017) measured dissolved phosphorous (DP) concentration at various sampling locations at the tributaries of the Lake Tana basin in which the DP concentration was 0.09 mg/l for samples from the lake and 0.51 mg/l for the headwater tributaries.

DP of greater than 0.15 mg/l is considered to cause an adverse water quality problem responsible for the eutrophication in freshwaters. In fact studies highlight that such non-point source pollution flowing into the Lake Tana basin may contribute to the existing water hyacinth infestation in the Lake (Moges et al., 2016). Water hyacinth infestation is also observed in other lakes in Ethiopia, for example the Aba-Samuel Dam, Koka reservoir, Lake Ellen, and Wonji in the Awash River system alone (Alemu et al., 2017). Surface water quality problem is, however, sever in some basins in Ethiopia. For example, the water quality of the Rift Valley Lakes is severely compromised due to horticultural, soda abstraction, and industrial activities (Ayenew and Legesse, 2007).

Textile pollution has a particularly negative impact on freshwater environments, with certain parts of the world being more affected than others. Streams and rivers often provide huge volumes of water for textile manufacturing while also acting as key consumers of industrial effluents, carrying contaminants to groundwater and marine habitats (Stone et al., 2020). Most of the industries in Ethiopia often discharge their wastewater into the freshwater system without any treatment (Girma, 2016). Mehari et al. (2015) conducted a study to determining the effects of

Bahir Dar textile factory effluents on the water quality of the Blue Nile river and reported that dissolved oxygen was higher at the upstream site where the effluent joins the river, whereas BOD, TDS, and total alkalinity values were higher at site downstream of the site where the wastewater effluent joins the river.

Awoke et al. (2016), applying physicochemical and biological analysis, showed that there is significant surface water quality deterioration in agriculture, coffee processing, and urban landscapes in the Nile, Omo-Gibe, Tekeze, and Awash River basins compared to corresponding pristine (or reference sites) in basins (Awoke et al., 2016). The TN and TP estimates in the impacted sites were 100- to 1,000-fold to that of the European WFD, and US-EPA standards, respectively. Exhaustive list of the surface water quality studies in Ethiopia are summarized in the **Supplementary Table S2**. The Table also presents the study sites with the studied parameters, and standards in which the parameters were evaluated. This indicates river water pollution in the agricultural and urban environment in Ethiopia is a growing challenge and needs urgent action to avoid negative environmental consequences.

The Awash River originates from the Ethiopian central highlands and drains some part of the endorheic river system in Ethiopia. It has no outlet to an ocean; it joins Lake Abe at the Ethio-Djibouti border. The catchment area of Awash basin upstream of Lake Abe is ∼113,304 km^2, which is almost within the Ethiopian boundary with negligible contribution from Djibouti. Its elevation is between 250 and 3,000 meters above sea level (masl). The main river length is about 1,200 km (Taye et al., 2018).

The Awash River basin is divided into four major stretches based on altitudinal variation, i.e. Upper basin which represents the areas from the head water to the Koka Dam (>1,500 masl); Upper Awash Valley which ranges from Koka Dam to Awash Station (1,500–1,000 masl); Middle Awash Valley which represents the area from Awash Station to Gewane (1,000–500 masl), and; Lower Awash Valley which is the area that extends from Gewane to Lake Abe (<500 masl) (Duguma et al., 2021; Jin et al., 2021).

The Awash basin has varied landscape, vegetation, rainfall, temperature and soils across the basin. For example, the climate ranges from semi-arid lowlands to cold highland mountains. The mean annual rainfall varies from ∼1,600 mm at Ankober to ∼160 mm at Asayita (Tufa, 2021). Land use in the basin is mainly rain fed agriculture which is used for rain fed crops, shrub land and grazing land. There are some irrigated lands in the basin, which are mainly developed by the government. In fact, a large part (∼60%) of the large-scale irrigated agriculture in Ethiopia is located in the Awash basin (Keraga et al., 2017a). Crops cultivated in the basin include cereals (e.g., teff, beans, wheat, barley and oil seeds), vegetables, flowers, cotton, perennial fruit trees and sugarcane (Tufa, 2021). The other land use includes urban areas, industrial zones, forest, and swamps. Major cities in Ethiopia (e.g., Addis Ababa, Dire Dawa, Nazert, Debrezeit, Dessie and Semera) are located in the Awash basin. More than 65% of the national industries in Ethiopia are located in the Awash basin (Keraga et al., 2017a). Administratively, the basin is shared by Afar, Amhara, Oromia and Somali Regional States, and Addis Ababa and Dire Dawa City Administrations (**Figure 1**). The population living in the Awash River Basin was estimated to be more than 18 million with population density greater than 6,452 persons/km^2 (Aklilu and Necha, 2018). Such evidence shows that the Awash basin is enduring extensive socio-economic pressure existing that threatens the surface water quality and quantity in the basin.

The Awash basin is home to extensive smallholder rain fed and large scale agricultural farms, and large industries, it has been exposed to sever pollutant sources (Eliku and Leta, 2018). Although the pollution situation in the Awash basin is sever, pollution of fresh water systems in developing countries is becoming prevalent due to rapid urbanization and industrialization (Tamiru, 2001; Gebre et al., 2016; Keraga et al., 2017b). Such surface water quality degradation issues are alarming in the developing countries as limitation to access to clean water exist, people will be compelled to consume such polluted water for domestic consumption (Tamiru, 2001; Keraga et al., 2017b; Olbasa, 2017), which has critical public health consequences.

The Little and Tiliku Akaki rivers are major tributaries of the Awash River which joins the Awash river system at the Aba-Samuel lake. Tinishu Akaki includes Burayu, Gefersa, Leku, Qille, Gerbeja, Worenchiti, Melka Qorani, Kera as its tributaries and while Ginfile, Kebena, Kechene, Kurtume and Yeka are tributaries to the Tiliku Akaki (Tufa, 2021).

The objective of this paper is, therefore, to review surface water quality related literature in the Awash basin to understand the biogeochemical pressures identify research gaps. The review focused on non-heavy metals and biological parameters.

METHODOLOGY

Systematic review (SR) is useful to synthesize trends and conceptualizing findings from large bodies of information (Özerol et al., 2018). The recent and innovative approach in undertaking SR is the PRISMA (Preferred Reporting Items for Systematic Review and Meta-analysis statement) (Moher et al., 2009). A synthesis of Water Quality Researches in the Awash Basin has been valid explanatory topic for our review.

For this SR, we developed a search strategy to identify relevant literature. This search strategy was tailored to three databases: Web of sciences, Scopus, Google and Google scholar, and the search terms used were the following: water quality, water pollution, point source pollutants, and non-point source pollutants. All searches included journal articles, books and book chapters. The selection criteria were based on the PRISMA checklist 2009. The search mainly focused on the mapping existing literature on the water quality, water pollution, and sources of pollution in the field of environmental sciences, and earth sciences. The search span was from the year 2000–2021 in English only. The search was mainly focused on Ethiopia. The search from any other country was considered accordingly. A total of 12 research articles were excluded at this stage. There were 171 records extracted at this stage.

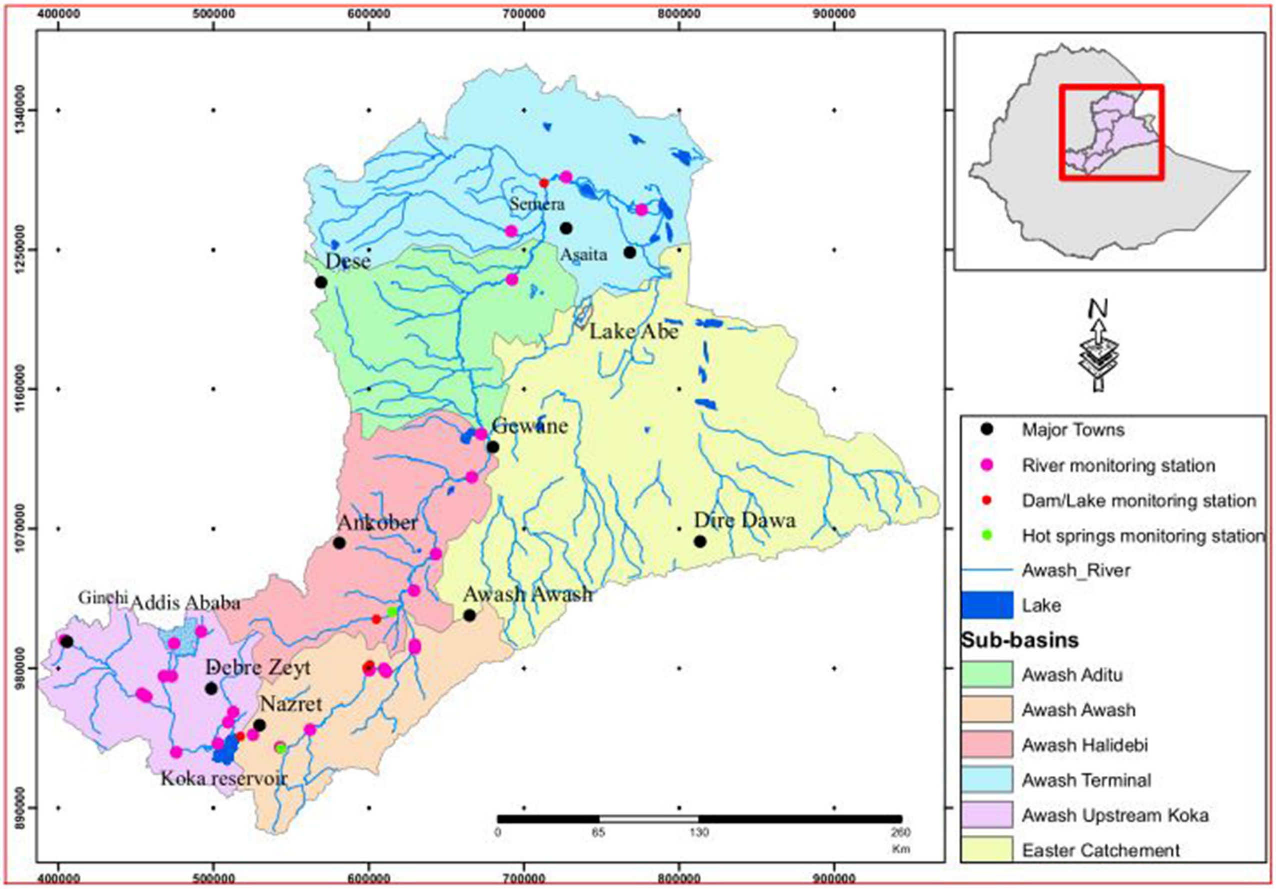

FIGURE 1 | Map of Awash Basin with administrative, monitoring sites and sub basin boundaries.

We extracted information on the following subtopics from each study: status of surface water quality monitoring, status of surface water quality, causes of surface water quality impairment, and surface water quality impairment indicators in Awash basin. All data extraction and coding were performed using Microsoft excel and medley reference manager.

All duplications were extensively examined to maintain the review's quality. For the analysis and purification of the papers, the abstracts were checked deeply to ensure the quality and relevance of research papers included in the review process. We read the abstracts of the 159 studies to see if they were relevant to the study topic and research questions. We got the full-text article for quality assessment after a total of 135 studies were deemed relevant. A later stage a careful examination of each study publication was carried out. We looked through the full-text publications to assess the studies' quality and relevance. 41 more publications were excluded from the study once the duplicate records were filtered out. After evaluating each article against the aforementioned inclusion and exclusion criteria, we chose 94 papers. The literature inclusion and removal at each level is depicted in **Figure 2**. 94 papers were chosen for data extraction, and the following aspects were extracted: articles must be published journal articles. Reports, dissertations, and unpublished documents were excluded. Through cited references, we discovered an additional 3 studies. In total, 97 studies were considered in this review.

RESULTS

Status of Surface Water Quality Monitoring

Water quality monitoring provides an reliable assessment of water quality enabling decision-makers to understand, interpret, and apply this information in support of management activities aimed at conserving the resource (Behmel et al., 2016), surface and ground water quality monitoring in Ethiopia has been incipient in most of the rivers (Graichen, 2011). If monitoring exists, the monitoring is very infrequent, for example, twice in a year in Ginchi river at Ginchi town, Awash river at Asaita. For proper surface water quality monitoring, samples should be collected at least once in a month to have a better understanding of the surface water quality situation in the watershed (Graichen, 2011). In order to monitor water quality, the following factors must be taken into account: determining a sampling site network for lakes and rivers; determining monitoring objectives (e.g., the

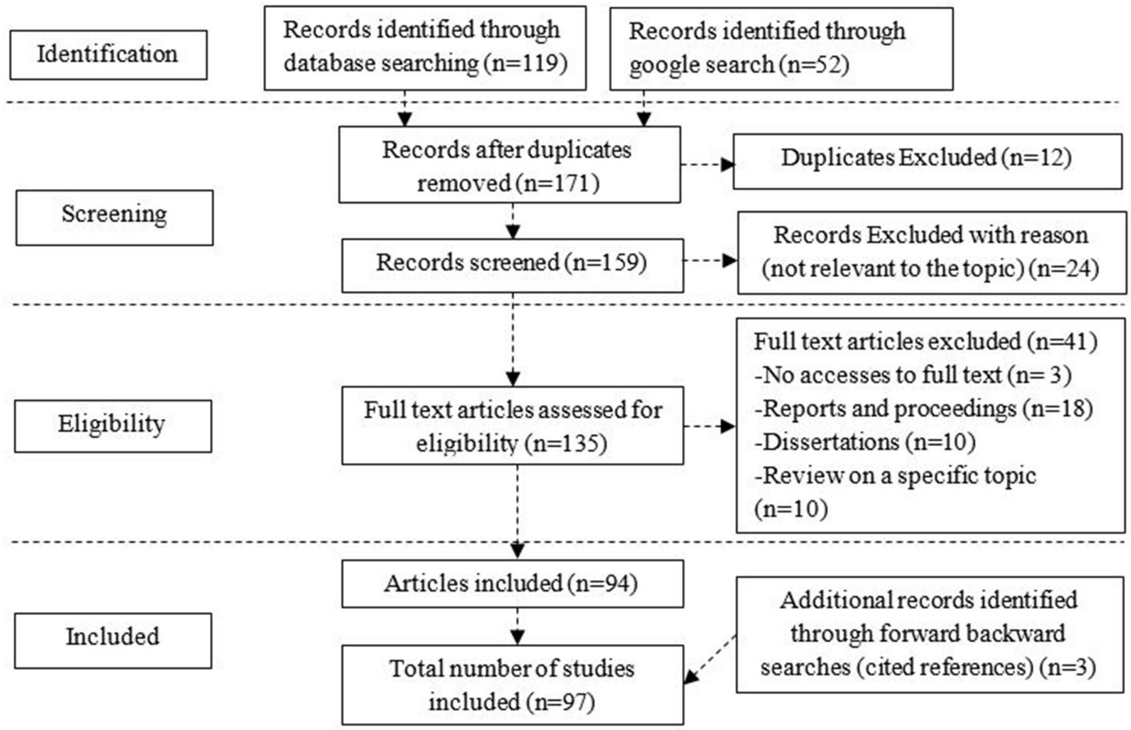

FIGURE 2 | Literature search and evaluation process and decision making for inclusion.

information that must be provided); selection of water quality parameters (WQP); frequency and recurrence of sampling; estimation of human, technical, and financial resources; logistics planning (e.g., field work, laboratory work, quality control and assessment, data handling, data storing, data analysis); and the identification of information dissemination pathways (Behmel et al., 2016). In Ethiopia, poor technical and financial capabilities restrict monitoring of rivers and sediments and understanding on the effects of pollutants (Zinabu et al., 2019). Moreover, consistent monitoring over a long period of time helps to acquire extensive surface water quality data that can be used to better understand surface water quality status of river basins (Vega et al., 1998) and thereby helps to take appropriate measures.

Currently, relatively better surface water quality monitoring exists in few water and environmental agencies, such as the Ethiopian Environmental Protection Agency (EPA) and Addis Ababa City Environmental Protection and Green Development Commission. The Awash basin authority (AwBA) also started monitoring surface water quality in the Awash basin in 2004 over 35 sites. Of selected thirty-five monitoring stations three trend, three impact and seven flux monitoring stations have been collected data monthly since July 2011. Quarterly surface water quality monitoring has been conducted in eight trends, four impact and five flux monitoring stations since July, 2011. There are also stations that measure twice per year, which are located at Ginchi, Saburie, Deho, Logia, and Affambo towns (**Figure 1**) but all these efforts are not in a comprehensive way as stated by Jin et al. (2021).

Surface water quality parameters collected in the Awash basin include pH, turbidity, electric conductivity, TDS, TS, TH, Alkalinity, Na^{+}, K^{+}, Ca^{2+}, Mg^{2+}, Fe, Mn, Cl^{-}, F^{-}, NH_3, NO_3^{-}, NO_2^{-}, SO_4^{2-}, PO_4^{3-}, HCO_3^{-}, and CO_3^{2-}. The data collection was conducted both in the wet and dry seasons although there is an emphasis to the dry season data collection. Fifty percent of the researchers collected their data both in dry and wet seasons (e.g., Masresha et al., 2011; Prabu et al., 2011; Awoke et al., 2016; Keraga et al., 2017b; Mengesha et al., 2017; Eliku and Leta, 2018; Kassegne et al., 2018; Adugna et al., 2019) while about the remaining 50% collected only dry season (Jebessa and Bekele, 2018; Kassegne et al., 2018; Tarekegn and Truye, 2018). However, there are few studies that monitor surface water quality only in the wet season (e.g., Eskinder, 2019). There are also studies that do not report periods of monitoring of their surface water quality data (e.g., Itanna, 2002; Awol, 2018; Bedada et al., 2019; Zinabu et al., 2019).

There are limited surface water quality monitoring at a finer temporal resolution, e.g., at biweekly (Akalu et al., 2011), monthly (Tesfay, 2007; Degefu et al., 2011; Abhachire, 2014; Keraga et al., 2017b; Dirbaba et al., 2018; Yimer and Jin, 2020), quarterly in Ginchi and Awash Below towns and in Awash river at the inlate of koka reservoir stations (Chernet et al., 2001; Akalu et al., 2011; Degefu et al., 2013). Dirbaba et al. (2018) collected 10 years monthly surface water quality data, which were helpful to assess trends of Hg, As, Pb, Ni, Cu, Cr, Zn and Cd at different stations of Awash river in Awash-Awash, Awash Halidebi and upper Awash sub basins. There is also seasonal basis (both dry and wet season) surface water quality monitoring as shown in **Supplementary Table S1**.

Surface Water Quality Status

Recent studies on freshwaters and river basins all around the world have found that river water pollution from organic and inorganic contaminants has gotten significantly worse over time (Kumar et al., 2021). Although water quality problem is apparent to most Ethiopian Rivers, Awash leads in the extent of impairment due to its service as a sink for the basin-wide urban, industrial and rural wastes (Keraga et al., 2017a). Land deterioration, high population density, natural water degradation, salinity and wetland degradation are all problems in the Awash River Basin (Tufa, 2021). Due to the repeated and poor irrigation practices and the increasing amount of Beseka Lake water flow to the downstream area, soil salinity becomes a challenge especially in the middle and lower Awash River Basin areas (Aregahegn and Zerihun, 2021).

Some of the most important services given by the Awash River water are irrigation, electric power generation, fish production, and serving as a water source for domestic consumption for residents living near the river course, as well as for domestic and wild animals in the area (Degefu et al., 2013). However, water quality index based evaluation showed that the water is below the standard for these purposes e.g., WHO and Canadian water quality ranking (Keraga et al., 2017a). Keraga et al. (2017a) showed that drinking and irrigation water quality indices of the upper basin were 34.79 and 46.39, respectively, which were in the poor and marginal categories of the Canadian water quality ranking. While the drinking and irrigation water quality indices of the middle/lower basin (which were 32.25 and 62.78) fall in the poor and fair ranges of the ranking. Surface water quality is frequently threatened or impaired; conditions often depart from natural or desirable levels of the ratings (Davies, 2006).

Non-point source pollution was severing in the Awash basin due to the presence several irrigation schemes that produce banana, sugar and cotton. Because of poor irrigation practices and drainage in these irrigation schemes, salt and hazardous materials have accumulated in the irrigated fields, where they were easily carried into freshwater habitats (Tufa, 2021).

Untreated domestic, industrial, commercial, and institutional liquid waste discharged into rivers harmed the rivers' water quality. Because the city's solid and liquid waste treatment systems are poor and ineffective, all point and non-point sources in the city release their effluents directly or indirectly into surrounding rivers, which eventually joins the Awash River (Yohannes and Elias, 2017). About 30% of the City's inhabitants do not have liquid waste disposal and treatment facility. Of the total waste generated in the City, only 65% is collected and disposed of while about 10% of the waste is recycled and composted; and the remaining 25% join freshwater systems without any treatment. Besides the liquid waste, the City produces about 0.45 kg/capita/day of solid waste (Mohammed and Elias, 2017).

The Akaki River is the country's most contaminated river system. Almost all of the assessed locations along the Akaki rivers had poor water quality and did not meet the river water quality criterion. This degradation was caused by a variety of contaminants both point (factories discharge, urban waste water discharges, garage wastes, hospital wastes, etc.) and non-point sources (e.g., different sewages runoff, agricultural runoff). The most common sources are industrial wastes (Yohannes and Elias, 2017). Water pollution in the Tinishu Akaki River is higher than in the Tiliku Akaki River, owing to industrial units located in and around the city, intense farming activities along riverbanks, and indiscriminate disposal of domestic and municipal wastes (Melaku et al., 2004). Similar to the Tinishu and Tiliku Akaki river, the Mojo river sub basin in Awash river basin consists of several industries, which dispose directly into the river and subsequently to the Koka reservoir without appropriate treatment (Gebeyehu and Bayissa, 2020). However, the water quality deterioration of Tinishu Akaki River is highly sever than Mojo River due to alarming municipal and industrial wastes from Addis Ababa (Mulu et al., 2013).

Surface Water Quality Impairment Indicators

Evaluations of the water quality in the Awash rivers using indicators showed that it is above global and Ethiopian minimum standards of water quality. For example, mean value of phosphate, ammonia, nitrite, COD and BOD of the upper stream of Gullele in Shankela river were above the permissible limit of the WHO and Ethiopian standards. Likewise, TDS in Shankela river exceeded the permissible limit. Concentration levels of the nitrogen and phosphate compounds of PO_4^{-3}, NH_3 and NO_2^- ion in Shankela river were above the standard limit WHO and Ethiopian EPA standards (Tarekegn and Truye, 2018).

Turbidity, DO, BOD, COD, NH_3 and TH did not meet the WHO's requirement for DWQG. F^-, alkalinity, and PO_4^-. Likewise, TN, SO_4, NH_3, TH in the UB and F^-, alkalinity, HCO_3^-, PO_4^-, did not meet FAO's irrigation water quality guideline (**Figure 3**). It is generally believed that the water quality of the Awash river is below the required standard. As such the Awash river water did not meet the surface water standard of Ethiopia (Tarekegn and Truye, 2018).

Bussi et al. (2021) examined under population growth scenarios, water quality is expected to deteriorate significantly, particularly in the Akaki River, which drains Addis Ababa, where nutrient loads could increase by up to one-third (nitrate) and more than 50% (phosphorus) compared to baseline conditions, greatly increasing the risk of eutrophication. In the eutrophication of aquatic bodies, dissolved phosphorus plays a critical role (Moges et al., 2016). Phosphates from detergents, urban areas, industrial waste (such as sugar cane production), and intensive agriculture (Girma, 2016; Moges et al., 2016) can cause nutrient levels in the water to rise, resulting in algal blooms (Girma, 2016).

Mengesha et al. (2017) reported that nitrite, phosphate, COD, BOD concentrations from sampling sites on the Akaki river exceeded the minimum standard levels. Likewise, a study in

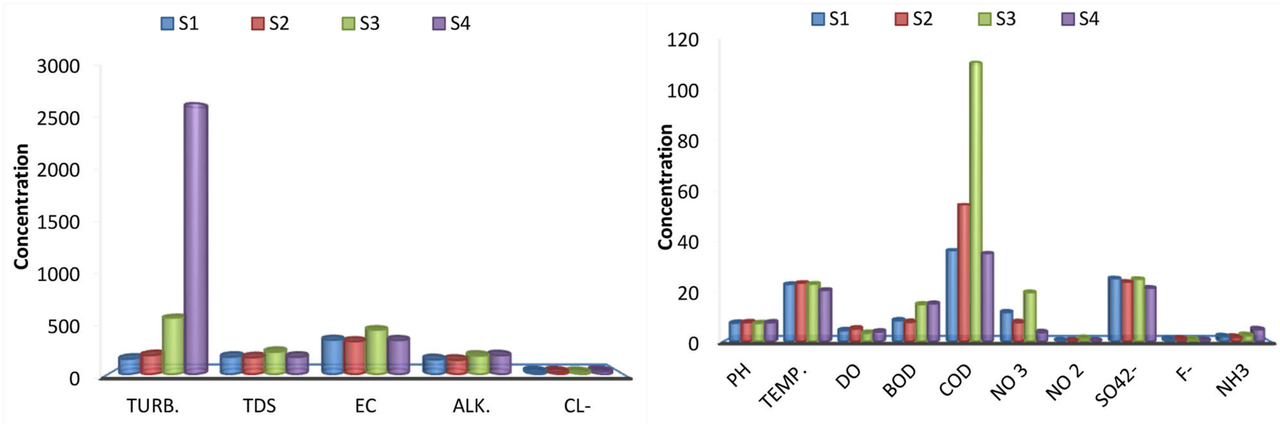

FIGURE 3 | Mean concentrations of water quality parameters in five selected sites of upper Awash river. S1 = after Lake Koka, S2 = at Koka Dam, S3 = before Lake Koka, S4 = at Melka Kuntire.

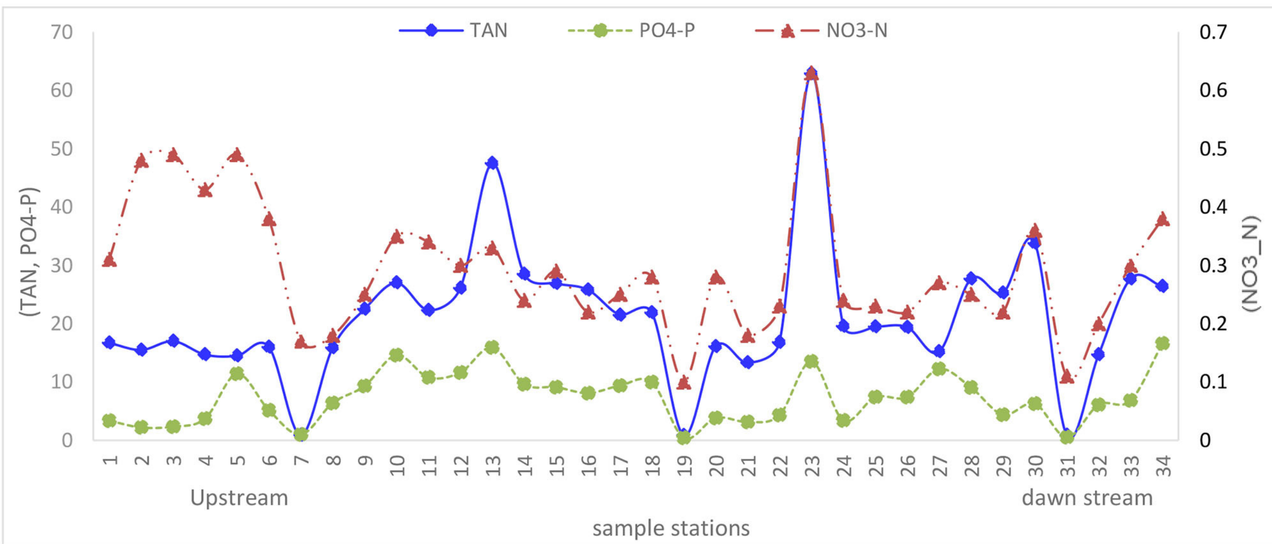

FIGURE 4 | Addis Ababa rivers water quality in terms of total ammonia nitrogen (TAN), NO_3-N, and PO_4-P (mg/l) and pH P (mg/l) (Eriksson and Sigvant, 2019).

the Tinishu and Tiliku Akaki Rivers showed that the dissolved oxygen was very low for aquatic species to survive (Eshetu et al., 2004; Melaku et al., 2007; Angello et al., 2021). Major pollutants of concern are sediment, nutrients, biodegradable organic wastes, and salt. According to studies, the Lake's expansion has impacted the soil salinization of a nearby sugarcane plantation (Yimer and Jin, 2020).

Eriksson and Sigvant (2019) studied the concentrations of phosphate and total ammonia nitrogen in the rivers of Addis Ababa (e.g., Kebena, Little and Tiliku Akaki rivers) and reported that the nutrient levels can lead to eutrophication. The study showed that concentrations of total ammonia nitrogen, NO_3, and PO_4 were lower in the upstream part of the city, higher within the dense parts of the city, but lower in the downstream part of the city around Akaki-Kaliti area. High concentration of TAN and NO_3-N was found in Kebena river in station 22 locally known by Abuara area near by Abune Gorgorios School (**Figure 4**). Similarly, the mean concentrations of NH_3-N, PO_4^{3-} and BOD_5 levels were significantly lower in the headwaters than the other sites especially dense part of the city; the mean concentrations of NH_3-N, PO_4^{3-} and BOD_5 decreased in the lower reaches of the city (Akalu et al., 2011). The main reason for this spatial variation is the dense part of the city poorly served with sanitation facilities and solid waste collection systems; second, the lower concentration downstream possibly from dilution effects of increasing discharge. Usher and van Biljon (2006) pointed out that the dominance of impervious surfaces, coupled with the altitude difference between upper and lower reaches, increased the discharge of rivers in the lower reaches of the city.

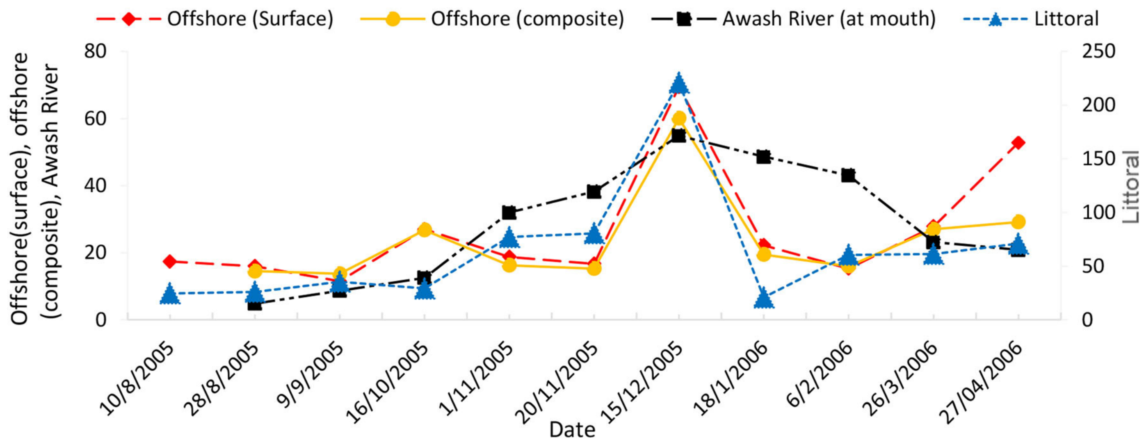

FIGURE 5 | Chlorophyll a (mg/l) from stations at the littoral, offshore, and mouth of the Awash River (Tesfay, 2007).

TABLE 1 | Status of water quality in the Koka reservoir.

Parameter	Unit	Parameter concentration (range)	References#
Temp	(°C)	21–26	Abhachire, 2014
		20.6/24*	Masresha et al., 2011
pH	–	6.13–8.6	Abhachire, 2014
		8/7.4*, 8.4	Mesfin et al., 1988; Masresha et al., 2011
DO	(mg/l)	4–11.6	Abhachire, 2014
EC	(μs/cm)	200–380	Mesfin et al., 1988
		274, 480/251*	Wood and Talling, 1988; Masresha et al., 2011
NH_3-N	(mg/l)	89.3 (μg/l)	Degefu et al., 2011
NO_3 -N	(mg/l)	0.69/1.43*, 44.4 (μg/l), 47–200	Tesfay, 2007; Degefu et al., 2011; Masresha et al., 2011
NO_2-N	(mg/l)	16.86–81.01	Tesfay, 2007
PO_4-P	(mg/l)	36.10 (μg/l)	Degefu et al., 2011
TP	(mg/l)	477.2 (μg/l)	Degefu et al., 2011
		NIL –0.14	Mesfin et al., 1988
$SO_4{}^{2-}$	(mg/l)	0.24, 6.4/6.24*	Wood and Talling, 1988; Masresha et al., 2011
		4–56	Abhachire, 2014
$CaCO_3$	(mg/l)	2.59–289	Mesfin et al., 1988
HCO_3	(mg/l)	3.22, 272/83*	Wood and Talling, 1988; Masresha et al., 2011
CO_3	(mg/l)	0.2–6.6	Abhachire, 2014
CO_2	(mg/l)	2.8–32, 0.25–0.49	Mesfin et al., 1988; Abhachire, 2014
Cl^-	(mg/l)	0.16, 15.6/5.9*	Wood and Talling, 1988; Masresha et al., 2011
		24–221.01	Tesfay, 2007
Chl *a*	μg/l	214.1, 22.4**	Mesfin et al., 1988; Degefu et al., 2011

**Dry/wet time data; **1984; #Reference arranged in respected order of parameter concentration (range).*

The accumulation of the nutrients translated into eutrophication in some freshwater systems in the Awash river basin. For example, blue-green algal bloom was observed in the Koka reservoir (Abhachire, 2014). Samples from Koka reservoir offshore zone at a depth of 6 m, littoral station at a depth 2 m, and Awash River mouth station at a depth of 2 m showed that the Chlorophyll *a* concentration was relatively high in the littoral station (**Figure 5**), which indicates there is spatial and temporal variation in the Chlorophyll *a* concentration in the reservoir. In addition to this there is high concentration of chlorophyll *a* in all station in the month of December (Tesfay, 2007). The algal biomass (chlorophyll-a, 214.1 μg/l) in Koka reservoir may likely occur due to high concentrations of nitrate (NO_3-N, 47–200 mg/l), (NO_2-N 16.86-81.01 mg/l) phosphate (PO4-P, 36.1 mg/l), (TP, 477.2 μg/l) and ammonia (NH_3-N, mg/l) (**Table 1**). Stations of Littoral and Awash river (at mouth) showed an increment in Chl a concentration from September to December. Awash river (at mouth) showed a

TABLE 2 | Mean concentration of different parameters from Mojo river.

St.	NH_4-N	NO_3-N	NO_2-N	PO_4-P	pH	TDS	BOD*	COD	Tem	EC	Turbidity
1	0.11	0.74	0.12*	0.29	7.7	384	61.2	86.3	–	–	–
2	0.18	3.23	0.22*	0.69	6.69	487	132	181	–	–	–
3	35.12*	5.44	0.12*	0.63	8.83	388	354	461	22	419.5	366.6
4	0.36*	0.726	0.14*	0.77	8.28	263	111	151	22.6	211.4	438.4
5	0.43*	0.71	0.22*	0.75	8.16	550	81.7	95.7	22.6	236.2	830.45
6	0.35*	4.23	0.18*	0.18	8.46	549	85.8	131	23.6	218.4	718.45
7	0.24*	3.44	0.08	0.27	8.14	506	61.8	111	23	307.3	669.85
8	39.1*	6.45	0.35*	0.88	9.93*	566	162	254	23.5	394.3	564.6
9	29.85*	7.84	0.08*	19.15	11.1*	395	231	342	23.8	427.6	763.95
10	4.45*	5.92	0.58*	0.52	8.85	855	221	342	23.2	238.2	619.25

Above Ethiopian EPA and WHO standards.

decreasing trend from January to July. The Offshore (surface) and offshore (composite) sites showed fluctuating concentration in different time period.

The concentration of some water quality parameters of Koka reservoir showed temporal increment. Some of the evidences by different researchers (**Table 2**) showed that the parameters like Cl^-, SO_4^{2-}TP, EC, NO_3, PO_4-P, NH_3-N, DO and Chl *a* concentrations increased in the different time periods.

The Mojo River serve as a good example to demonstrate water pollution due to industries since it has water quality monitoring stations (**Figure 6**) along the river course at eight industries (i.e., Kolba Tannery, Ethio-Japan Textile, Soap factory, Gelan Tannery, Organic Export Abattoir, Derartu Tannery, Mojo Tannery and Food and Oil Complex). Most of the measured water quality indicators showed that the minimum acceptable limit was exceeded (Gebre et al., 2016). The mean concentration of NH_4-N and NO_2-N in all stations were exceeded Ethiopian EPA and WHO standards (**Table 2**).

There is a distinct seasonal variability in water quality in the Awash river basin. During the dry season, all the sampling sites of the basin showed a decrease in EC, TH and Cl^- from upper to lower parts of the basin (Keraga et al., 2017a). However, TDS, Cl^-, and SO_4^{2-} decreased in the rainy season. Both seasons, maximum Cl^- and EC/TDS/SO_4^{2-} were observed at Beseka and before Beseka lake, respectively. On the other hand, in both seasons TH was at its absolute minimum at Beseka station. Beseka, before Beseka and Sodere spring sites were accountable for the spatial variation of water quality, for example EC, TDS, TH, Cl, and SO_4^{2-} showed major differences in these sites (**Figure 7**).

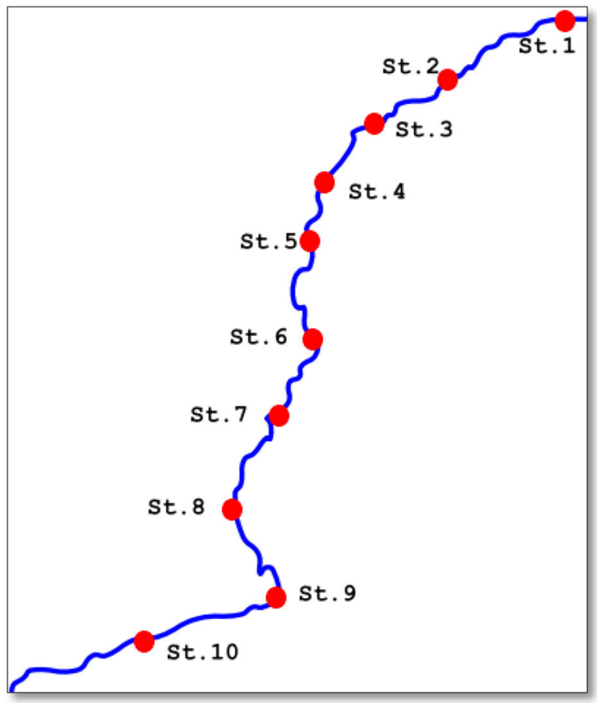

FIGURE 6 | Sketch map of Mojo river. St. 1: upstream, St. 2: food oil complex, St. 3: Mojo tannery, St. 4: Japan textile, St. 5: soap factory, St. 6: Derartu tannery, St. 7: organic export abattoirs, St. 8: Gelan tannery, St. 9: Kolba tannery, St. 10: Dawn stream.

Causes of Surface Water Quality Impairment

The Awash River Basin is Ethiopia's largest, most developed, and most extensively utilized river basin. Furthermore, the Awash River basin contains the bulk of irrigated farmland in the country (Keraga et al., 2017a), with a variety of small-, medium-, and large-scale irrigation projects, industries positioned along the river, a significant rural population, and rapid urban development (Aregahegn and Zerihun, 2021). The water quality of the Awash River has been harmed by numerous types of pollution resulting from waste generated from various socioeconomic activities, poor farming practices, and large-scale irrigation intensified irrigation schemes throughout the basin (Tamiru, 2001; Keraga et al., 2017b). This is due in part to the fact that the main sources of water pollution in the Awash River Basin include excessive irrigation pumping and overflowing, discharge of saline Beseka Lake water and hot spring water from various

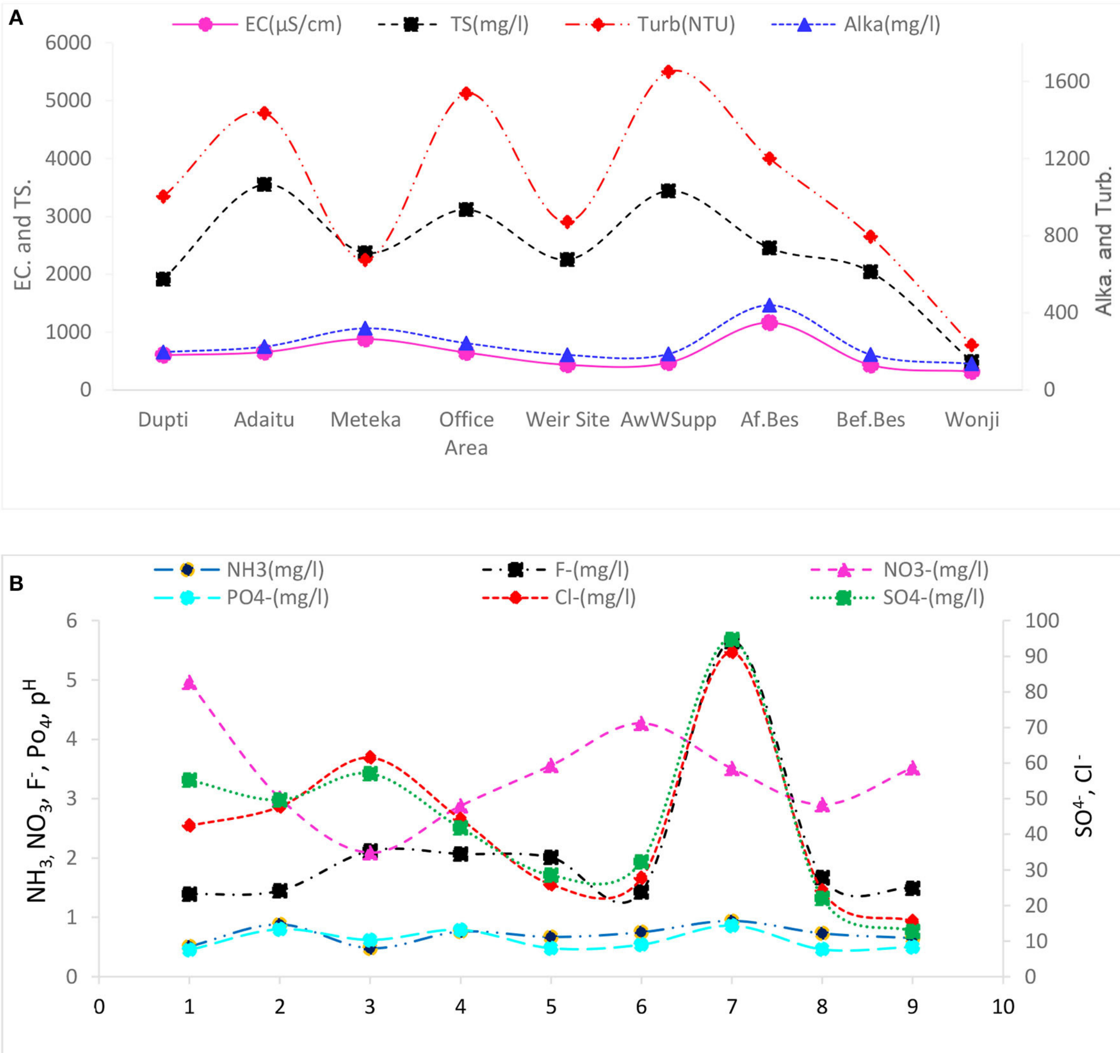

FIGURE 7 | Mean values of water quality parameters for nine sampling sites of Awash river 2005–2013. **(A)** is for parameters EC,TS, Alkalinity and Turbidity and **(B)** is for parameters NH3, NO3, PO4, pH, SO4 and CL (Keraga et al., 2017a).

places to the river, urbanization, and industrial waste (Taddese, 2019; Aregahegn and Zerihun, 2021).

The Awash River is polluted by liquid and solid effluents released from industries (Eliku and Leta, 2018) and households (Abebe, 2019) and runoff from agricultural and urban areas, irrigation drainage and Lake Beseka (Elias et al., 2016). One of the major sources of pollution for the Awash River is untreated domestic discharge from the city of Addis Ababa (Worku Giweta, 2018) and upstream effluents from industries (Itanna, 2002). For example, Large and small factories around Addis Ababa, Mojo and Adama, Wonji, and Metehara sugar factory are among the upper basin's industrial operations, while Kesem Kebena and Tendaho sugar factory are the middle and lower basin's important industrial activity, respectively (Aregahegn and Zerihun, 2021).

The water quality of the Awash River has been affected by various types of pollution caused by waste produced from various socioeconomic activities, as well as inadequate agricultural and irrigation management in the basin. Excess pumping and overflowing during irrigation, discharge of saline Beseka. Lake water and hot spring water from various places to the river, urbanization, and industrial waste are the main sources of water pollution in the Awash River Basin (Taddese, 2019; Yimer and Jin, 2020; Aregahegn and Zerihun, 2021).

The Upper Awash River Basin has poor water quality, which was largely mainly due to poor farming, untreated industrial effluents, and a lack of sanitation facilities for riparian communities (Degefu et al., 2013). There is extensive agricultural intensification (Alemu et al., 2017) and industrialization (Degefu et al., 2013) which has been exacerbating the surface water quality impairment. Besides receiving all industrial and domestic pollutants from the Upper Awash region, the middle Awash experiences substantial soil erosion and other non-point source pollution due to inappropriate agricultural practices.

Addis Ababa's water resource is extremely polluted as a result of rapid population increase, unregulated urbanization and industrialization, and inadequate waste management methods, affecting human health and ecosystem function as a whole. Addis Ababa's rivers are simply used as a dumping ground for all of the city's waste (Yohannes and Elias, 2017). Several studies have found that untreated and inadequately treated industrial wastewaters, household wastes, residential and commercial activities, and sewage discharged into waterways pollute Akaki river (Mekuria et al., 2021). According to Tarekegn and Truye (2018), the causes like indiscriminate dumping of refuse into the river, indiscriminate dumping of industrial wastes, scattering settlement or urbanization and others like vehicle washing effluents released into the Shankila river.

Anthropogenic activities account the lion's share of surface water quality deterioration in several rivers (Degefu et al., 2011; Abhachire, 2014) where indiscriminate dumping of domestic and industrial wastes, and wastes from other sources such as agriculture, petrol stations, health facilities, and garages, etc. are rampant. Textiles, slaughterhouses, tanning, leather products, and other activities, among others, are located in this basin (Aregahegn and Zerihun, 2021).

Water pollution sources could be point sources (direct identifiable sources) and non-point sources (different non-identifiable sources of origin and number of ways that contaminants enter into the water body) (Singh and Gupta, 2017). Nutrients in surface water have been mainly related with land use activities (Eliku and Leta, 2018). Anthropogenic activities of point and non-point sources of pollution are the major causes for nutrient enrichment of surface water (Singh and Gupta, 2017).

Point Sources

Wastewater generated from a single source like industrial influents and municipal wastewater/wastewater treatment facility as well as leaking septic systems, chemical and oil pills and illegal dumping (Kebede et al., 2012), and certain agricultural activities, such as animal husbandry (Gebre et al., 2016) are point sources of pollution.

Historically the establishment of modern industries in Ethiopia has started one hundred years ago (in 1920s) (Gebreeyesus, 2013). However, Many Ethiopian leather processing industries, for example, lack suitable waste treatment methods. By its very nature, leather processing entails soaking, fleshing, washing, and other water-based methods for removing dirt, flesh, salt, and other foreign substances (Wassie, 2020). Many textile and garment industries in Ethiopia lack waste treatment plants, making it difficult to properly dispose of their waste. They just discharge their waste into the environment, which in most cases is a freshwater. As a result of several studies conducted on a small number of individual textile factories, it has been suggested that the textile and garment sector's wastewater is perhaps the major source of water pollution in Ethiopia (Menbere, 2019).

Along the Awash River and its tributaries, particularly the Akaki River, a number of polluting industries and flower farms have been developed in the previous two decades. In addition, these companies discharge highly polluted sewage into Lake Koka's waters (Girma, 2016). According to Yohannes and Elias (2017), Addis Ababa hosts about 65% of the country's industries and more than 90% of the industries discharge their waste to nearby rivers without proper treatment. In recent years, the expansion of industries around the cities of Akaki, Mojo, and Adama has increasing the influence of industrial pollution to the Awash River water (Aregahegn and Zerihun, 2021). Addis Ababa Tannery, Tikur Abay shoe Factory, Gulele Soap Factory, Ethio Marble Industry and Gulele Shirt Factory discharge their waste into Kera river with little or no treatment applied (Itanna, 2002). Most industries in Gelan and Dukem have established neither treatment plants nor adequate storage or discharge channels for their wastes. As a result, polluted liquids are directly discharged into the open landscape (Dadi et al., 2017). There is no monitoring system that follows if industries treat their effluents before discharging it into the Awash River system.

Jebessa and Bekele (2018) studied physicochemical characteristics and impacts of raw and treated effluents from the Anmol Product Paper factory on upstream and downstream water qualities at factory and 5 different sampling station on the upper Awash river and showed that both raw and treated effluents had water quality levels that are above the WHO and Ethiopian standards (**Supplementary Table S3**).

Chemical wastes and byproducts from industry, as well as mismanaged urban trash disposal at open dump sites from major cities, continue to pollute the environment (Wassie, 2020). Despite generating large amounts of solid waste from domestic activities, Addis Ababa does not have adequate waste management facilities. As a result solid waste is often piled on available open grounds, stream banks and near bridges, where it is washed off into rivers (Yohannes and Elias, 2017). The 29 hospitals in Addis Ababa produce 430.7 tons of infectious waste each year. Laboratory cultures, wound dressings, blood and other human fluids, and needles are examples of contagious clinical waste. Despite the fact that most hospitals have waste treatment facilities, some clinical waste makes its way into neighboring tributaries (Yohannes and Elias, 2017).

Non-point Sources

Non-point source pollution (NPS) is pollute on that does not originate from a single, easily identified source and is caused by the scouring effect of rainfall and dissolved pollutant solids entering recipient waterbodies (such as rivers, lakes, reservoirs, and bays) by runoff (Liu et al., 2015). Non-point sources contribute more pollution to surface water than does point source pollution sources. Relatively little is known about the non-point source pollution in sub-Saharan Africa (Jones-Lee et al., 2011).

Water quality of surface waters is impaired by several factors such as the non-point source contaminants through runoff (Carpenter et al., 1998). This affects the impairment of surface water quality and the aquatic life in lakes especially developing countries like Ethiopia (Awoke et al., 2016).

Agriculture

Agriculture is intensifying in Africa, increasing pressure on the environment. Agriculture is a large contributor of non-point source pollution to aquatic environment. The degradation of water quality caused by widespread agricultural activities released into river water put extra pressure on surface water (Islam et al., 2020). The interaction between agricultural malpractices and the environment in Ethiopia results in relentless pollution of freshwater. Agriculture-induced pollution contributes significantly to damaging aquatic ecosystem health in the country (Awoke et al., 2016).

Pollution from agricultural activities includes nitrogen and phosphorous based chemical fertilizers, insecticides, herbicides, and organic matter. Large farms are the primary users of pesticides and herbicides (Girma, 2016). As a result of runoff or irrigation return flows, these pollutants end up in waterways (Awoke et al., 2016). For example, presumably due to pollution of the whole stream reach by the catchment nutrient sources in upper Awash (Degefu et al., 2013).

Both the main Awash River and its tributaries in Upper Awash have substantial rain-fed and commercial agricultural farms, high vegetable production, and animal husbandry activities (Eliku and Leta, 2018). Animal husbandry is dominantly found in the surrounding parts of Addis Ababa, Nazreth and Debre Zeit. As a result of these activities, it is expected that a significant amount of organic waste is generated on rainy days (in runoff). Storm water runoff or debris blown into waterways from agricultural land, inorganic fertilizers in agricultural fields and animal manure are non-identifiable sources of pollution which are responsible for nutrient enrichment in aquatic environments (Tamiru, 2001; Keraga et al., 2017a). Agricultural wastes have been polluting freshwater systems jeopardizing socio-economic and ecological assets in the river basin (Mengistie et al., 2017).

The chemical constituents of irrigation water can affect plant growth directly through toxicity or deficiency, or indirectly by altering plant availability of nutrients (Belay, 2019). The rising concentration of salt and toxic elements in the drainage waters from irrigated lands is a common awareness in middle Awash. Availability of good quality water in Middle Awash Valley due to agro-industries have created great concern on surface water quality (Taddese et al., 2007; Taddese, 2019). Loiskandl et al. (2005) point out that community-based irrigation schemes are more feasible at highlands than at lowlands due to surface water quality deterioration, this is probably linked to the original water quality of the source.

Erosion by Water

Soil erosion is very common and some of the lakes are affected by the consequences of sedimentation and increased turbidity (Abhachire, 2014; Girma, 2016). Anthropogenic forces that alter the physical landscape cause substantial soil erosion which have adverse impact on surface water bodies (Issaka and Ashraf, 2017). Soil erosion and other sediment sources can also be significant nutrient sources, as nutrients often tend to be found in particulate form. Sediment that comes from active construction sites and washes off of particulate materials from impervious surfaces is one of the most common and potentially damaging pollutants found in urban runoff (Shaver et al., 2007).

According to Moges et al. (2017) the decreasing water quality trend of the Lake Tana was attributed to the non-point source sediment and nutrient inflow to the lake with high erosion rate from the watersheds.

One of the major pollutants with regard to agriculture is associated with erosion of the soil in the upper catchments of Awash River. This is especially intense in the rainy season when there is high surface runoff. Chemical fertilizers used to boost production enter streams as a result of soil erosion. The erosion process is linked to pollution of local water bodies and wetlands. On cropland, soil erosion causes a reduction in yield potential, a decrease in surface water quality, and a breakdown in drainage systems. Non-point nutrient contaminants and chemicals are also transported with soil particles, resulting in greater sediment levels and, ultimately, water eutrophication and disruption of fragile aquatic ecosystems (Issaka and Ashraf, 2017).

Urbanization

Storm water or urban runoff contains a mixture of constituents: sediment, nutrients (nitrogen and phosphorus), Chlorides, Petroleum hydrocarbons and Organic chemicals (pesticides, herbicides, and industrial) (Shaver et al., 2007). The pollution sources of the Shankila River, one of the most dominant causes were domestic wastewater releases along the entire river course (Tarekegn and Truye, 2018).

Urbanization and industrialization significantly reduce the agricultural land and causes environmental damage in the basin. Urban areas like Addis Ababa, Dukem, Mojo, Debrezeit and Nazert increase the influence of domestic pollution to the Awash and the Mojo rivers; and Lake Koka (Melaku et al., 2020). As the number of hotels, commercial establishments, and factories grow, the amounts of solid and liquid wastes being generated are also growing (Girma, 2016).

Even though Addis Ababa is the only city with sewer networks, it has a very limited sewer network coverage that accounts for 7.5% of the built-up areas. Since only parts of the older sections of the city are connected to the central sewer system, both residential and business premises use septic tanks. There is a high amount of waste disposal in the river and riverbanks from municipal source (municipal solid and liquid wastes), liquid wastes from toilets, houses that are built at the edges of the city's rivers link their toilets directly to them (as a result, the residents use the river as toilet), open urination and defecation in and around Addis Ababa, 25% of the city's residence do not have toilet. Therefore, status of river pollution is increasing as time elapsed (Yohannes and Elias, 2017).

Other Sources

In addition to the socio-economic pressures, environmental pressures also play a major role in the surface water quality of the basin. This is evidenced by the high fluoride concentrations in rift valley soda springs, alkaline lakes, hot springs and geological formations (Taddese, 2019; Yimer and Jin, 2020; Aregahegn and Zerihun, 2021). Other waste sources come from construction buildings, roads and dams, fuel stations, garage operations and congested settlements (Yohannes and Elias, 2017). Physical factors like heated water discharged from a power plant (Walker et al., 2019), for example as it is observed that discharge of an industry in Sebeta area (One Weha bottling and Balezafu Alcohol Industry) the temperature is about 28.2 and 32°C respectively, contribute by changing the temperature of the water body.

DISCUSSION

Gaps and Problems Identified

This review identifies several water quality research efforts, but it also identifies research gaps. The most important relates to the scope and delimitation of the study. Much of the reports are either separate graduate thesis, unpublished reports, and research limited to specific location and or time. For example, there is no a comprehensive surface water quality study, there is a lack of detailed combined spatial and temporal surface water quality data to show the overall picture of the sub watershed or the basin in general. In addition to this, there is no sound and comprehensive surface water quality information system or database at federal and local levels which is open and accessible for the public. This review work tries to focus some of these research gaps.

Assessing the relative contribution from diffuse and point sources is a major research gap in the basin. There is lack of non-point source pollution (urban based or agricultural based) investigation in a basin or country level except (Eskinder, 2019) in Kombolcha area. There is little evidence based investigation into the influence of agriculture on surface water quality impairment for example organic compounds or chemicals like herbicides, insecticides, hydrocarbons, DDT, lindane and other forms of chemicals are not investigated. For the problem of surface water quality, there is no well-coordinated research and no meaningful discussion between researchers and the community.

There is inadequate good spatial and temporal scale surface water quality data and/or monitoring in the basin. Biological parameters monitoring is very limited in the research works. This could be probably, some surface water quality parameters to be monitored are too expensive (some not available in the country) to be monitored so as to make scientific researches and to provide policy direction recommendations. In addition to this, the existing laboratory facilities are not fully equipped and not well organized to analyze the overall surface water quality parameters unless they are upgraded. Economic and financial pressures dominate other concerns and the impact of pollutants on water is neglected (Zinabu et al., 2019).

Policy responses for surface water quality drivers for the case studies have little attention. The analysis of legal, policy, and institutional framework showed a lack of cooperation between stakeholders, lack of knowledge of the policy documents, absence of enforcement strategies, unavailability of appropriate working guidelines, and disconnected institutional setup at the grass root level to implement the set strategies as the major problems (Awoke et al., 2016).

Opportunities

There are several institutions, organizations and agencies or authorities that have the mandate and responsibilities for water resource management. This is an opportunity for the sector. Revising the policy (Awoke et al., 2016) based on the research findings and participating implementers, local community, investors etc. are vibrant to improve the quality of rivers and lakes.

Out of the 14 industrial parks to be established in the country ten (71%) are to be built in the basin. Out of the total seventeen agro industry corridors, four (24%) are found in the basin thus there would be an opportunity for surface water quality improvement by applying zero liquid discharge. The Hawassa Industrial Park and Kanoria Textile Industry (the first denim manufacturing plant) which are so far operational that have a zero-liquid discharge take as a model and implement in Awash basin.

The central wastewater treatment plants of Addis Ababa are being expanded, but the sewerage network remains limited. In 2014, a decision was taken to systematically introduce decentralized waste water treatment in 15 newly built condominiums. Their combined treating capacity is over 27,000 m^3/day serving 185,000 residents if these experiences continue for the newly built condominiums and real estate it will have a good contribution to minimize surface water quality issues.

The Kaliti wastewater treatment plant has about 100,000 m^3/day (McFarland et al., 2019) capacity but currently it is working at only 40% of its capacity. This is due to different challenges of connecting the sewerage system of the city with the newly built sewerage network. If this will be solved i.e., the city wastewater network properly connected with the main Kaliti wastewater treatment plant main network line and work with its full capacity, it will have a future hope to minimize surface water quality problem. In addition to this, the riverside ongoing project by Addis Ababa city administration at the moment will likely improve the situation in part of Addis Ababa watersheds.

CONCLUSION

Surface water quality monitoring in Ethiopia has been incipient in most of the rivers this is due to poor technical and financial capabilities monitoring of rivers and sediments and understanding on the effects of pollutants becomes limited. In addition to this, surface water quality status of river basins not better understood and appropriate measures could not have been taken. There are limited surface water quality monitoring at a finer temporal resolution as well as appropriate locations so that hydrological water quality modeling in the basin is very limited.

Some of the most important services given by the Awash River water are irrigation, and serving as a water source for domestic consumption for residents living near the river course, as well as for domestic and wild animals in the area. However, water quality index based evaluation showed that the water is below the standard for these purposes; conditions often depart from natural or desirable levels of the ratings.

The Awash Basin's surface water quality is degrading. Rapid urbanization and industrialization have resulted in substantial water pollution from untreated domestic, industrial, commercial, institutional liquid waste presence, and several irrigation schemes (both point and non-point sources). The bulk of the factories in the basin do not have wastewater treatment facilities; they have not built treatment plants, nor have they established appropriate storage or discharge paths for their waste; instead, they release their wastewater into neighboring rivers, lakes, and streams. The

Akaki sub-basin (Tinishu Akaki river) is the country's most contaminated river system. Almost all of the assessed locations along the Akaki rivers had poor water quality and did not meet the river water quality criterion.

Water quality in the Awash rivers was assessed using various indicators and found to be above global and Ethiopian minimum standards for surface water quality. As such the Awash river water did not meet the surface water standard of Ethiopia.

Numerous types of pollution resulting from waste generated by various socioeconomic activities, poor farming practices, and large-scale irrigation intensified irrigation schemes throughout the basin have harmed the water quality of the Awash River. The surface water in Addis Ababa is an example of this. As a result of rapid population growth, unregulated urbanization and industrialization, and inadequate waste management systems, it is very polluted, impacting human health and ecosystem function as a whole. The rivers of Addis Ababa are simply used as a dumping ground for the city's waste. Several studies have found that untreated and inadequately treated industrial wastewaters, household wastes, residential and commercial activities, and sewage discharged into waterways pollute Akaki river.

Agriculture is a large contributor of non-point source pollutants to aquatic environment. Pollution from agricultural activities includes nitrogen and phosphorous based chemical fertilizers, insecticides, herbicides, and organic matter. Large farms are the primary users of pesticides and herbicides. Both the main Awash River and its tributaries in Upper Awash have substantial rain-fed and commercial agricultural farms, high vegetable production, and animal husbandry activities. As a result of these activities, it is expected that a significant amount of organic waste is generated on rainy days (in runoff) which are responsible for nutrient enrichment in aquatic environments. As agriculture erosion by water, storm water or urban runoff and other natural sources of pollutants like soda springs, alkaline lakes, hot springs and geological formations are sources of pollutants for surface water quality impairment.

The majority of the papers are either distinct graduate theses, unpublished reports, or studies focused on a specific location and/or time period. Furthermore, the majority of research projects are located in upper Awash this is due to the high population number and high population density (like Addis Ababa, Mojo, Debrezit, and Adama), high urbanization and comparatively large number of industries. Assessing the relative contribution from diffuse and point sources is a major research gap in the basin. There is lack of non-point source pollution (urban based or agricultural based) investigation in a basin.

RECOMMENDATION

High temporal and spatial resolution surface water quality monitoring stations and comprehensive monitoring systems need to be integrated and improved. The monitoring site selection shall consider land use/cover, drainage network, watershed size/area, as well as river junction points of the watershed outlets as a criterion. In addition to this, monitoring of the sewerage systems shall be included in the water quality monitoring system. Furthermore, individual research works of students and researchers and their data which is related to surface water quality issue shall be systematically collected and synchronized with the central database of AWBA on a regular basis. Finally, build a water quality database for better management and flow of information and water quality mapping as well as an open access for the user. Surface water quality monitoring technologies like remote sensing (satellite images) shall be practiced so as to minimize monitoring costs as well as to get high temporal resolution water quality data.

According to Awoke et al. (2016) river water pollution is a growing challenge and needs urgent action to implement intersectoral collaboration for water resource management that will eventually lead toward integrated watershed management. Revision of policy and increasing the awareness and participation of implementers are vital to improve surface water quality. Strengthen the coordination mechanism of different stakeholders who are involved in surface water quality management for continuous and structural monitoring and evaluation of surface water quality.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

EA is a researcher and lead author. GZ and TA contributed to project design, conceptual framework development, and manuscript preparation. YD, HB, and BT reviewed different versions of the manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2022.782124/full#supplementary-material

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Impacts of Surface Water Quality in the Awash River Basin, Ethiopia: A Systematic Review

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Water quality impairment, due to anthropogenic activities and limited enforcement capacity, is a rapidly growing threat to water security as well as public health in developing countries. Cumulative effects of deteriorating water quality undoubtedly put pressure on public health and socio-economic developments. For example, most industries in Ethiopia discharge their effluent directly into freshwater systems without any treatment process. The problem is severe for rivers such as the Awash that pass through major cities. Although there were a few studies that looked into the issue, there is a lack of comprehensive water quality impact assessment on agriculture, health, and socio-economics. This article systematically summarizes current research on water quality issues in the Awash River Basin to generate comprehensive information that captures the water quality status of the river and impacts of water contamination, and identify information and management gaps. Results showed that water quality degradation along the river course and in selected tributaries exceeds water quality standards by the WHO and national guidelines. For example, E-coli bacteria concentration in two tributaries, Tinishu and Tiliku Akaki, reach up to 6.68 and 6.61 billion CFU 100 ml/L. Virological profile of creeks receiving wastewater from hospitals in the City of Addis Ababa contains coliphages levels reaching as high as 5.2×10^3 pfu/100 ml for urban rivers and up to 4.92×10^3 pfu/100 ml. Heavy metals that far exceed the tolerable levels for humans were also detected in vegetables produced using impaired water. Heavy metals such as Cd, Cr, Cu, Hg, Ni, and Zn were detected in potato, Zn and Hg in Cabbage, and Cr in onion and red beet. Lettuce irrigated with Akaki river water found to contain 0.263 (Cd), 420 (Fe), 13.44 (Zn), 7.87 (Cr), 7.49 (Cu), and 6.55 (Pb) in mg/kg both in excess of WHO guideline. In addition, a high concentration of Cr has been also found in fish tissues. There has never been a systematic evaluation of the impact of contaminated water in the Awash Basin. Comprehensive impact of water quality investigation that takes into account the different pollutants dynamic needs to be made to protect the well being of downstream beneficiaries including the aquatic ecosystem. In conclusion the systematic review has shown that for a river that cross-through emerging mega-city like Addis Ababa, the human and ecosystem health impact of aquatic ecosystems pollution should not afterthought action

Keywords: impact, water quality, pollution, toxicity, Awash Basin, Ethiopia, Awash River

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INTRODUCTION

The role of clean water in social development, economic growth, and sustaining a healthy economic system has been well established (Katko and Hukka, 2015). The global community has been mainstreaming water supply and sanction as one of its core activities. Ensuring the availability and sustainable management of water and sanitation for all (SDG 6) is among the 17 sustainable development goals the global community is grabbling to achieve by 2030 (Kroll et al., 2019). Moreover, due to its cross-sectoral nature, improved water security has a catalyst role in the achievement of other SDGs targets.

Despite this, water security particularly in developing countries tends to be at a cross road (Yomo et al., 2019). Growing population, expansion of cities, rapid urbanization, the expansion of industrial activities, the difference in inter-sectoral priorities, and the low enforcement capacity are threatening the rivers, and lakes (McGrane, 2016; Berg et al., 2019). Environmental law enforcement in South Africa, as in other developing nations, has suffered significant setbacks due to a lack of technical expertise, insufficient finances, corruption, and penalties with low deterrent effects (Edokpayi et al., 2017).

Anthropogenic activities are responsible for the majority of water quality degradation in several rivers, where indiscriminate dumping of domestic and industrial wastes, as well as waste from other sources such as agriculture and health facilities, is common (Igwe et al., 2017; Amoatey and Baawain, 2019) and justified in Ethiopia (Tadesse et al., 2018), Bangladesh (Hasan et al., 2019; Islam et al., 2020, 2021), India (Pareek et al., 2020; Rakhecha, 2020), Rakiraki town in Fiji (Kumar et al., 2021), Kenya (Chebet et al., 2020) and South Africa (Edokpayi et al., 2017). Land and water quality degradation in Ethiopia, in general, was not impacted much by anthropogenic activities for the past decades due to the low population density that practice slash and burn agriculture with minimum fertilizer use (Ligdi et al., 2010). However, in the recent past, a wide range of pollutants including organic matter, salts, nutrients, sediments, heavy metals, etc. due to natural processes and anthropogenic sources are posing a serious threat to the land and water qualities of many of the basins in Ethiopia (Moges et al., 2017). The problem is aggravated further due to climate change, rapid population growth, urbanization, and agricultural practices that put intense pressure on natural resources including the availability and quality of freshwater resources (Berg et al., 2019).

The environmental impact on local rivers increases as a city gets bigger, especially if the city cannot properly handle solid waste and wastewater. Untreated wastewater from industries and households may be discharged into rivers, where solid waste may accumulate along the course of the river (Dagnachew et al., 2019; Chebet et al., 2020), especially in developing countries where wastewater treatment facilities are not well developed. The discharge of untreated municipal and industrial wastes into water bodies, which resulted in increased heavy metal concentrations in river water, is linked to severe water quality degradation (Islam et al., 2020). Most cities of developing countries generate on the average of 30–70 mm^3 of wastewater per person per year (Edokpayi et al., 2017). Urban development interferes with water resources by altering the biophysical processes and fluxes of water, sediment, chemicals, microorganisms, and heat (McGrane, 2016). As cities develop in population, so does the total amount of water required for adequate municipal service. This rise in total municipal water demand is due to a combination of factors, including an increase in urban population and a trend toward economic development (McDonald et al., 2014). The rapid economic development of China has come at a cost to the environment, increasing volumes of untreated wastewater from households, and industrial and agricultural runoff all contributing to severe pollution of the aquatic environment (Ma et al., 2020). Water quality is becoming a serious problem in some basins in Ethiopia. For example, the Rift Valley Lakes and their contributing rivers are used for irrigation, soda abstraction, fish farming, and recreation (Ayenew and Legesse, 2007).

The pollution of surface water with trace elements has gotten a lot of attention around the world (Islam et al., 2020). Because of their extreme toxicity, abundance, and ease of accumulation by different organisms, heavy metals are regarded one of the most dangerous environmental pollutants (Islam et al., 2021). Industries in developing countries generate volumetric wastes which are discharged without treatment into nearby water bodies. For example, most industries in Uganda use outdated manufacturing technologies and do not have functional effluent treatment plants (Srinivasan and Reddy, 2009) and in Bangladesh and Ethiopia often discharge their wastewater into the freshwater system without any treatment (Naser et al., 2014; Girma, 2016). Therefore, raw and harmful wastes are discharged into the surrounding water bodies. Textile industries are huge industrial consumers of water and producers of wastewaters, with growing demand for textile products leading to an increase in textile wastewater output, making the textile sector one of the most serious sources of pollution globally (Mehari et al., 2015). Dadi et al. (2017) investigated the environmental and health impacts of effluents from four different textile and garment plants in Gelan and Dukem areas around Addis Ababa and found that the bacteriological pollutants in the effluent are higher than the permissible limit given by the Federal Environmental Protection Authority (FEPA) (Dadi et al., 2017). Such practices lead to water quality deterioration of many freshwater systems making them unsuitable for irrigation, domestic or industrial purposes (Keraga et al., 2017b).

Point and non-point source pollutions from towns and cities contribute nutrient-rich effluents that are conducive for eutrophication where an upsurge of algae growth in the lakes will happen, and thereby depletes the oxygen needed by fish and other ecosystems (Girma, 2016). Addis Ababa, which is part of the Akaki catchment, has a rapidly growing population, unregulated urbanization and industrialization, poor sanitation, and uncontrolled waste disposal, all of which contribute to a substantial deterioration in surface water quality (Kassegne et al., 2018). Rapid loss of ecosystems and land-use change, in part due to agricultural intensification, have been among the major drivers for recent increases in water in sedimentation and water quality issues in Ethiopia (Moges et al., 2017).

The river basin is convenient for irrigated agriculture and industrial development due to its proximity to major cities such as Addis Ababa, Nazert, Debre Zeit, Dessie, and Dire Dawa. It has been impaired by pollutants from large-scale irrigation scheme (Alemayehu, 2001; Keraga et al., 2017b). On top of these, most of the industrial plants and cities do not have wastewater treatment plants (Rooijen and Taddesse, 2009) releasing their effluents directly to the river basin. Therefore, the discharges of these domestic, industrial, and agricultural wastes have been polluting freshwater systems jeopardizing socio-economic and ecological assets in the river basin (Mengistie et al., 2017).

The costs of water scarcity, misallocation, and pollution can be difficult to measure, and they are not always visible (Mekonnen and Amsalu, 2018). Smallholder farmers grow a variety of vegetables in and around Addis Ababa. Without developed modern irrigation techniques, water scarcity is rampant and these farmers rely on the Akaki River as their primary source of water for irrigation. Due to a scarcity of freshwater, partially treated and untreated wastewater from a variety of industries, as well as gray water from the Addis Ababa city environment, are now used for irrigation (Mengesha et al., 2021). While water quality is a complex issue and involves multiple disciplines, this review focuses on water quality with respect cation, metals and heavy metals in surface water, and their impacts on vegetables, soil, biodiversity, human health, toxic and socioeconomic effects. The river collects untreated and unmanaged domestic, industrial, and agricultural pollutants from the catchment immediately along its course, which could lead to a change in quality of water. As a result, among the major rivers of Ethiopia, the Awash River is the most vulnerable to many types of serious pollution (Keraga et al., 2017b).

There has been little research on the impact of contaminated water on human and animal health, as well as the socio-economic implications on the riverine community, the downstream population, the basin, and the country as a whole. Although it is not complete and does not cover the entire basin and sub-basins, this systematic review provides valuable insight into the positive aspects of several studies that reveal the state of rivers pollution by heavy metals and their sources.

Although various initiatives have to investigate the state of pollution in Awash (Keraga et al., 2017a), basin-wide synthesis of the state of surface water pollution is lacking. Hence, the purpose of this article is to synthesize and generate information that captures the impact of contaminated water on human health, vegetables, and soil, as well as toxic, biological, and socio-economic effects that rely on river systems, as well as to identify knowledge gaps that are needed for the basin's long-term development and management. The following clear, logical, and well defined research question was formulated: what is the impact of contaminated water in Awash Bain and the knowledge gap that is needed for the sustainable development and management of the basin?

METHODOLOGY

Systematic review (SR) is useful to synthesize trends and conceptualizing findings from large bodies of information (Özerol et al., 2018). The recent and innovative approach in undertaking SR is the PRISMA (Preferred Reporting Items for Systematic Review and Meta-analysis statement) (Moher et al., 2009). Synthesis of impact of water quality in the Awash Basin has been a valid explanatory topic for our review.

For this SR, we developed a search strategy to identify relevant literature. This search strategy was tailored to three databases: Web of sciences, Scopus, Google and Google scholar, and the search terms used were the following: water quality, Impact of water quality, water pollution, industrial pollutants, and heavy metals. All searches included journal articles, books and book chapters. The selection criteria were based on the PRISMA checklist. The search mainly focused on the mapping existing literature on the impact of water quality, water pollution, and heavy metals in the field of environmental sciences, and earth sciences. The search span was from the year 2000–2021 in English only. The search was mainly focused on Ethiopia. The search from any other country was considered accordingly. A total of 85 research articles were excluded at this stage. There were 105 records extracted at this stage.

All duplications were extensively examined to maintain the quality of the review. For the analysis and purification of the papers, the abstracts were checked deeply to ensure the quality and relevance of research papers included in the review process. We read the abstracts of 182 studies to see if they were relevant to the study topic and research questions. We got the full-text article for quality assessment after a total of 97 studies were deemed relevant. In a later stage, a careful examination of each study publication was carried out. We looked through the full-text publications to assess the quality and relevance of the studies. One article was not included in the study since it was written in a language other than English. In addition, 29 more publications were excluded from the study once the duplicate records were filtered out. After evaluating each article against the aforementioned inclusion and exclusion criteria, we chose 68 papers. The literature inclusion and removal at each level is depicted in **Figure 1**. Sixty eight papers were chosen for data extraction, and the following aspects were extracted: Articles must be published journal articles. Reports, dissertations, and unpublished documents were excluded. Through cited references, we discovered an additional 31 studies. In total, 99 studies were considered in this review.

We extracted information on the following subtopics from each study: (1) water quality status of rivers in the Awash Basin; (2) seasonal fluctuations of trace metals in lakes and reservoirs in the Awash Basin; (3) point source pollutants; and (4) health, vegetable, soil, biological, socioeconomic, and toxic effects of water pollution. All data extraction and coding were performed using Microsoft Excel and Mendeley Reference Manager.

THE AWASH BASIN

The Awash River originates from the Ethiopian highland plateau around the Ginchi area and drains part of the northern rift valley system in Ethiopia (**Figure 2**). The river has no outlet to an ocean; rather it joins Lake Abe at the Ethio-Djibouti border. Most of the ~113,304 km^2 catchment area of the basin is within

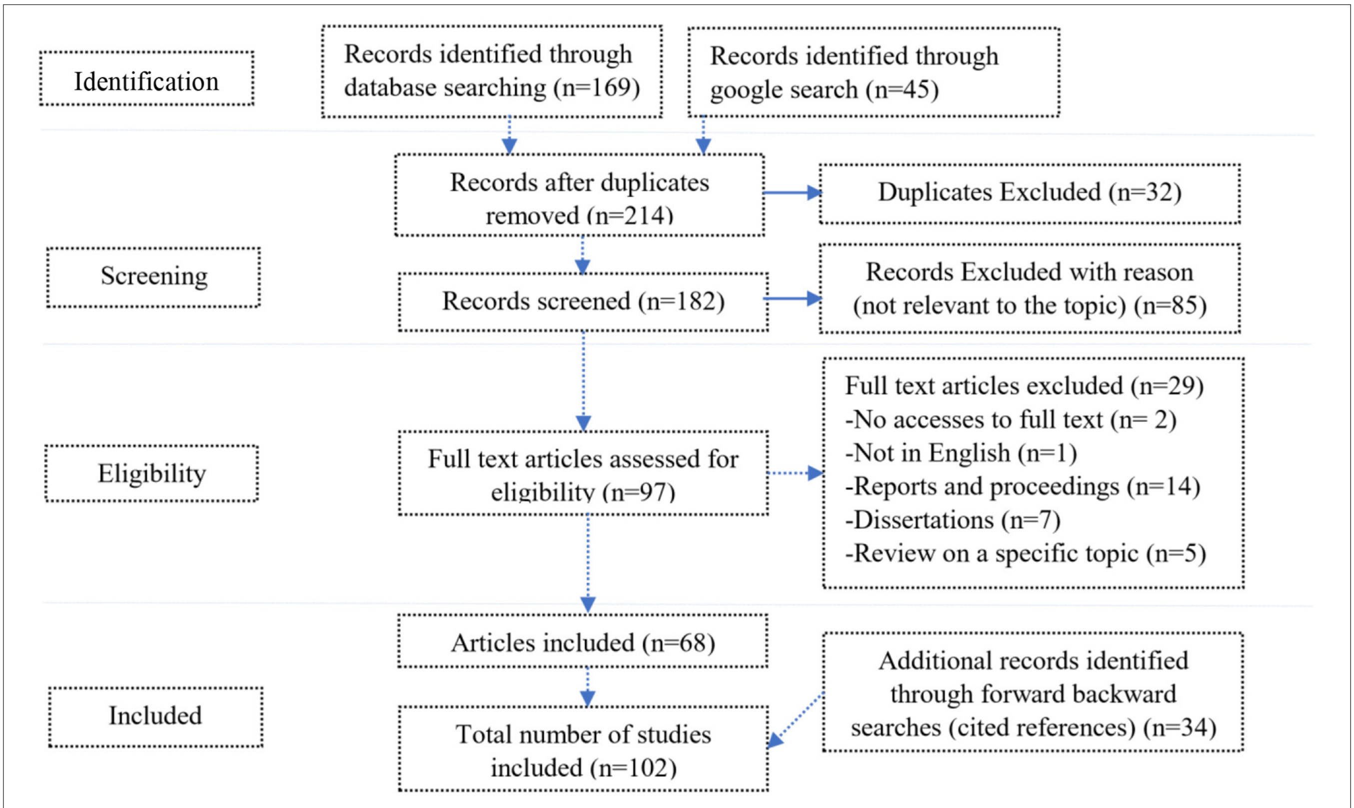

FIGURE 1 | Literature search and evaluation process and decision making for inclusion.

the Ethiopian boundary. Elevation in the basin ranges between 250 and 3,000 masl. The basin covers the central highlands of Ethiopia including west of Addis Ababa and the north-eastern part of the Ethiopian Rift Valley system. The main river's length is about 1,200 km (Taye et al., 2018).

The basin has varied topography, vegetation, rainfall, temperature, and soils. The climate ranges from semi-arid lowlands to cold highland mountains. The average total rainfall in the highlands is 1,600 mm, while in the lowlands it is 160 mm (Taye et al., 2018). Awash is fed by several major tributaries in the upper, middle and lower parts of the basin. Ginchi, Berga, Holleta, Bantu, Leman, Akaki, Mojo, Hombole, Arba I, Arba II, Keleta, Kesem, Najeso and Logia are the major tributaries of the upper Awash (Amenu, 2013). Land use in the basin is mainly agricultural which is used for rain-fed crops, shrub land, and grazing land. The basin accounting over 60% of the irrigated agriculture in the country (Keraga et al., 2017b). Crops cultivated in the basin include cereals (e.g., teff, beans, wheat, barley, and oilseeds), vegetables, flowers, cotton, perennial fruit trees, and sugarcane (Tufa, 2021). The other land uses/covers include urban areas, industrial zones, forests, and swamps. Major cities in Ethiopia such as Addis Ababa, Dire Dawa, Adama, Bishoftu, Dessie, and Semera are located in the basin. More than 65% of the national industries are located in the basin (Keraga et al., 2017b). The Awash River Basin is one of Ethiopia's 12 major river basins, which is shared by five administrative regions (Amhara, Oromia, Somali, Afar and the Southern Region) (Mersha et al., 2018).

WATER QUALITY ISSUES IN THE AWASH RIVER BASIN

The purpose of this systematic review was to discuss the current situation of water quality in the Awash Basin. It evaluates the principal impacts of contaminated water in the Awash Basin on the biological aquatic environment, toxicity, health, irrigated crops using contaminated surface water and soil, and socio-economic impacts of trace metals in lakes and reservoirs.

Water Quality Status of Rivers in Awash Basin

The population living in the Awash River Basin was estimated to be more than 18.6 million (FAO and IHE Delft, 2020) with a population density > 6452.4 persons/km^2, in Addis Ababa and 0-10 persons/km2 in the low land areas (Andualem and Takele, 2018). Substantial rain-fed and commercial agricultural farms, and several industries exist in the basin that is sources

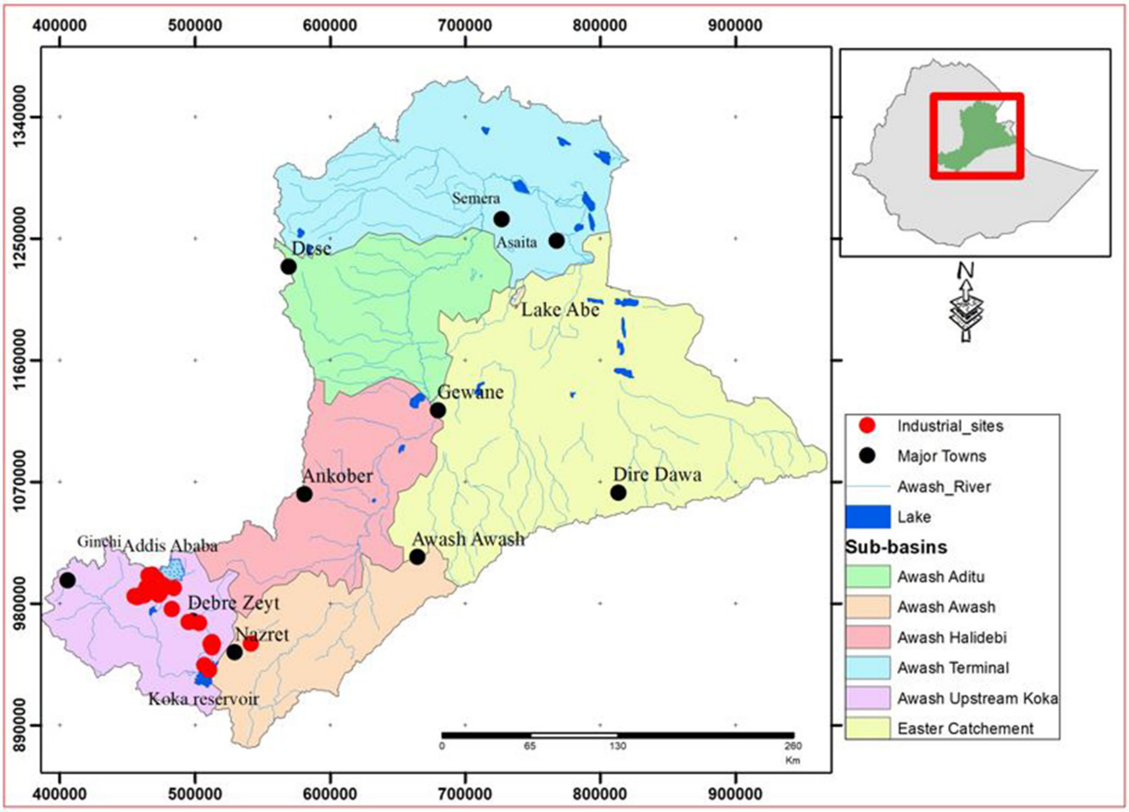

FIGURE 2 | Map of the Awash River Basin with administrative and Basin Management boundaries. The river basin is divided into four major stretches based on altitudinal variation, i.e., Upper basin which represents the areas from the headwater to Koka reservoir (>1,500 masl); Upper Awash Valley which ranges from Koka reservoir to Awash Station (1,500–1,000 masl); Middle Awash Valley which represents the area from Awash Station to Gewane (1,000–500 masl), and; Lower Awash Valley which is the area that extends from Gewane up to Lake Abe (<500 masl) (Duguma et al., 2021; Jin et al., 2021).

of pollutants (Eliku and Leta, 2018). The basin is experiencing severe point source water pollution due to rapid urbanization and industrialization (Gebre et al., 2016) and non-point sources from agricultural fields (Alemayehu, 2001; Keraga et al., 2017a). The Akaki catchment is located in central Ethiopia along the western margin of the main Ethiopian Rift Valley. Addis Ababa, which lies within the Akaki catchment. Tinishu Akaki River contained a higher load of trace metals than the other regions, which is due to the existence of most of the industrial establishments and commercial activities (Kassegne et al., 2018). The Akaki River is heavily polluted, owing to the emission of harmful industrial effluents with little or no treatment (Abebe, 2019). Untreated pollutants from industries, residential, and commercial activities are discharged into the Tinishu Akaki River, which runs through the Addis Ababa City Administration. Several studies have found that discharges of inadequately treated and untreated industrial wastewaters, residential wastes, and sewerages into waterways pollute rivers and streams (Abebe, 2019; Mekuria et al., 2021). **Figure 3** shows water quality monitoring stations used by different studies in the Akaki sub-basin. Another main tributary of the Awash River is the Mojo River. Shoa and Ethiotanneries, Mojo oil mill plant, abattoir houses, and poultry farms are major sources of wastewater effluents downstream of the Awash River, which release their raw effluent directly into the Mojo river, a tributary of the upper Awash and eventually into the Koka Reservoir. The Akaki River is a major tributary of the Awash River, which drains its effluents from its source to the Koka reservoir (Degefu et al., 2013).

Kassegne et al. (2018) reported that trace metals occurred in varying concentrations along the course of the sampling stations in Tinishu Akaki River and Aba Samuel reservoir. Relatively lower levels of trace metals were recorded at Aba Samuel reservoir due to the lower residence time of the sediment. Ecological risk assessment using USEPA sediment guidelines, geoaccumulation index, contamination factor, and pollution load index revealed the widespread pollution by Cd and Pb, these were followed by Mn, Ni, and Zn.

In addition, mean concentrations of heavy metals including Mn, Cr, Ni, Pb, As and Zn were also above their allowable limits in these rivers (Keraga et al., 2017a). Arsenic and zinc were found higher in irrigated areas using water from the Akai River (Itanna, 2002) than rain-fed agricultural areas. Beyene et al. (2017) on these Tinishu and Tiliku rivers reported that Cu, Cr and Pb concentrations were greater than the standard limit set by the European directives for soil contaminants.

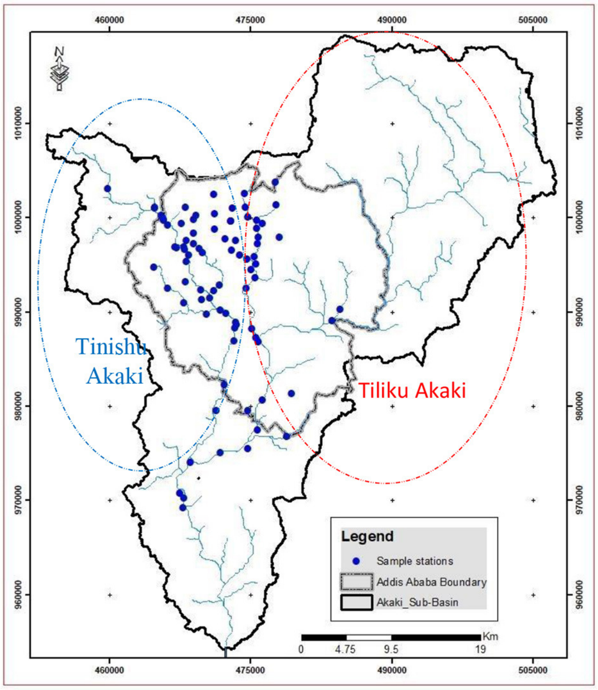

FIGURE 3 | Water quality monitoring stations used by several studies in the Akaki sub-basin.

The water quality of the Tinishu and Great Akaki river basins has been classified, according to the WHO drinking water guideline (WHO, 2004), as "badly polluted" to "very badly polluted," making the water non-suitable for drinking. The presence of trace metals in the tested samples indicates that industries have a significant contribution to surface water pollution. Gebre and Rooijen (2009) reported that E-coli bacteria concentrations in Tinishu and Tiliku Akaki rivers were 6.68 x 10^9 and 6.61 x 10^9 CFU 100 ml/L, respectively. The mean E.coli and Non-E.coli values in the measured water in Akaki river were 2.09 and > 3.48 log10 CFU 10 mL^{-1}, respectively, which were higher than the WHO recommended standard (WHO, 2006; Mengesha et al., 2021). The presence of trace metals in the tested samples indicates that industries have a significant contribution to surface water pollution and the high concentrations of E.coli bacteria indicate fecal pollution (Gebre and Rooijen, 2009).

Rooijen and Taddesse (2009) also reported that heavy metal concentrations that exceeded the natural levels were observed from vegetables grown in Tinishu and Tiliku Akaki Rivers and found that Cd, Cr, Cu, Hg, Ni, and Zn in potato; Zn and Hg in Cabbage; and Cr in onion and red beet. Water quality studies in different parts of Awash Basin are summarized in **Supplementary Table S2**. Another study by Itanna (2002) showed that cabbage was, in general, the least accumulator of metals/metalloids compared to other leafy vegetables with the exception of Ni and Cr. Lettuce had the highest concentrations of Cd, Co, Cr, Fe, and Mn; while Swiss chard contained the highest concentrations of As, Cu, Ni, Pb, and ZN (Itanna, 2002). Observed concentrations of As, Cr, Fe, and Pb were also greater than the maximum permitted levels in leafy vegetables and pose greater health concerns.

Fecal coliform levels in most vegetables in the Akaki River, except swish Chard, cabbage, and spinach in the wet season, were higher than the World Health Organization (WHO) and International Commission on Microbiological Specifications for Food (ICMSF) recommended level of 103 fecal coliform g/L fresh weights in both dry and wet season campaigns (Beyene et al., 2017). This was attributed to the Akaki River water, which is higher than the WHO recommended standard used for irrigation of vegetables particularly in dry seasons due to flows from upstream through the major industrial, commercial, institutional, and residential areas of the town. In addition, the application of organic manures is a common practice of farmers for the production of crops in that area.

Seasonal Fluctuations of Trace Metals in Lakes and Reservoirs in the Awash Basin

Rivers pick up heavy metals as they carry surface water through areas with a variety of human induced inputs. Changes in the spatial distribution patterns of heavy metals in surface water and sediments may result as a result of this (Kumar et al., 2021). The presence, transport, and fate of toxic and persistent heavy metals and organic compounds in water bodies is a major area of concern around the world (Edokpayi et al., 2017). One of the world's greatest worries is the contamination of the environment with hazardous heavy metals (Kumar et al., 2021). Because of their non-biodegradability, extended biological half-lives, and water solubility, the majority of heavy metals are extremely toxic (Naser et al., 2014). The buildup of high levels of Pb, Cd, Cr, Ni, and Zn in river basins is most prevalent in areas with a lot of industrial and commercial activity (Islam et al., 2020). Most lakes and reservoirs in the Awash Basin are experiencing water quality degradation. There are 22 lakes and reservoirs within the Awash Basin. This section summarizes the water quality status of selected lakes and reservoirs within the basin. Speciation of selected trace elements on samples collected from the Koka reservoir showed that Cr, Mn, Co, Ni, Cu, Zn, and Pb were predominantly present at high molecular masses (HMM), i.e., > 10 kilo Daltons. The presence of trace elements at higher masses during the wet season suggests the reduced mobility of elements along with colloids and particles (Masresha et al., 2011).

Because Lake Beseka water is saline (EC$\sim$6.3 dS m^{-1}), sodic (SAR$\sim$300), or alkaline (pH$\sim$9.6), it cannot be used for irrigation or drinking (Dinka, 2012). The drastic expansion of the lake has led to many problems in the surrounding area, and is a severe threat to the well being of the indigenous people and the economic welfare of the nation in general. Between 1960 to 2015, salinity and alkalinity levels in Lake Beseka showed decreasing trends in ionic concentrations of quality parameters due to the dilution effect (Dinka, 2017). In general, the water quality of the Awash river downstream of Lake Beseka has deteriorated between 2013 and 2017 due to the release of unregulated Lake Water into the Awash River (Yimer and Jin, 2020). At the Awash inlet, Koka reservoir and Awash outlet, reported that the mean

TABLE 1 | Lake Koka cations and heavy metal study result by different studies.

Parameter	Unit	Parameter value	Compared to WHO guideline
Ca^{++}	(mg/L)	31.6 dry season, 22 wet season (Masresha et al., 2011)	
Mg^{++}	(mg/L)	6.9 dry season, 8.2 wet season (Masresha et al., 2011)	
Na^{++}	(mg/L)	46.6 dry season, 11 wet season (Masresha et al., 2011)	
K++	(mg/L)	6.4 dry season,11 wet season (Masresha et al., 2011)	
Fe	(mg/L)	6.8 dry season,37 wet season (Masresha et al., 2011)	(0.3)*
Cr	(μg/l)	27.8 dry season, 50.9 wet season (Masresha et al., 2011), 1.7-4.2 (Dsikowitzky et al., 2013)	(50)*
Mn	(μg/l)	303 dry season, 422 wet season, (Masresha et al., 2011)	(400)
Cu	(μg/l)	15.5 dry season, 20.8 wet season, (Masresha et al., 2011)	(2,000)
Co	(μg/l)	4.8 dry season,7.7 wet season, (Masresha et al., 2011)	(110)
Zn	(μg/l)	48 dry season, 98.4 wet season, (Masresha et al., 2011)	(3,000)
Pb	(μg/l)	4.9 dry season,8.5 wet season, (Masresha et al., 2011), 0.24–0.68 (Dsikowitzky et al., 2013)	(10)
Ni	(μg/l)	22.4 dry season, 39.4 wet season, (Masresha et al., 2011)	(20)*
As	(μg/l)	2.8 dry season, 2.9 wet season (Masresha et al., 2011), 0.57-3.0 (Dsikowitzky et al., 2013)	(10)
Cd	(μg/l)	0.04 dry season, 0.06 wet season, (Masresha et al., 2011), <0.1 (Dsikowitzky et al., 2013)	(3)
Se	(μg/l)	0.63 dry season, 1.2 dry season, (Masresha et al., 2011), <0.1–0.12 (Dsikowitzky et al., 2013)	(50)
Hg	(μg/l)	<0.1 (Dsikowitzky et al., 2013)	(6)
Viruses	(ml/l)	800E + 07 (Fasil et al., 2011)	
Bacteria	(ml/l)	502E + 06 (Fasil et al., 2011)	

**Higher than the WHO standard.*

concentrations of metals ranked (high to low) was Fe > Cr > Cu > Zn > Pb > Cd > Ni and Fe > Cu > Zn > Pb > Cr > Cd > Ni during dry and wet seasons, respectively. Overall, concentration of heavy metals during dry season was higher than the wet season except for Fe. Increases in concentration of Fe during the wet season was attributed to increased runoff during the rainy season that eroded the soil particles containing iron (Eliku and Leta, 2018). Some heavy meatal related water quality studies in lakes, reservoirs and rivers in different parts of the Awash basin is annexed in **Supplementary Table S2**.

Masresha et al. (2011) also observed differences in metal concentrations in Koka reservoir during dry/wet seasons with reported dry/wet season values (mg/L) of 46.6 /11, 6.4/1, 31.6/ 22, and 6.9/8.2 for Na^{++}, K^{++}, Ca^{++} and Mg^{++}, respectively. In addition, heavy metals like Fe, Cr, and Ni were in higher concentrations than the WHO limit (**Table 1**). The lakes have primarily been used for commercial fishing, irrigation, recreation, and residential uses. Although these limited water resources are critical to the population's survival, there are signs that Koka reservoir is undergoing changes that could lead to water quality degradation.

The temporal and regional fluctuations of trace heavy metal concentrations in Mojo river in the extreme wet rainy season, semi-wet and semi-dry period (autumn), and extreme dry season (winter), according to Tamene and Seyoum (2015) showed that the level of As rises as the year progress from wet to dry, indicating dilution effects. Except for one result, all of the assessed As results are higher than the WHO Drinking Water Guidelines (DWG) (0.01 mg/L) (WHO, 2004). In all study locations and sampling periods, the average Cd pollution load was found to be 0.12 ± 0.075 mg/L. All of the Hg experimental results are significantly higher than the WHO guidelines for fresh water (0.05 mg/L) and maximum allowable DW for livestock (0.003 mg/L), respectively (Carr et al., 2004). More than half of the examined results of Pb was above the WHO's maximum acceptable limit for DWG (0.01 mg/L).

Dagnachew et al. (2019) observed higher concentrations of Cr (VI) in Tinishu Akaki and Jemo rivers. **Figure 4** shows Cr (VI), CU, Mn, and Zn concentrations from studies conducted on different rivers. Overall, Cr (VI) and Mn concentrations exceeded the Ethiopian standard in both the dry and wet seasons in most locations. However, concentrations were greater during dry seasons compared to the wet season. This is probably due to the dilution effect of the wet season. In the different studies, there is very limited temporal heavy metal load analysis in rivers as well as in reservoirs/lakes in the different parts of the basin. The three rivers are the western side of the Akaki catchment **Figure 2** which receives untreated wastewater from industries as well as from urban waste.

Point Source Pollution

Water contamination is caused by a variety of factors, including industrial wastewater and hazardous chemicals. Although Ethiopia has a small number of industries, its pollution impact

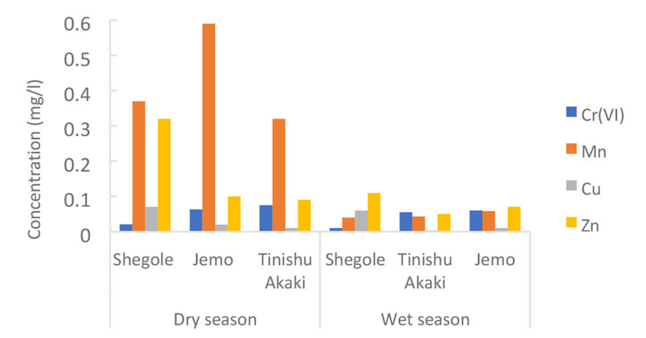

FIGURE 4 | Trace metal content in Addis Ababa rivers in dry (D) and wet (W) seasons. Sources (Dagnachew et al., 2019).

TABLE 2 | Metals and heavy metals Anmol product paper factory.

Parameter	Concertation range (mg/L)		Standards	
	Raw effluent	Treated effluent	WHO limit	EPA limit
Na	140–900	130–800	400	400
K	2.9–12.1	2.1–11.6	–	–
Ca	11.09–1,150	8.71–1,104	200	200
Mg	5.23–110.4	6.18–66.24	150	150
Fe	0.27–2.77	0.18–1.67	-	-
Cu	0–0.03	0 –0.03	2	2
Zn	0–0.59	0.13–0.55	10	6

Sources: Adapted from Zerihun and Eshetu (2018).

is substantial. Industrial waste from poorly managed industries is a major source to water pollution, particularly in Ethiopian rivers. This is because most Ethiopian factories lack wastewater treatment facilities (Menbere, 2019). In Ethiopia, most industries just dump their untreated toxic wastewater into adjacent rivers, lakes, and streams. Pollution from industrial wastewater discharge has increased as a result of hazardous chemicals (Alayu and Yirgu, 2018). The city of Addis Ababa hosts about 65% of industries in the country and more than 90% of those industries discharge their waste to the nearby river without proper treatment (Yohannes and Elias, 2017). However, in recent years, industrial activity is extending beyond Addis Ababa into towns like Mojo, Debrezeit and Nazret, increasing the influence of industrial pollution to the Awash and the Mojo rivers, and Koka reservoir as shown in **Figure 2**. The Awash River is polluted by liquid and solid effluents released from industries and households that release untreated their domestic and industrial effluents (Teshome, 2019). One of the major sources of pollution for the Awash River is untreated domestic discharge from the city of Addis Ababa. In Addis Ababa, for example, there are roughly 1,200 significant industrial enterprises, which combined with institutions, commercial centers, and hotels generate 18 percent of the city's entire solid wastes (Menbere, 2019). The majority of the waste produced by residents and industries is deposited in the city's streams and rivers, which are consumed by livestock and also used for various purposes like as irrigating vegetables and crops (Weldegebriel et al., 2012).

Mengesha et al. (2021) reported the Akaki River, like many Addis Ababa streams, is heavily contaminated by anthropogenic influences from upstream to downstream. The causes are specifically indiscriminate dumping of refuses into the river, indiscriminate dumping of industrial wastes (Mekonnen and Amsalu, 2018). The majority of pollutants are discharged into a single collection location, such as reservoirs that can act as a sink for a variety of contaminants. Heavy metal concentrations in stream sediments are relatively high, according to several studies, due to significant anthropogenic metal loadings carried by tributary rivers. As a result, surficial sediments may act as a metal puddle, releasing metals into the underlying water and potentially harming riverine ecosystems (Astatkie et al., 2021).

Most industries in Gelan and Dukem have established neither treatment plants nor adequate storage or discharge channels for their wastes. As a result, polluted liquids are directly discharged into the open landscape (Dadi et al., 2017). A study by Dadi et al. (2017) on the environmental and health impacts of effluents from textile industries in the Gelan and Dukem watersheds of the Upper Awash river showed the presence of substantial concentrations of Zn in industry effluents. Zerihun and Eshetu (2018) reported that both raw and treated effluents from the Anmol product paper factory contained higher concentrations of heavy metals that significantly deteriorated the water quality of the Awash river (**Table 2**). The study found that, very high Na and Ca concentrations, greater than the national and WHO discharge limits, in both raw and treated effluents.

The Mojo watershed is one of the sub-watersheds of the Awash Basin. The Mojo river Basin is experiencing rapid population growth, industrialization, and agricultural activities, all of which are potential causes of surface and groundwater contamination. Residents along the Mojo River use the river water for many purposes. However, the discharge of domestic and industrial pollutants of the town severely restricts the use of surface water (Tamene and Seyoum, 2015). Kolba Tannery, Ethio-Japan Textile, Soap factory, Gelan Tannery, Organic Export Abattoir, Derartu Tannery, Mojo Tannery, and Food and Oil Complex drain their influent into the Mojo river. A study by Gebre et al. (2016) found that mean concentration values of Cr in water samples ranged between 0 and 8.02 mg/L. Cr concentrations downstream of the Mojo, Kolba, Gelan and Derartu Tanneries were greater than NEQS standard (1 mg/L).

IMPACTS OF WATER POLLUTION

Water quality affects the economic, social and political development of society (Mekonnen and Amsalu, 2018). This article focuses on the effects of water quality on biological, toxic, health as well as vegetable production and soil.

Biological Effects

Nutrient loadings affect water quality throughout the world and have resulted in the eutrophication of many fresh water lakes (Ligdi et al., 2010; Jonathan et al., 2012; Alemu et al., 2017).

Water pollution in the basin is found to have contributed to the disappearance of aquatic species (Rooijen and Taddesse, 2009). Dissolved phosphorus plays an important role in the eutrophication of water bodies (Moges et al., 2016). Phosphates entering the water from detergents urban areas, industrial waste (such as sugar cane production), and intensive agriculture (Rooijen and Taddesse, 2009; Girma, 2016; Moges et al., 2016) can cause the nutrient levels in the water to rise and lead to algal blooms (Girma, 2016). A study by Ingwani et al. (2010) describes eutrophication from anthropogenic drivers as the main cause for the rapid spreading of water hyacinth over reservoirs. Water hyacinth is one of the biodiversity issues that contribute to the degradation of aquatic ecosystems. This is a case in Ethiopia where by degradation in water quality results in water hyacinth (Eichhornia crassipes) invasion (Hailu et al., 2020). This can increase the incidental occurrence and spread of water hyacinths in Lake Tana (Moges et al., 2017), as also observed in Lake Koka and Aba Samuel Lakes are indictors of the effect. Similarly, very high chlorophyll *a* values were observed upstream of Sebeta River (Tassew, 2007). The most severe area coverage by water hyacinths in Lake Tana was noticed at the mouth of the Megech River, which stretched both east and north with an estimated area coverage of 80–100 ha and wide distribution of daughter plants that pushed forward with the wave's assistance (Tewabe, 2015).

When nutrient-rich effluents enter a lake, it overloads the ability of the lake to provide oxygen to aquatic lives in it. This is a eutrophication process in which there is an upsurge of algae growth in the lake, which then results in the depletion of oxygen and fouling up of the lake water (Rooijen and Taddesse, 2009; Girma, 2016). This, in turn, can alter the food chain and ionic composition of the water, increase organic matter in the sediment, decrease metalimnetic and hypolimnetic oxygen (which causes fish suffocation), and cause changes in the water temperature (Girma, 2016).

In many places of the world, the occurrence of harmful toxic algal occurrences has increased over the last three decades. Many bloom-forming algae species can produce biologically active secondary metabolites that are extremely harmful to humans and other animals (Reddy and Mastan, 2011; Edokpayi et al., 2017). Water pollution in the basin is found to have contributed to the disappearance of aquatic species (Keraga et al., 2017b).

Heavy metals concentrations in water and tissue samples from edible fish species from Hwassa and Koka lakes showed that metal concentration in Koka from highest to lowest was Cr > As > Pb > Cd > Se > Hg (Dsikowitzky et al., 2013). Metal concentrations in fish tissues also showed significant differences with average concentrations of metal in the gills from highest to lowest was: Cr > Pb > Hg > As > Cd > Se. In fish muscles, the rank was Cr > Hg > As > Pb > Cd > Se and in fish livers Cr > Hg > Cd > As > Pb > Se. Overall, Cr concentration was the highest in both water and fish tissue samples.

Toxicity Effects

Toxic substances from farms, towns, and factories readily dissolve into and mix with it causing water pollution. Heavy metals are known to pose a variety of health risks such as cancer, mutation (Itanna, 2002). Metals such as arsenic, lead,

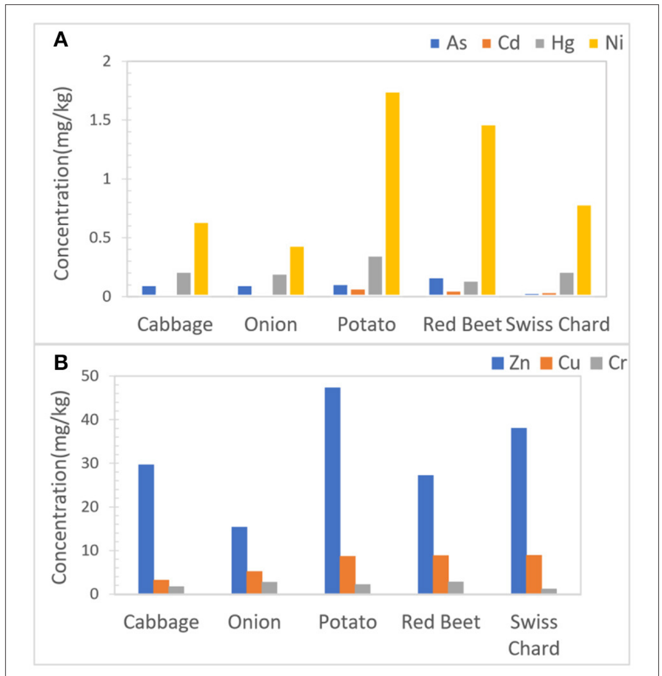

FIGURE 5 | Trace metal levels in vegetables (Gebre and Rooijen, 2009). **(A)** Concentration of As, Cd, Hg and Ni in vegetables and **(B)** Concentration of Zn, Cu, and Cr in vegetables.

cadmium, nickel, mercury, chromium, cobalt, zinc and selenium present in natural waters are highly toxic even in minor quantities (Masindi and Khathutshelo, 2018). Long-term exposure to heavy metals can cause significant toxicity in the dermal and ingestion pathways of contaminated materials (Islam et al., 2020). Some of the cations and heavy metal investigation results by different researchers in Lake Koka are shown in **Table 1**. For example, Fe, Cr, and Ni are higher than the maximum permissible limit of the WHO standard. The investigation made by Bahiru (2021) showed that concentrations (mg/L) of metals in the Akaki river water samples were found to be in the ranges of 0.18–0.28, 1.40–2.67, 0.97–1.40, 0.037–0.087, 0.037–0.080, and 01–0.14 for Fe, Zn, Cu, Cd, Pb, and Cr, respectively. All are above the recommended limit of both (Fewtrell and Bartram, 2001).

The Tinishu Akaki catchment area has a high influx of trace metals. High levels of trace metals in sediments probably have adverse effects on the bottom-dwelling aquatic organisms as well as to the health of the people who depend on the water for various activities (Kassegne et al., 2018). The poor quality of river water in Addis Ababa cause and affect the production of different crops/vegetables (Bedada et al., 2019); this is justified by an investigation made by Gebre and Rooijen (2009) trace metal content in vegetable leaves (Cd, Cr, Cu, Hg, Ni and Zn in potato and Cr in onion and red beet in Addis Ababa). The concentrations of trace metals in vegetables cultivated with wastewater are shown in **Figures 5A,B**. Although all of these metals have not yet reached phytotoxic levels, some plants have exceeded the normally occurring amounts. This is especially true in the case of Cd, Cr, Cu, Hg, Ni, and Zn in potatoes, as well as Cr in onion and red beet.

Health Effects

Excessive anthropogenic activities, such as the discharge of industrial effluents, agricultural waste, and toxic waste into surface waters, have a negative impact on human health (Islam et al., 2021). Typhoid, cholera, encephalitis, hepatitis, skin infection, hair loss, liver cirrhosis, renal failure, and neural disorder spread through dermal and oral ingestion of metals contaminated water (Islam et al., 2021). Virological Quality of Addis Ababa rivers and Hospitals total coliphages enumerations ranged from <1 pfu/100 ml to 5.2×103 pfu/100 ml for urban rivers and <1 pfu/100 ml to 4.92×103 pfu/100 ml for hospitals wastewaters. Coliphages were detected in 44 (52.4%) and 3 (10%) samples of 30 streams and rivers and four hospital waste waters, respectively.

Novel contaminants continue to pose new challenges to monitoring and treatment regimes in urban settings, where a variety of contaminants have an impact on water quality (McGrane, 2016). For example, as a result of fast population growth, uncontrolled urbanization and industrialization and poor waste management practices Addis Ababa's water resources are highly polluted which threatens human health and ecosystem function as a whole (Yohannes and Elias, 2017). Since downstream Addis river water is being used for various purposes such as drinking water supply (example, Nazareth town) and irrigation, public health risks are high (Rooijen and Taddesse, 2009). Contaminated drinking water has been linked to substantial illness and mortality around the world. It is used to spread communicable diseases such as diarrhea, cholera, dysentery, typhoid, and guinea worm infection (Wolde et al., 2020). For example, the negative impact on human health and the ecosystems as a result of the elevated level of several pollutants and irrigation products (vegetable) will ultimately affect the people that depend on the Akaki River water (Zinabu and Desta, 2002). An investigation conducted by Bedada et al. (2019), in nine sub-Cities of thirteen rivers and four hospitals wastewaters of Addis Ababa, reported poor water quality in all rivers and one-half of the hospitals (detection of coliphages) will continue to cause a major health risk and will result in more number of deaths and also will affect the aquatic life and drinking water.

The overall mean count of *E. coli* and Non *E. coli* from water samples from Akaki River was 2.09 and >3.48 log 10 CFU 10 mL^{-1} which is higher than the WHO recommended standard (Beyene et al., 2017). A high level of total *E. coli* was recorded in effluents from ALSAR and ALMHADI textile industries in Gelan and Dukem (Dadi et al., 2017). Downstream residents use river water for domestic and agricultural purposes. Such practices have created major health risks to people who rely on the river for their livelihood. Despite the varied character of the Kebena River's and its neighboring buffer zones' environmental concerns, pollution remains the dominant worry (Asnake et al., 2021). Consumption of heavy metal-contaminated food crops is one of the most common routes for harmful compounds to enter the human body, with some symptoms appearing only after several years of exposure (Srinivasan and Reddy, 2009). The existence of total coliforms across the River has been a major threat to human health. Water pollution does not only have adverse health impacts, but it also imposes medical expenses to the population (Gebre and Rooijen, 2009). According to the World Health Organization (WHO), around 80% of diseases are transmitted through water, making surface water a major source of infection for marine species and humans (Islam et al., 2021). Some research activities around Addis Ababa recognized there is a signal that human health and life are threatened due to crop production using polluted water (EFDR, 2000). The negative impact on human health and the ecosystem as a result of the elevated level of several pollutants and irrigation products such as vegetables will ultimately affect the people that depend on the river water (Zinabu and Desta, 2002).

The local environment, people, and livestock of Gelan and Dukem towns are exposed to highly contaminated effluents. For example related to skin allergies and stomach health problems in humans and bacteriological infections specifically "Salmonella" in cattle and donkeys diagnosed in veterinary clinics (Dadi et al., 2017).

Impact on Vegetable and Soil

Urban and industrial wastes are common sources of anthropogenic metal pollution in soils. Because of the negative impacts on food quality, crop growth, and soil environmental health, heavy metal deposition in soil is a key concern in agricultural production (Naser et al., 2014). The use of water with poor quality for agricultural activities can affect crop yield and cause food insecurity. Several studies have reported higher levels of heavy metal concentrations from different part of the country (Edokpayi et al., 2017). Heavy metals are easily accumulated in the edible parts of leafy vegetables compared to grain or fruit crops (Mapanda et al., 2005). Heavy metals accumulate in the edible and inedible sections of vegetables in sufficient concentrations to induce clinical issues in animals and humans who consume these metal-rich plants (Arora et al., 2008). Haile and Mohammed (2019) reported that Cr, Zn, Fe, K, Cu, and Mn exceeded the (WHO, 2008) standards in lake Hawassa. Abate and Fitamo (2015) stated that the concentration of Na^{+} and K^{+} >200 mg/L permissible limit by WHO (2008). Worako (2015) also showed that Total Coliform and Fecal Coliform were greater than the acceptable limit of 1,000 MPN/100 ml set by WHO (2008) and CCME (1999); and above the 14 MPN/100 ml recommended limit by USEPA (1976).

Due to the high metal retention capacity of agricultural soil, it has been suggested that it is the most important sink for heavy metals. As a result of increased anthropogenic activity, there is evidence to suggest that agricultural soil has elevated amounts of heavy metals. The chemical contents of irrigation water can affect plant growth directly through toxicity or inadequacy, or indirectly by influencing plant nutrient availability Due to the high metal retention capacity of agricultural soil, it has been suggested that it is the most important sink for heavy metals. As a result of increased anthropogenic activity, there is evidence to suggest that agricultural soil has elevated amounts of heavy metals. The chemical contents of irrigation water can affect plant growth directly through toxicity or inadequacy, or indirectly by influencing plant nutrient availability (Belay, 2019). Heavy metals are inorganic pollutants with a wide range of negative effects on aquatic organisms, plants, and human (Inyinbor et al., 2018). The heavy metal concentration of irrigation water has been demonstrated to surpass the irrigation water standard (Keraga et al., 2017b).

Excessive accumulation of pollutants in soils, such as heavy metals, causes increased heavy metal uptake by crops, affecting food quality and safety (Srinivasan and Reddy, 2009). Mean concentration of heavy metals including Mn, Cr, Ni, Pb, As, and Zn reported more in vegetables irrigated by Awash River than their allowable limits (Keraga et al., 2017b). Vegetables like, Ethiopian mustard, Lettuce and Swiss chard, were collected and subsequently analyzed for selected heavy metals, Fe, Mn, Zn, Pb, Cr, and Cd. Zn was detected in all vegetable types, where around 51% of the samples have exceeded the amount of Zn when compared to the standard limit of 99 mg/kg in Akaki Rivers (Weldegebriel et al., 2012). Some of the vegetables tested in Tinishu and Tiliku Akakai Rivers have heavy metals exceeded the naturally expected levels. Based on the investigation, Cd, Cr, Cu, Hg, Ni, and Zn in potato, Zn and Hg in Cabbage, and Cr in onion and red beet (Rooijen and Taddesse, 2009; Teshome, 2019).

The mean counts of TC, FC, and total aerobic count (TAC) on collected vegetables irrigated with Akaki River were 3.22, 1.37, and 4.72 in the dry season, and 3.87, 2.57, and 5.09 log10CFU per gram in the wet season, respectively. All fresh vegetables were contaminated with total coliform, fecal coliform and total aerobic in the dry season (Beyene et al., 2017). In addition to this, as stated by Bahiru (2021), Cd, Pb, Fe, Zn, Cr, and Cu concentration in lettuce samples irrigated by Akaki river water are in the range of (0.047–0.263), (0.42–6.55), (339.83–420.00), (2.96–13.44), (0.95–7.87) and (1.68–7.49) (mg /Kg) respectively, all heavy metal concentration are above recommended level set by WHO (2008).

The investigation made by Itanna (2002) showed that Arsenic (As) and zinc (Zn) in soil irrigated by the Akaki River were higher than the normal limit. The concentrations of Pb, Cd, Mn, Ni and Zn in sediments in the Tinishu Akaki river were relatively greater than other trace metals at levels that may have adverse biological effects on the surrounding biota (Kassegne et al., 2018). Similarly, high concentration of tributary rivers and lakes (high concentration of salt) increases the pH level of the Awash River and this affects the producing of companies that engaged in cotton production, wheat, and other cereal crops and vegetables (Teshome, 2019). Akaki river water irrigated soil samples concentration (mg/kg) was found Cd (0.47–3.47), Pb (8.00–118.00), Fe (13,557.30–16,800.00), Zn (40.00–224.67), Cr (4.91–39.36) and Cu (35.00–149.88). All metals except Cd and Fe in the soil samples are below the recommended level set by Fewtrell and Bartram (2001), Bahiru (2021). Heavy metal levels in soil samples from Mojo sub-basin farmlands were measured. In soil samples from tomato cultivation, the mean concentration of arsenic (As) was found to be 21.00 mg/kg, and in soil samples from cabbage cultivation, it was found to be 30.73 mg/kg. Arsenic levels were found to be higher than the European Union's acceptable limit of 20 mg/kg in both soil samples tested (Gebeyehu and Bayissa, 2020). According to findings in Mojo river, the mean Cr value was 2.515.794 mg/L, with half of the findings falling below the FAO standard for surface water irrigation (0.1 mg/L) and WHO DWG (0.05 mg/L) (Tamene and Seyoum, 2015).

Soil pH varied between 6.9 to 8.9 for Melka Sedi and 7.06 to 9.1 for Melka Werer farm areas. EC value ranges from 0.33 to 82.1 deci Siemens per meter (dS/m) and 0.4 to 37.5 dS/m, respectively for soil samples taken from Melka Sedi and Melka Werer farms (Abebe et al., 2015). Soil salinity and sodicity assessment by Abebe et al. (2015) in the Amibara area revealed that substantial parts of farm areas were consistently and continuously affected by salinity problems.

Socio-Economic Effects

The economic effect of water quality can be seen in different perspectives. Decrease in water quality can lead to increased treatment costs of potable and industrial process water. Crops will be prone to hunger and quality deterioration as a result of poor water quality, resulting in a drop in agricultural yield. Water contamination has a considerable impact on agricultural economic growth, as detailed by Li and Li (2021), which is a major roadblock to China's rural revitalization plan. China's water pollution has a cumulative effect on agricultural economic growth that is increasing in time and space, harming the agricultural ecology. Agricultural economic growth in China dropped by 27.994 units for every unit increase in wastewater discharge intensity.

In case of Ethiopia, the mixing of lake Beseka (extremely saline) water with Awash river (fresh water) was done to slow down lake Beseka rapid expansion rather than to alleviate the basin's water scarcity problem. After the lake Beseka mix, the Awash River serves as an important water source for cattle, domestic use, and irrigation water for nearby wheat, vegetable, cotton, and sugar plantations. These crops are extremely important economically for both the local community and the country. The water utilized for irrigation in the downstream community has a variety of negative consequences, including decreased crop yield and financial benefits, decreased irrigable or fertile land, and increased domestic water shortages (Yimer and Jin, 2020). For example, Tadesse et al. (2018) from their study Rebu River in the Oromia region reported that Cr, Zn, Fe, K, Cu, Na, Mn and Pb concentrations were greater than the ESA (2013) and WHO (2008) standards as shown in summary of major water quality studies from different parts of Ethiopia supportive **Supplementary Table S1**. Water pollution does not only have adverse health impacts but it also imposes medical expenses on the population (Gebre and Rooijen, 2009). The town of Awash with a population of 30,000 has to shirt from abstracting water from river to groundwater primarily because of the pollution (Parker et al., 2016).

High concentration of salt in tributary rivers and lakes increase the pH level of the Awash River and this affects the production of companies that engaged in cotton production, wheat, and other cereal crops and vegetables (Teshome, 2019).

RESEARCH GAPS AND PROBLEMS IDENTIFIED FUTURE AGENDA

This review identifies several impact-related contaminated water research efforts, but it also identifies research gaps. The most important relates to the scope and delimitation of the study. Much of the reports are either separate graduate thesis research limited to specific location and or time. Consequently, there is no thorough integrated spatial and temporal water quality impact mapping to portray the overall picture of the sub watershed or the entire basin. There is little evidence-based research on the effects of contaminated water on agriculture, health, and socioeconomics. There is limited research on the socio-economic effects of water contamination and their estimated costs, human and animal health-related impacts of contaminated water and all vegetables species grown by contaminated river waters. In addition to this, there is lack of regular biological water quality monitoring in the basin.

It is expected to participate in a comprehensive spatial and temporal study of the impact of contaminated water on irrigated vegetable production, human and animal health, socio-economic effects, and impact on living organisms living in the aquatic environment in the basin or subbasin, utilizing the gaps identified in this review effort.

CONCLUSION

The water quality of the Awash Basin's rivers, lakes and reservoirs is deteriorating. Rapid urbanization and industrialization have resulted in serious point source water contamination in the basin and endangering the basin's socio-economic and ecological values. The majority of the factories in the basin lack wastewater treatment facilities, simply discharge their toxic wastewater into nearby rivers, lakes, and streams. There is also untreated domestic discharge. The industries in the Akaki and Mojo sub-basins discharge their waste into nearby rivers and streams. They haven't built any treatment plants, nor have they set up suitable storage or discharge pathways for their waste.

Heavy metal concentrations in rivers, as well as in plants irrigated by these river waters and in the soil, were beyond their permissible levels. Even in little amounts, heavy metals are extremely hazardous. This study found evidence of the presence of these harmful compounds over the WHO recommended limit in rivers, lakes, edible fish tissues, and vegetables, primarily in upper Awash. Despite the fact that no previous study has been conducted to determine the influence on human and animal health, it is thought that they have negative impacts on aquatic organisms as well as the health of people who rely on water for various purposes. The amounts of cations, metals, viruses, and bacteria in most water sources of the basin exceed WHO and EPA legal limits, leaving them unsafe for human consumption. Water hyacinth (Eichhornia crassipes) invasion and harmful toxic algal occurrence owing to eutrophication caused by anthropogenic factors have been observed in the Koka and Aba Samuel reservoirs, as well as the Sebeta river. As a result, the food chain and ionic composition of the water can be altered, making people and other animals particularly harmful.

A comprehensive and systematic research spanning from identifying sources of pollution and its impact the health of humans, livestock and ecosystem at regular interval is vital. Moreover, a vulnerable ecosystem, it is vital to have an institutional arrangement responsible for regular monitoring and evaluation to protect vulnerable riparian communities and ecosystems. More research is needed to fully comprehend pollution dynamics and cleaning capacity of aquatic and wetland ecosystems. including a comprehensive study of the effects of contaminated water on human and livestock health, a comprehensive spatial extent investigation of the impact of contaminated water on growing vegetables, and the magnitude of the polluted water's socioeconomic effects in the downstream community as well as the country as a whole. The novelty of this SR in that it is the first to combine information from many recognized research works on the impact of contaminated water on humans, vegetables, and soil, as well as toxic and socioeconomic effects. The output will give background information for future research as well as preliminary policy direction for water resource managers and policymakers.

This SR is unique in that there has not been such a comprehensive including the accessing reports from different institution in the country. The review also combines information from works on the impact of contaminated water on humans, vegetables, and soil, as well as toxic and socio-economic effects. The output will inform future research as well as plan management interventions. Building from narratives of different reports, the following immediate interventions: (1) absence of accountability for industries that discharge effluents directly into water bodies without sufficient treatment; (2) widespread vegetable production in the upper Awash sub-basin using contaminated water. In the last decade, the Upper Awash River Basin has experienced rapid urbanization. If things keep going this way, the dawn stream's water quality will deteriorate dramatically. Wastewater reuse, such as that from Addis Ababa, is often used by the poor for vegetable growing. This is therefore water quality protection in the basin necessitates effective management and policy guidelines.

RECOMMENDATION

A more extensive investigation of water pollution socio-economic, human, and animal health consequences, influence on aquatic creatures, and irrigated crop productivity in the upper Awash basin is needed, based on the findings of this systematic review. It is laudable to have strong institutions capable of formulating new laws and implementing the present environmental legal framework. Wastewater reuse, such as that from Addis Ababa, is often used by the poor for vegetable growing. This is therefore water quality protection in the basin necessitates effective management and policy guidelines.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

EA is a researcher and lead author. GZ and TA contributed to project design, conceptual framework development, and manuscript preparation. YD, HB, and BT reviewed different versions of the manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2021.790900/full#supplementary-material

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CONCEPTUAL ANALYSIS
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Commission for the Upper Cauca River Basin Recovery, Collaborative Governance for Sustainability and Water Security

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Rivers are essential for life, there is an indissoluble relationship between the natural system and the human system. Aquatic ecosystems guarantee ecosystem services to the human system, on the other hand, the human system makes use of these services and as a result of this generates effects on the natural system. However, an over use of these services could adversely impact the natural system. Therefore, the recovery of rivers is a priority for the planet. This work describes the progress of the Commission for the recovery of the upper Cauca river basin as a collaborative governance for sustainability and water security in the region. The upper basin is between the Colombian massif in the department of Cauca and the municipality of Cartago in Valle del Cauca. It is an important natural, cultural, social, and economic resource of Colombia, but it presents a continuous deterioration of water availability, both in quantity and quality, limiting its use for human consumption and a reduction in biodiversity. This work shows that the Commission for the upper Cauca river basin recovery is a process in development. The Commission is an instance made up of public and private entities, which arises from the failure of the current model of water resource management in Colombia. The central problem is how to transcend short-term planning in administrations to long-term planning based on a shared vision. Collaborative governance is proposed as a recovery of the Cauca river based on the concept of bioculturality and the rights of nature, due to the deep relationship of unity between nature and the human species. The need to achieve a shared vision is highlighted, to act under the watershed vision with all the actors involved. In addition, minimal and conclusive indicators must be defined that society recognizes and that motivates it to advance in the recovery. The aquatic ecosystems recovery is a priority, understanding that the investments required for achieving this goal can also significantly contribute to sustainability and water security for the region.

Keywords: river recovery, governance, water security, sustainability, upper Cauca river basin

INTRODUCTION

Maintaining and recovering a hydrographic basin is a requirement in order to have a multifunctional water system that generates environmental services for society and ecosystem conservation.

To do this, it is necessary to understand the inter-dependence of the different capacities of action of the living beings in the natural environment and the human system, joined with integrated approaches to reach the desired goals. Hydrographic basins are composed of dynamic, diverse, and complex ecosystems, which have been historically intervened and affected by humans, and their water sources have been degraded seriously due to the increase of multiple planetary activities (England and Wilkes, 2018). They provide the physical environment where different species live, reproduce and die; additionally, hydrographic basins generate ecosystem services that benefit people (Kaiser et al., 2020). The environments that the biological populations occupy to perpetuate their existence are diverse: the river bodies, the alluvial soils, the riverbanks, the wetlands, the alluvial plains, and the aquifers (FISRWG, 1998). The riverbanks act communally with the course of the river, establishing the capacity for sustaining life within the system (Naiman et al., 2005). What is more, taking into account the challenges imposed by climate change in terms of mitigation and adaptation, and at the same time, the urgent need for development in still growing economies countries (Baloch et al., 2019; Tauseef Hassan et al., 2020), to sustain hydrological services in a basin scale demands novel governance paradigms.

Rivers have been significant for many cultures. For instance, the notion of the "mother river" is included in Chinese, Indian, Thai, and Russian cultures and was considered the key for sustaining life and fertility (McCully, 2002). The effort toward improving the quality of life, the population increase, the urbanization of cities, as well as the increase of the demand for water resources and soil has caused a decreased ability of species to survive in many river systems, making these aquatic ecosystems the most threatened in the world (Dudgeon et al., 2005). The various forms of pollution have negative effects on the processes that take place in an ecosystem by affecting the biodiversity and the derived ecosystem services, such as water availability for human consumption, irrigation, industry, and ecological sustainability. Apart from pollution, climate change also affects crop production in hydrological basin scales, making the planning exercise exigent and requiring the design and implementation of innovative sustainable policies (Singh and Dhadse, 2021). However, river basins can be recovered, but they require a variety of measures to restore the processes that living beings are part of, thereby, guaranteeing species conservation that was affected negatively due to human intervention (Speed et al., 2016). Some reports show concerns regarding the efficacy of these measures due to the improbability that the ecological recovery desired will be reached in every river basin (Palmer et al., 2010; Bernhardt and Palmer, 2011; Wohl et al., 2015). The potential of ecological recovery depends on the scale of analysis and the study evaluation time horizon (Verdonschot et al., 2013; Schmutz et al., 2014; Morandi et al., 2017). The experiences of recovery show positive results in hydro morphological degradation, changes in soil use, riverbed reconfiguration, and riparian buffer zones (Lu et al., 2019). Economic benefits in terms of ecotourism have also been reported from river basins recovery as a result of the implementation of multi-criteria spatial decision-making techniques for regional planning (Omarzadeh et al., 2021). In Europe, environmental, social, and economic orientations were directed to the integral management of the rivers with greater multifunctionality and was not considered optimal to be used for only one purpose, disregarding the ecosystems and their ecosystemic services (Nijland and Cals, 2000).

The upper Cauca river basin has been progressively deteriorating, which has affected its quality. There have been several recovering attempts and began with the formulation of the agreement 014 of 1976 by the Regional Autonomous Corporation of Valle del Cauca (CVC) regarding the competence area. In this agreement, the control of the punctual pollution was the main focus, which was initially oriented to promote the constructions of wastewater treatment plants within the industrial sector and the last decades, in the municipalities. Nonetheless, despite the expensive investments made, this strategy has not given the expected results, while the water quality of the Cauca river has continued to deteriorate.

The failure in the recovery efforts of the upper basin of the Cauca river is because the structural issues have not been effectively addressed with a lack of an integral vision of the problem, and because the basin has not been used as the analysis unit for planning of integrated water resources management in the region.

In Colombia, the dominant water management scheme is based on the administrative political division, with weak interinstitutional coordination, limited leadership and teamwork, and in some cases with insufficient information. Planning is carried out for the short term, with little emphasis on products and results that show effective improvements in the river. Some interventions have incurred cost overruns due to errors in the selection of technology and irregularities in hiring processes. Additionally, there has been a lack of a governance model that addresses the problem with innovative solutions and with a shared long term, which is in harmony with the international agenda of conservation, sustainability, recovery, sustainable use of biodiversity, and improvement of the services and benefits of ecosystems for society (United Nations, 2018).

As a strategy to face the situations previously exposed in a different way and looking for an agreed work path, the need for establishing the Commission for the recovery of the upper Cauca river basin arose. This document presents the advances of the Commission for the recovery of the upper Cauca river basin. It is a process being developed in search for a process of collaborative governance with greater perspective.

THE CAUCA RIVER: IN SEARCH OF A STRATEGY OF WATER RESOURCE MANAGEMENT WITH A BETTER PERSPECTIVE

The Cauca river is 1,204 km long and its basin represents 5% of the national area. About 25% of the Colombian population lives in the watershed, with a total of 183 municipalities throughout the basin. The upper basin is an important region; 61 of the basin's municipalities are in the departments of Cauca and Valle del Cauca, and of the total 89 tributary sub-basins, 59 are between Salvajina (Cauca) and Anacaro (Valle del Cauca). In this region is the city of Cali, the biggest human settlement on the banks of the river, from which more than three-quarters of its population is supplied with drinking water. With its water, important economic sectors are supported; 79% of the superficial water collected is used for agriculture and industries.

For decades, efforts have been made to preserve the Cauca river, including national, regional, and local legislation, multiple planning tools of the territory, water quality and floods studies, construction works for flow regulation, damage minimization due to floods, and wastewater treatment. However the river show a grave condition: Of 36 hydrographic subzones that make up the Cauca river, for dry year conditions, 25 present a high index due to variability of water offer; 34 subzones have between high and very high pressure for demand and climatic variability; 28 between high and critical pressure on ecosystems; 26 have between high and very high pressure due to contamination; 14 subzones show high to very high water erosion and 31 sub-zones between high and very high transformation of highly flooded areas (IDEAM, 2019). **Figure 1** shows a schematic representation (without scale) of the route of the Cauca river, its tributary and activities that cause pollution in the Cauca river. The water resource management plans WRMP established in the regulation for tributary rivers will offer detailed information by section of the river. There is a great affectation due to the sediment load coming from the El Palo, Desbaratado, and Timba rivers that are located in the north of the Cauca Region. Moreover, due to the sediments transported by the rainwater channels in the city of Cali, there have been temporary closures of water intakes of the Water Supply Treatment Plant from Puerto Mallarino and Cauca river because of the high turbidity and pollutant load. From those channels, between 300 and 400 T/d of sediments, are removed (Galvis et al., 2018). From the El Hormiguero bridge until the La Virginia bridge, the water quality of the river with maximum and minimum flow rates is between the categories 'fair' and 'poor' as a source for human consumption. According to Galvis et al. (2018) the specific amount of pollution discharged in the upper Cauca river basin (La Balsa—Anacaro) estimated for summer was 131.6 T BOD_5/d, where most of the higher discharges were associated with the sub-basins of the El Palo river (8.3 T/d), Zanjón Oscuro (7.5 T/d), Guachal river (7.1 T/d), Yumbo river (4.5 T/d), La Paila river (5.2 T/d) and the municipality of Cali (61.1 T/d), which contains 46.4% of the total of pollutant load to the river. It also includes household and industrial dumping and untreated rainwater drainage that affect the water bodies' quality, compromising aquatic ecosystems Vojinovic and Huang, 2014; Samant and Brears, 2017; Schuch et al., 2017).

On its way, the Cauca River receives domestic wastewater from more than 10 million people, starting with a high pollutant load that it receives in the Popayan city (Cauca department), where several rivers and streams bring untreated wastewater from about 400,000 people. Continuing with the tour, in the Salvajina dam the river rests and becomes a little oxygenated, however, later it crosses gold mining sectors, where some of them use mercury in their extraction, as well as sandboxes between artisan and industrialists. After passing through Cali, the river is again affected by high levels of contamination (i.e. organic matter, total solids). Studies by Madera-Parra et al. (2018) show that the presence of diffuse contamination in the Cauca river by compounds such as 10,11-dihydro-10,11-dihydroxycarbamazepine, ibuprofen, gemfibrozil, naproxen, paracetamol, bisphenol A, 4-isononylphenol, estrone and sulfamethoxazole, with the highest concentrations at the wastewater treatment plant of Cali, the southern channel and at the exit of the city of Cali, in concentrations of up to 27,000 ng/L. These compounds have a high threat to the aquatic biota present in the Cauca river.

Water quality research carried out in the Cauca river found a variety of emerging micro-pollutants with endocrine disruption potential, as well as a composition of the river microbiome close to a sewage stream without treatment (RICCLISA, 2018). The quality of the Cauca river has worsened despite all efforts, which include copious regulations, multiple plans, projects, and investments (e.g., many PTAR). The problems of the upper Cauca river basin are reflected in the loss of navigability function, reduction of ecosystem diversity, and critical quality parameters for the different uses (raw water does not meet the defined standards in the national regulations in order to be used as a source for human consumption). Operational effects for increasing the closure of the Cauca river intake for aqueduct service, is an indicator of the increasing pollution that at the same time is a risk indicator for the city water supply, which has been forced to build and put into operation for two reservoirs with a capacity of 180,000 m^3 to reduce the suspension of the service to the users. Between 1950 and 1986, 90% of the river wetlands were desiccated or removed by filling them with debris. Flow rates of the tributaries used to supply Cali today are below the expected amount in the design of the water treatment plants. Ingram (2008) claims that institutions responsible for river basins are incapable of providing evidence of improvement in problems that have been in development for many decades, especially when they are ruled by forces beyond their control.

The causes of pollution are complex; they are beyond technical issues, and they must be recognized and addressed to achieve a shared and consistent vision of long term recovery (30 years minimum), which transcends government periods. Also, it is necessary to work in teams, guaranteeing the participation of all actors, recognizing that nobody owns the truth and that nobody can cover all the necessary interventions. The governance model has not been successful and it is mandatory to improve it in order to arrange the recovery. Now it is required to put into practice the

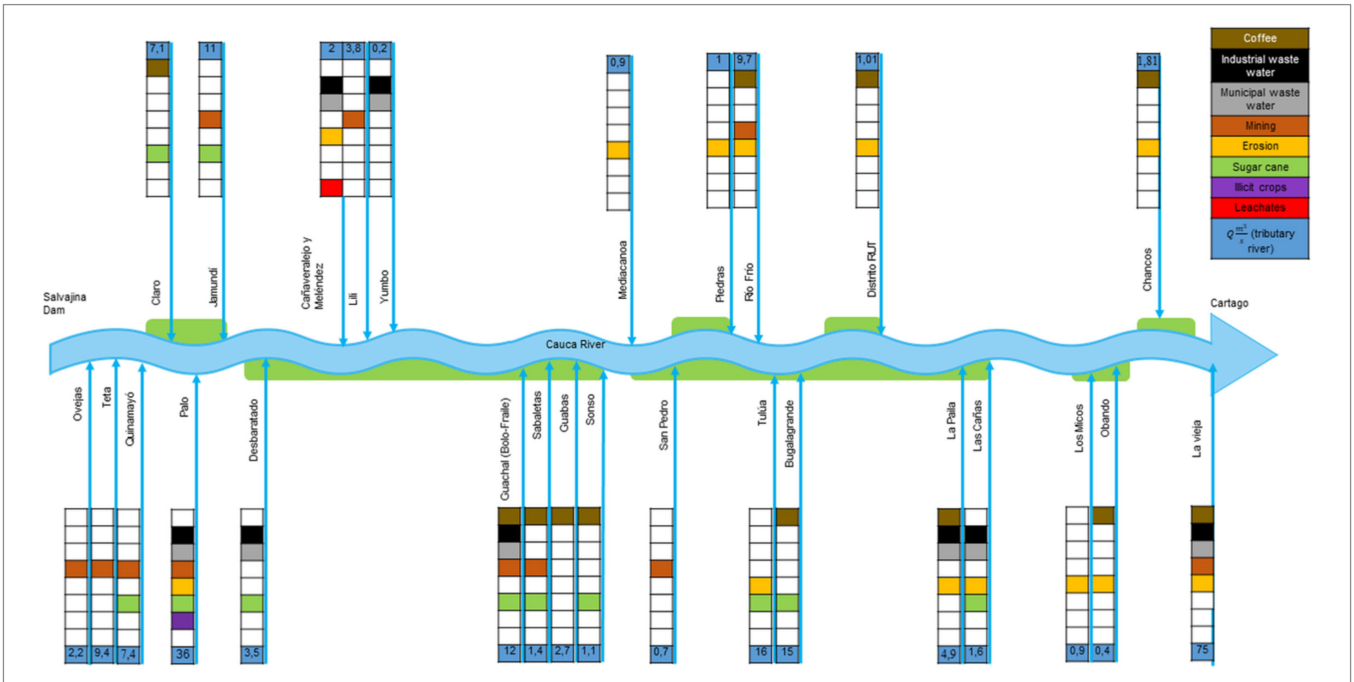

FIGURE 1 | Pollution process of the Cauca River.

basin approach as an analysis and action unit, and to look at the water integrally considering different uses and users.

Investments must be prioritized according to their impact on the water quality of the river, changing the paradigm of solutions at the end of the pipe, and encouraging the implementation of nature based solutions. In addition, it is essential to move forward systematically with specific strategies such as prevention as the effective option to control the punctual and diffuse pollution as well as the minimization, reuse, and use of the self-purification capability of the river (natural or stimulated) (Galvis et al., 2018; Galvis, 2019). Interventions must consider comprehensive actions aimed at: the strengthening of capacities and effective interventions to the basins that facilitate the follow-up and control (integrating a monitoring network); to evaluate the institutional performance based on the impact of the investment, e.g., how many milligrams of oxygen dissolved per liter will increase in the critical sections; exchange information and experiences—including national and international networks; to promote biocultural approaches and to involve the community taking advantage of the wide variety of communities and ethnic groups existing in the river basin.

The consequences of the degradation of the upper Cauca river basin already present risks to human health, hydric safety, and ecosystems sustainability. It presents an opportunity to guide efforts to improve the conditions of the ecosystem, thus improving the health of people and neighboring communities (Naiman and Dudgeon, 2011). Such is the case of Cali, a city of two and a half million inhabitants, which captures 80% of the water directly from the Cauca river for human consumption. All this implies massive environmental costs that will be transferred to future generations.

SUCCESSFUL BACKGROUND RELATED TO THE RECOVERY OF RIVERS

After several failed attempts to integrally address the recovery of the Cauca river upper basin, the Comptroller General of Santiago de Cali and the Cinara Institute of the Universidad del Valle, promoted a forum for the recovery of the Cauca river in August 2017. This activity included a tour around the river and a meeting with the international invited lecturers and important key actors of the management of the Cauca river. The purpose of the was to provide the region with the learned lessons of successful processes of recovery of rivers around the world. Experiences to recover Elba river (Schütze, 2017), the Rin river (Gangi, 2017), and the Thames river (Oates, 2017) were reviewed. A summary of the experiences of the successful recovery of those rivers is described below:

The Elba River

A basin that is shared by four countries, principally the Czech Republic and Germany, and Poland and Austria with a smaller area. The basin has a length of 1,096 km, an area of 148,268 km^2, a population of 24.5 million, and an average flow of 870 m^3/s at the mouth of the river. It is used as a source of water in cities such as Dresden and Torgau with river bed filtration technology and was the most polluted river in Europe. There were so many chemical industries (acid discharge, oil, photography, and a lot of open lignite mines), that the population normally said "you can print photographs inside the river because of the number of chemicals in it." Federal states did not agree over the river basin, which made the management more difficult. Between Germany and the Czech Republic in 1990, the International

Commission of the River Protection was established in order to generate action recommendations: a central office of eight people (at Magdeburg); Committees: authorities, scientists, NGOs (120 people in total). The improvement of the water quality was established as a priority, and flood problems were addressed. The establishment of spaces for nature and to promote tourism was emphasized, and today it is Unesco biosphere reserve (Schütze, 2017).

The Rin River

The river basin covers nine countries: the Netherlands, Germany (50%), France, Luxembourg, Belgium, Switzerland, Austria, Liechtenstein, and Italy. With a length of 1,233 km and an area of 200,000 km^2, it is the third long river in Europe. It has the most important navigation European route (825 km), 60 million people inhabit the basin, and the basin supplies 30 million people. In 1970 the Rin river was considered the European sewer. The chemical and metallurgical industry used the river as transport and there were a lot of disagreements that obstructed the recovery progress. Ambitious goals were set; such as the return of the salmon, which was defined as an indicator of a healthy river. Commissions were appointed and by 1999, a more integral approach was adopted through the sustainable development of the whole ecosystem, creating the "Rin 2020" program, where all countries developed their legislations with the obligation of implementing measures considering the basin unit (Gangi, 2017).

The Thames River

The Thames basin covers an area of $\sim$12,935 km^2, it has a length of 300 km, with 80 million people settled in its valley (7 million who live in London) and a large industry that generates high demand of human consumption and industrial water, generating too much residual water. One hundred and fifty years ago, during the Industrial Revolution, London had 2 million inhabitants, and the industrial pollution and domestic waste went directly in the river, deteriorating its quality. The Thames river became the most polluted river in the world. Many diseases were spread, and by 1849 Cholera had killed 14,000 people. Meanwhile, nothing lived in the Thames river. The British Government adopted integral management under the following principles: a vision for the river—achieved in an agreement with all sectors; integration—of all policies and sectors in only one plan for the river; scale—to work at the same time in all the scales: basin, tributaries and locally; synchronization—to take action in all problems; participation: of the communities, businessmen and affected people; capacities—for all sectors and this way everyone can contribute; associations—to create accompaniment in public-private sectors in order to plan, finance and execute together; knowledge—to take advantage of the best scientific knowledge to learn continuously if necessary; and implementation strategy—agreed and with the possibility to be changed if necessary. In 2010 the Thames river won the award for the most improved river quality. All parties involved agreed that every cent invested was worth it in terms of health, safety, and economy (Oates, 2017).

The three experiences show that those river systems throughout history were in critical condition and each one had a specific trigger. However, with an organized and integrated process, the rivers could be recovered with the establishment of a form of organization that facilitated the implementation of an agreed roadmap. The labor took decades and required significant economic resources that were recovered with health achievements for the people, cheaper expenses of treatment, decreasing risks and flood damages, recovering healthy ecosystems for many species, and benefits for the economy and companies. All actors should be linked to the process and their interests should be considered, until a shared vision and a long-term consensual work plan is built. The rivers became pleasant environments that can be also used for recreation. The discussion and analysis of those three experiences with the invited experts contributed to define the organization strategy to approach the recovery of the upper Cauca river's basin through the Commission.

COLLABORATIVE GOVERNANCE TO FACILITATE THE CAUCA RIVER RECOVERY

The recovery of rivers has been a subject of little interest in Colombian society, due to the complexity in the process of making decisions and the lack of clarity regarding the concept of governance. Collaborative governance is important to reach negotiated agreements, interactive planning, and the participation of the public opinion and of all those who are interested. Besides, gaining support and promoting public awareness is equally essential to obtain effective results, given that the structures of social networks relevant to influence ecosystem governance. In addition, certain actors contribute as agents to promote beneficial network structures (Ernstson et al., 2010).

The scientific literature does not have a clear agreement about the concept of governance. The definitions are more associated with the reflection and meaning approach of the place where the problem is analyzed. The recovery of the rivers is a complex problem; that is to say, it is characterized by a lack of clarity in its definition, objectives, and steps to follow, such as relationships between diverse groups involved (local organizations, municipalities, departments, institutions) and the equity criteria, accessibility, and sustainability. Colombia was accepted in 2018 into the Organization for Economic Cooperation and Development OECD; this organization is guided by the definitions of "Governance in Transition" (OECD, 1995). In this context, governance is related to the decentralization of State power and to the emergence of the co-responsibility of different actors facing development and social welfare. The principles of the OECD regarding water governance focus on efficiency, effectiveness, trust, and commitment (Akhmouch and Correia, 2016). According to the Global Water Partnership (Global Water Partnership, 2009), water governance is defined as "the range of political, social, economic, and administrative systems that exist to develop and to manage the hydric resources and the water provision services at different social levels." According to the Ministerio de Ambiente y Desarrollo Sostenible (MADS) (2013), water governance is a process for its integral management that promotes the active and inclusive participation of different social actors in the decisions articulating multiple cultures. These definitions contribute to the principles for good water governance, but has a limited reach facing the real complexity of systems. In essence, water governance seen from the perspective of human intervention is looking for changing the water cycles with social or environmental purposes (Bouckaert et al., 2018). The strategy of governance contributes to identifying challenges for implementing policies and recommending reforms, as well as identifying relationships between the programs, regulations, and achieving goals (Jacobson et al., 2013). Ernstson et al. (2010) and Meerow and Newell (2017) emphasize the necessity of establishing an appropriate governance model in order to secure long-term sustainability. In the context of the recovery of hydrographic basins and freshwater systems, the necessity of collaboration between diverse interested people has been identified in order to share visions, objectives, and rules. This facilitates collaborative governance (Imperial, 2005; Baldwin and Ross, 2012; Yeboah-Assiamah et al., 2018) allowing the achievement of the results in consensus and benefits for all the interested parties with better transparency and social commitment (Baldwin and Ross, 2012; Brower, 2016; Greenhalgh and Samarasinghe, 2018). The collaboration is about the degree of connectivity between all the relevant interested parties and their capacity to participate in the governance processes (Bouckaert et al., 2018). Collaborative governance facilitates achieving consensus (Innes and Booher, 1999) and integrating learning (McLoughlin and Thoms, 2015).

The conceptual framework for the collaborative governance strategy must consider that water is not only a human survival element, it is an integral part of society, culture, and nature. Therefore, for Colombia, the incorporation of approaches of bio-culturality and biocultural rights developed in the judgement T626/16 by the constitutional court of Colombia, is perhaps the guiding reference framework for the recovery of rivers, being a framework of relevant work in research and development.

In recent years, individual or collective lawsuits against the Colombian government have been advancing; they are based on the political constitution for the protection of the fundamentals right to life, health, and a healthy environment. It is sought that the State assumes responsibility of the recovery of the Bogotá, Atrato, Cauca rivers, and the Amazonia Region. This shows the citizens' concern for the deterioration of rivers and demonstrates the discontent for the lack of effectiveness, inability, and indolence of the authorities designated by the society for its care. These kinds of processes are derived in a better institutional articulation that, if fulfilled, it would contribute to the optimization of resources and to a better impact; it demands coordination between the different environmental and territorial planning tools and the responsible actors. It also goes beyond the government periods facilitating the long-term planning and the continuity of the actions. These experiences are not yet consolidated, but they become opportunities for strategies like the ones for the upper Cauca river basin Commission because they make the institutions take the search for solutions seriously, as well as act as a positive signal of citizen sensitivity.

The conceptual model of governance for the Cauca river recovery, which is presented in **Figure 2**, is proposed as part of the postulates of the constitutional court of Colombia that has reviewed different approaches as anthropocentric, biocentric, ecocentric, and bio-culturality. Judgement T626, 2016, considers that "nature is not only conceived as the environment and the human habitat but also as an individual with own rights that has to be protected and guaranteed." Therefore, this is a new imperative of integral protection and respect by the part of the States and societies, where "only from an attitude of deep respect and humility with nature, its members and its culture, it is possible to start a relationship with them in fair and equitable terms, leaving aside all concepts that are limited or simply utilitarian, economic or efficiency-based." The central premise where the conception of bio-culturality and biocultural rights are based, is the relationship of the deep connection between nature and human species, where the conditions to preserve the biodiversity are guaranteed in order to keep unfolding its evolutionary potential in a stable and indefinite way [sentence Corte Constitucional de Colombia (2016)]. On the other hand, judgement 38-2019 of the Medellin High Court, declared the Cauca river as a subject of rights and it implies its protection, conservation, maintenance, and recovery (Tribunal Superior de Medellín, 2019). These referents make the Commission promote a collaborative strategy of long-term innovative governance.

COMMISSION FOR THE RECOVERY OF THE UPPER CAUCA RIVER BASIN. ALTERNATIVE CONSTRUCTION PROCESS OF COLLABORATIVE GOVERNANCE

Several articulation initiatives have been proposed to improve the quality of the Cauca river upper basin, but have had little significance. In 2001 the "Pact for the Cauca river recovery" was signed. In 2009 the document of the National Council of Economic and Social Policies was elaborated, CONPES 3624, DNP and MAVDT (2009), named "Program for the Sanitation, Management and Environmental Recovery of the Cauca river upper basin" which was updated in 2014. In 2015 the Regional Environmental Management Plan (REMP) was formulated with a horizon of 21 years (2015–2036) [Corporación Autónoma Regional del Valle del Cauca (CVC), 2015]. In the Cauca department, a REMP with a horizon of 10 years (2013–2023) was also elaborated [Corporación Autónoma Regional del Cauca (CRC), 2014], and by 2018 the CONPES 3915-2018 document that established "Policy and Strategies Guidelines for the Sustainable Regional Development of the Colombian Massif," Departamento Nacional de Planeación (DNP) (2018a) was developed. These initiatives have been characterized by having a conventional approach to delimit the problem, a weak articulation between departments, limited participation of the civil society which focuses on the actors with high economic and political influence, a lack of political will aggravated by the changes between governments, a weak control over the institutions' development, and weak social and media participation. The limitations in the indicators for the follow-up on the recovery of the river's quality are also evident, and this includes at least one that is socially recognizable.

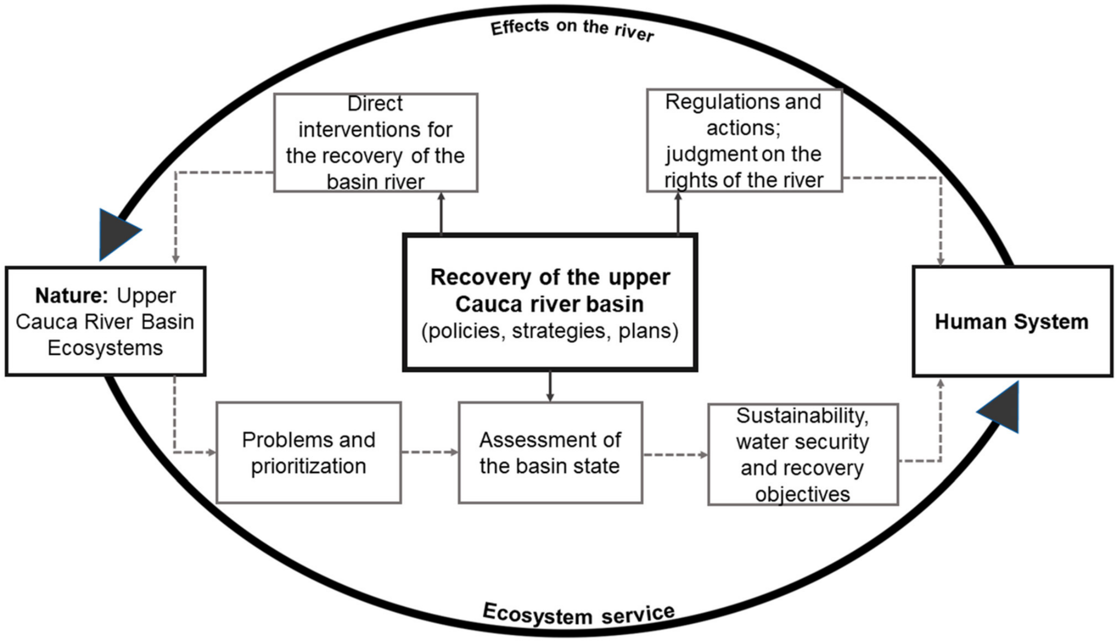

FIGURE 2 | Guiding conceptual framework of the commission for the recovery of the upper Cauca river basin.

The Commission arose due to the crisis of the water resource management model within the region. The first steps were given in 2017 when dialogue was established. It was facilitated by the Comptroller General of Cali together with the Universidad del Valle-Instituto Cinara as a result of the forum about rivers recovery with the participation of the international guests' representatives of the Commissions for the recovery of the Elba, Rin, and Thames rivers. In Latin America, México has a national water Commission with 26 basin councils around the country, and 215 subsidiary bodies with 36 basin Commissions that work at the sub-basin level [Comisión Nacional del Agua (CONAGUA), 2021].

The Commission for the upper Cauca river basin was established initially by representatives of: Comptroller of Santiago de Cali, DAGMA, CVC, EMCALI, Camara Colombiana de la Infraestructura (Colombian Chamber of Infraestructure), Univalle-Instituto Cinara, Universidad Autónoma de Occidente, ACODAL Occidente, independent consultants and advisers, Fundación Empresarial para el Desarrollo de Yumbo (Business Fundation for Yumbo Development)—Comité empresarial (Business Committee) and Citizenship. A Technical Secretariat of the Commission was agreed; it would be made up of the following institutions: ACODAL, Univalle- Instituto Cinara, EMCALI and the Santiago de Cali Comptroller General. In the future, the participation of more institutions from Valle del Cauca and from the Cauca departments has to be included. The Cauca river upper basin was prioritized in the first phase of the process, beginning with the city of Cali's impact the river into the framework of a basin vision. In order to start the process, different aspects and challenges of the Commission were considered to facilitate and guide the recovery of the river in the next 30 years, which are presented below.

- It started by recognizing that it is a long-term process, that requires patience where it is necessary to understand and analyze the problem.
- The people involved agreed to lead a process with a shared vision, and with the implementation of actions.
- Many institutions and organizations carried out actions oriented to the recovery of the Cauca river, but they felt frustrated because the actions were not articulated and did not achieve significant environmental impacts on the river.
- It was agreed to define common goals and measurements to value them with the involved actors.
- One formal group work with the stakeholders was defined. It can be extended in an agreed way if it is considered necessary and relevant.
- The development of the Commission with a technical voluntary secretariat, started the work.
- It was established to advance prioritizing integral management plan for the upper Cauca river basin, integrating the upper basin actors (for the Cauca department and Valle del Cauca) looking for immediate or short-term results.
- This was done through consulting to integrate the Environmental and Sustainable Development Ministry, as they lead the sector.
- It was agreed that the Commission doesn't require technical groups in each municipality. Through the Ministry of the Environment of each department, it is possible to ensure that the guidelines are implemented with a hydrographic basin approach instead of a political-administrative division.

The sustainability possibilities of the strategy are defined by the capacity of teamwork between all the actors considering their interests in a long-term horizon, construction of a shared vision over the basin, and an agreed agenda based on the trust generation and common goals. The risks of the initiative would be structured by the ineffectiveness to approach problems, lack of citizen participation, lack of well-structured projects, reduced budget, and political will for the integral work and the integrity of the processes.

On April 18, 2018, the Technical Secretary of the Commission had a meeting with the Environmental and Sustainable Development Minister to discuss the initiative. In the meeting delegates of the environmental authority of Cauca department (CRC), and the public services company from Popayán (Cauca) also participated. The minister proposed setting up a macro-basin council for the Cauca river, articulated with the Magdalena river to develop its distinct dynamic that facilitates the coordination of national, regional, and local actors, through a Pact for the Recovery of the Cauca river.

On June 18, 2018, a memorandum of understanding was signed by the legal representatives of each member of the Commission and the Environmental and Sustainable Development Ministry. The aim of the agreement is to develop the following strategies: sustainability and resilience of ecosystem services within the main basin of the Cauca river and its tributaries; alternatives to improve the quantity and quality for the different users and uses (including human and domestic consumption, agricultural, livestock, recreational, aesthetic, industrial, fishing, aquaculture, navigation, and power generation); identify the financial arrangement mechanisms through which the river can be managed; recover the water sources in the Cauca river basin and the management of the urban and rural drainage, contributing to the strengthening of the economy, productivity, risk mitigation, sanity improvement and life quality of the communities, to generate better conditions for the prosperity of the territory and its social fabric.

The memorandum of understanding was a useful tool to start the articulated work (locally, regional and national) of the Commission around the construction of a work agenda for the next 30 years. On that basis, several analysis and discussion meetings were established with the perspective of prioritizing short-term direct actions for improving the Cauca river upper basin. A synthesis of that analysis showed that the Cauca river pollution has changed and the strategies have focused on "solutions at the end of pipe," neglecting aspects as point- source and diffuse pollution both at the rural and urban level. The difficulty lies in making coherent the large number of plans that develop in different aspects and territories associated with the political-administrative divisions was identified, not considering the hydrographic basin as an analysis unit. The necessity of having a shared vision with short, medium, and long-term strategies and the necessity of teamwork, was evidenced. It was also clear the lack of participation of the indigenous, afro, and peasant communities located in the upper basin.

Some short-term priority actions do not necessarily have to do with the construction of new infrastructure, for instance: (i) to avoid the progressive deterioration of the basins (deforestation, illegal mining, informal settlements, etc.), (ii) to avoid continuous losing of buffer strip of the river banks (main channel and tributaries), and (iii) to rethink inadequate decisions related to land use. Additionally, several efforts have been made, but the river quality has not recovered for the required uses. In that sense, it is key to focus on the river's condition, taking into account the vision of rivers as subjects of rights, which implies improving the understanding of a river in terms of dynamic behavior, to check its routes and its spaces, the self-purification, and the kind of pollution that affects it the most in order to sustain its ecology.

The beginning of the Commission's work implied understanding diagnostics, programs, and plans of the institutions with an emphasis on the basin. On that basis, team groups discussed and agreed on the first priorities as guiding to the responsible institutions of its planning and execution: (a) to improve the conditions of environmental sanity of the south sewer system of the city of Cali, as its discharge affects the ecosystem and the water quality collected for human consumption; (b) strategies for improving the discharge of sewage water of the city of Cali for the second phase of the wastewater treatment plant of Cañaveralejo; (c) to prioritize in the regional environmental management plan for the recovery of the Guachal river basin; and (d) to implement jointly with the Cauca department a strategy for controlling the impacts upon the Cauca river brought about by the discharges of El Palo and El Desbaratado rivers, which have high suspended solids concentrations.

The Commission established the steps for the Cauca river recovery process as presented in **Figure 3**. This was made by the technical secretariat as coordinator, articulator, and facilitator group of the policies and decisions adopted, guaranteeing the coherence and compliance of the established roadmap. The mission: to position the recovery of the upper Cauca river basin as a regional and national priority, influencing the materialization of urgent initiatives while articulating strategic actors; 2020 vision: in 2020, with the leadership of the Commission and in the framework of a Regional Pact (collaborative platform), it was agreed to elaborate an integral strategic plan for the recovery of the upper Cauca river basin from the Colombian massif to Cartago (Valle del Cauca); 2025 vision: in 2025, with the leadership of the Commission, the integral strategic plan for the recovery of the upper Cauca river basin, it looks for having prioritized projects for execution; 2050 vision: in 2050, the recovery of the upper Cauca river basin will be a successful case at a national level, for being an initiative of efficient management achieved by the government, private institutions and the community, with the leadership and coordination of the Commission.

Commission Activities Between 2019 and 2020

During this period the following objectives were proposed: to develop in a collective way the conceptual framework of the recovery of the Cauca river upper basin; to formulate the strategic plan of the Commission and to formulate the integral strategic plan for the recovery of the Cauca river upper basin; to identify

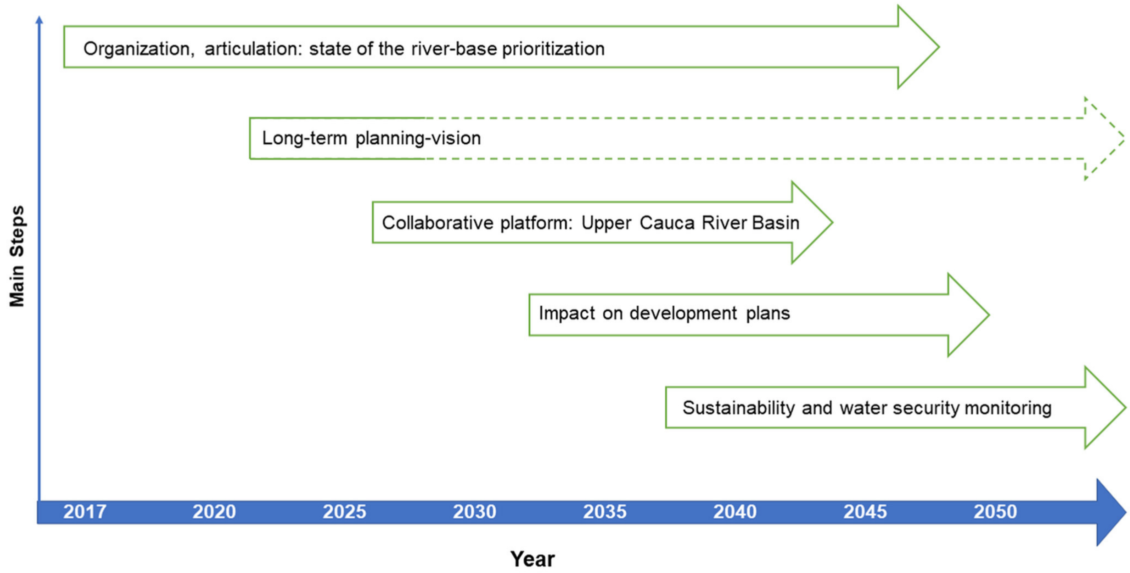

FIGURE 3 | Steps for the process of the recovery of the upper Cauca river basin.

the committed initiatives and resources for the different public and private institutions for its recovery; prioritization of the projects; interinstitutional formulation of the project of the south drainage system; to manage the structuring and the strategy of financing the reduction of the specific and diffuse pollution project in the Cauca river (CARMAC-MADS); to incorporate the recovery of the Cauca river upper basin in the national, regional and municipal agendas. To check possible projects in the framework of the National Development Plan 2018—2022, departmental and municipal development plans 2020—2023, the CVC 2020—2024 action Plan, and the revision and adjustment of the 2015—2036 PGAR. It was also proposed the key actors sign the Regional Pact of the recovery of the Cauca river upper basin, which derived in the conformation of the collaborative platform for the recovery of the Cauca river upper basin that is described below.

Collaborative Platform for the Recovery of the Upper Cauca River Basin

The collaborative platforms are initiatives promoted by the National Government of Colombia within the framework of the National Plan of Development, to establish guidelines of politics, strategies, goals, and indicators for the country's development. The Ministry of Environment and Sustainable Development established for the 2018–2022 period the formation of eight Collaborative Platforms [Departamento Nacional de Planeación (DNP), 2018b]. These initiatives are understood as a governance strategy of the public sector that promote the collective action of public and private actors, oriented to the restoration and recovery of degraded ecosystems, especially on basins where instrumentalization processes of the water integral management are being carried out, articulating technical, economic and administrative efforts [Ministerio de Ambiente y Desarrollo Sostenible (MADS), 2020]. In that sense, the work carried out by the Commission of the upper Cauca river basin is addressed to the national strategy, becoming the second Collaborative Platform of the country.

Through a concurrence of wills in 2020, the collaborative platform for the recovery of the upper Cauca river basin was established, made up of 28 actors of the Cauca and Valle del Cauca departments that belonged to the productive sector, the community and territorial entities, the academy and public services companies. This type of inititatives contributes to facilitating the collaborative governance according to Imperial (2005), Baldwin and Ross (2012), and Yeboah-Assiamah et al. (2018). In this way, it seeks to establish guidelines to improve the basin in terms of its ecosystem condition and to perform articulated actions oriented to the identification of funding sources and the impulse of strategic projects backed by the national and regional government.

As a result of this exercise of interinstitutional and intersectoral articulation, initially coordinated by the Environmental and Sustainable Development Ministry (as guardian in the legal representation of the Cauca river, Judgement T-038 of 2019), the action plan that consolidates the projects took into account the different instruments of planning grouped in four main topics was constructed: quality, offer, demand and governance. Each one of the topics was led by members of the collaborative platform, who promoted environments of dialogue to define the main lines of work in the prioritized aspects, as well as an initial proposal of indicators for the respective follow-up, which are presented in **Table 1**.

Even though the action plan of the collaborative platform does not define all the actions and projects that are required to achieve definitely the integral recovery of the Cauca river upper basin, it is an initiative that will allow setting strong, concrete,

TABLE 1 | Topics, work strategic axes, and follow-up indicators of the action plan of the collaborative platform for the recovery of the upper Cauca river basin.

Topic	Strategic axis	Follow-up indicator
Quality	Monitoring water quality	Number of seasons or monitoring points of water quality operating or characterized/Number of seasons or monitoring points of water quality available (%)
	Formulation and execution of management instruments, management and planning.	Number of tools or formulated rules and in execution/Number of tools or projected rules (%)
	Pollution and sanity management	Number of actions* executed for the reduction of pollutant load discharge in the Cauca river/Number of actions* projected for the reduction of the pollutant load discharge to the Cauca river (%).
Demand	Characterization and quantification of the water demand.	Water use index
	Incorporation of the GIRH in the principal productive services of the water users.	Quantity of water demanded by the system/quantity of water in the source (%)
	Water efficient use and sustainable.	Efficiency index in the water use.
Offer	Restoration, rehabilitation and reforestation.	Ecosystem hectares in restoration, rehabilitation and reforestation.
	Payment for ecosystem services	Areas under schemes of payment for ecosystem services and conservation incentives, for each basin.
	Management instruments, management and planning.	Planning tools implemented/planning tools formulated (%)
	Protected areas	Hectares of protected areas/total hectares (%)
Governance	Citizen participation	Number of basin councils implemented
		Number of the organization of the civil society strengthen in environmental topics.
	Water culture	Number of municipal CIDEA* working.
		Number of actions in environmental education and cultural citizen.
		Number of municipal councils in rural development currently working.
		Number of PRAES** formulated and in execution.
	Conflicts management	Number of conflicts socio-environmental strategically and technically intervened

*Interinstitutional technical committees for environmental education.
**Environmental and educational proposals.

and measurable goals in the medium and long term, so that the subsequent exercises will have a referent for strategic planning.

In addition to the action plan, a collaborative governance scheme was projected that will allow the definition of mechanisms of participation and interaction between the different actors, which improves the connectivity of all the parties interested (Bouckaert et al., 2018). Thereby, the follow-up, articulation, and monitoring of established activities in the collective action plan of this instance. Although the collaborative platform depends on the will of the national government in power with a short-term horizon, this initiative will be very useful in the formulation of future plans of development to the national, department, and municipal level facilitating the identification of strategic projects and of significant impact for the Cauca river upper basin.

This is the first time that a governance and government exercise is developed facilitating a scenario of articulated work between all the competent actors of the Cauca river upper basin, identifying those committed initiatives and resources for the different public and private institutions, as a starting point for the process of short-term recovery (2020–2023 period). In this way, it becomes a scenario for the strengthening of the long-term objectives and vision of the upper Cauca river basin Commission, as well as, a starting point for the construction of collective planning, in a basin that demands the integrality as a base for the solution of the structural problems.

Balance of the Developed Activities

- Knowledge integration and socialization: Institutional meetings to socialize and learn about what each one has done in the basin.
- Articulation of learned lessons of the different actors: Definition of problems and priorities in teamwork with institutions.
- Memorandum of understanding signed with the Environmental and Sustainable Development Ministry: Signing of a cooperation agreement between the different institutions interested in the Cauca river recovery. The Ministry of Environment and Sustainable Development coordinates the agreement and further developments.
- Integration of the Commission with the CARMAC-MADS: The Ministry of the Environment and Sustainable Development integrates the Commission with the Regional Environmental Council of the Macrobasin.
- Strategic planning: Colaborative work between institutions to develop the strategic plan: central problem definition, prioritization, mission and vision, resources and schedule.
- Prioritization of the actions to start the roadmap highlighting: south drainage system, Guachal river basin; agreement and understanding meetings of the strategies for the sewage water discharge of the city of Cali; encounters with Cauca department to check strategies related to the problem of high discharge of solids by the Palo and Desbaratado river.

- Inclusion of projects in the National Plan of Development 2018–2022: Negotiation with the National Planning Department in order to include prioritized projects in the National Development Plan.
- Regional projects: To implement environmental sanity plan of the Cauca river and the Pacific watershed.
- Environmental recovery and intervention in water and sanity in hydrographic basins from Valle del Cauca: It was agreed to begin with actions in the sub-basins of the greatest impact on the Cauca river: Guachal river, Yumbo river, Jamundi river, Melendez river, Lilí river and Cañaveralejo river.
- Through the Housing, City, and Territory Ministry, to look for funding for the construction of WWTPs, that contribute to the reduction of the specific and diffuse pollution of the Cauca river, especially in the Cali Municipality.

With the Environmental and Sustainable Development Ministry:

- It was discussed that the recovery of the upper Cauca river basin is significant for everyone, and should be a national priority, with support requested in order to materialize the prioritized initiatives and the articulation of strategic actors of all the macro-basin.
- It was requested to reactivate the Regional Environmental Council of the Magdalena—Cauca macro-basin (CARMAC) and to update the strategic plan.
- Formation and management of the collaborative platform.
- We participated in the formulation of an action plan approaching structural topics of the progressive deterioration of the river's upper basin with the relevant actors of the region for prioritization in the CARMAC.
- It was requested to reactivate the Water National Conseil conformed by the Ministries of Environmental, Housing, Mining, Agricultural, Health, DNP, and the IDEAM.

CONCLUSIONS

The Commission for the recovery of the upper Cauca river basin is a process in development that arose due to the limitations of the current model of hydric resource management in Colombia. The main issue has been transcending the short-term planning of the local and regional administrations to a long-term planning in function of a shared vision. The background shows that rivers can be recovered; that all of the studied rivers were at the time in deficient conditions of quality, but the process of recovering took several decades.

The recovey of th upper Cauca River basin is a long-term process wich requires overcoming several limitations through the following actions and innitiatives: (a) defining the participation of the basin communities that are representative and recognized; (b) define the indicators that allow monitoring the evolution of the state of the river, in harmony with the investments and actions carried out; (c) greater investment by the state in the basin and (d) guarantee the commitment of the productive sectors that intervene and significantly impact the basin. The near future scope of this huge task considers firstly establishing the agreed action plan for the short term with financial resources and secondly adopting the agreed roadmap for achieving the long term goals.

The conceptual model of collaborative governance proposed for the recovery of the upper Cauca river basin, is grounded in the conception of the bio-cultural and the rights of nature due to the indissoluble relationship between nature and humans. This proposal has facilitated a better understanding between the problem and prioritization of consensus actions with a better connectivity between the stakeholders through the collaborative platform. It is imperative to achieve a shared vision, to act under the vision of basin with all the involved actors, of proposing minimum and convincing recovery indexes including at least one that would be a symbol that the society recognizes and motivates it to advance in the recovery. It is key that the recovery of aquatic ecosystems and the investment that requires the process can be carried out, with the guarantee of sustainability and water security for the benefit of the biodiversity and the society as a whole.

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Water and Sanitation as a Wicked Governance Problem in Brazil: An Institutional Approach

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The world is facing a large number of interrelated crises that have seriously increased the level of uncertainty and ambiguity in many areas. In 2018, the UN anticipated that the world was careering toward a global water crisis with a 40% shortfall in freshwater resources by 2030 coupled with a rising population. This nascent crisis represents a "connected challenge" for countries: it contains a multitude of causes and consequences, a multitude of actors and interests for which no "one-size-fits-all" solutions are available. The adequate approach to this type of complex—or "wicked"—problems is not to search for technological solutions only, but to consider new forms of governance that make use of complementary institutional logics. Effective governance depends on the extent of alignment with the complexity and the root causes of the issues. This paper applies wicked problem theory to identify the root institutional and governance causes of uncertainty in a developing country like Brazil, which provides insights to (also) identify approaches that could navigate change in less uncertain and ambiguous directions. We distinguish three types of relevant institutional constraints: logics, complementarities, and voids. Based on semi-structured interviews with representatives from Brazil's water and sanitation sector, we delineate institutional constraints precipitated by the plurality of the governance system. We argue why a tripartite partnership approach—as for instance pioneered by Dutch international water projects in the global South—presents a way out of the wicked water and sanitation problems in Brazil.

Keywords: institutional complementarity, institutional constraints, institutional logics, institutional voids, tripartite partnerships, water and sanitation sector, wicked problems

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INTRODUCTION: A GOVERNANCE CHALLENGE?

Too many people still lack access to safely managed water supplies and sanitation facilities. Water scarcity, flooding, and lack of proper wastewater management also hinder social and economic development. Clean water and sanitation problems are among the most significant challenges the world is facing in the decade to come (UN-United Nations, 2018a). Despite substantial progress during the 1990–2015 period in increasing access to clean drinking water and sanitation, 2.1 billion people (29% of the global population) lacked access to safe, readily available water at home, and 6 on 10, or 4.5 billion did not have safely managed sanitation in 2015 (WHO/UNICEF, 2017), including 892 million people—mostly in rural areas of Southern Asia and sub-Saharan Africa—that still practiced open defecation, and 2.3 billion people that lacked even a basic level of service (UN-United Nations, 2018b). In 2018, the UN anticipated the world was careering toward a global water crisis with a 40% shortfall in freshwater resources by 2030 coupled with a rising population. In March 2018, the UN General Assembly launched the Water Action decade to mobilize action to transform how water has been managed. The COVID-19 pandemic has reiterated the tantamount importance of sanitation, hygiene, and adequate access to clean water to prevent and contain diseases.

Water and sanitation problems do not only refer to water-scarce countries but also to relatively resource-abundant countries like Brazil. The country presents a very controversial situation regarding to water, even though it holds 12% of the surface fresh water of the planet (Whately and Campanili, 2016), about 16% of the population (35 million) in 2019 did not have access to piped treated water, and 46% (100 million) had unsanitary ways of dealing with wastewater (SNIS, 2019). The 9th largest economy in the world scores #106 in terms of access to basic water and sanitation services (ABCON, 2019), which has also contributed to its greater susceptibility to the COVID pandemic. Brazil has the highest open defecation rate in Latin America (WHO/UNICEF, 2017). Water and sanitation have become one of the key targets of the Sustainable Development Goals (SDG6) as it has many externalities that requires a "nexus" approach and the involvement of different societal actors to address the problems (Cronin et al., 2015; Rasul, 2016; Pahl-Wostl, 2019; Van Zanten and Van Tulder, 2021).

Water and sanitation problems are primarily rooted in poorly managed governance systems and policies, resulting in a skewed allocation of resources and a relatively low provision of services (Cosgrove et al., 2000). For many decades the discussion on appropriate governance approaches centered around decentralized governance models, privatization policies (Bakker, 2010; Boelens, 2015), and market-based approaches to overcome the failure of governments to adequately deliver services and manage scarce resources (Achterhuis et al., 2010). Countries are struggling with the nature of water and sanitation as a natural monopoly, a private, public, or common pool good for which appropriate governance models must be developed. Water and sanitation challenges have all the traces of a "tragedy of the commons" or "common pool" problem, where wrong decisions can lead to its overuse and depletion (Hardin, 1968; Ostrom et al., 1999).

Studies claim for novel governance models that promote a better balance between public and private participation in the water and sanitation systems and to encourage the involvement of multiple stakeholders (Cain et al., 2020). This trend brings potential opportunities for solving the problems but also increases the complexity of governance systems.

Successful complex network governance results from the self-articulation between different leaderships, interests, and power relations (Pahl-Wostl, 2015). Overcoming complexity requires a better understanding on the roots of the institutional "wickedness" of the water and sanitation problems that block innovative governance approaches for these systems. More integrated governance approaches require improved dialogue and collaboration between government, civil society, and the private sector (Lane and Robinson, 2009). Defining the institutional preconditions for "complexity-sensitive" interventions and collaborative arrangements (Van Tulder and Keen, 2018) still lacks theoretical elaboration and empirical testing.

This study aims to explore the dimensions of institutional complexity on the water sector by investigating the institutional constraints—complementarities, voids, and logics—that make it difficult to discuss and resolve agency, administrative structure, and the relationship between three key institutional spheres of society: state, market, and civil society. Institutional complexity contributes to fragmentation of water management and characterizes the wickedness of the governance challenge of the sector in Brazil. In section 2 (theory development), we construct a theoretical model that identifies key components of those societal complexities that could be blocking decisions and frustrating advancements to address (wicked) water and sanitation problems in weak institutional contexts like Brazil. Multi-stakeholders' engagements in network approaches as partnerships represent a governance proposition to come up with effective solutions to pressing needs of society, as sanitation, mainly originated by the failure of acting of government, civil society, and market actors. Although partnerships have been introduced to deal with complex problems in diverse contexts in developed, developing and under developing countries, it is relatively unclear what are the elements of the institutional setting that can hamper or encourage engagement processes between partners in the formation of this arrangements. We applied these theoretical insights to document the water and sanitation sector's governance situation in Brazil.

In section 3 (Methodology) we explain the use of semi-structured interviews to understand—from the perspective of those involved in the sector—the extent to which the institutional constraints contribute to the wickedness of the governance problems on the water and sanitation sector in Brazil and affect the effectiveness of establishing new solutions such as partnerships arrangements. In section 4 (Findings), we critically reflect on the policy initiatives in the country and accumulate relevant insights on key aspects to way out of the crisis. Our analysis examines the roots of governance complexity of the water and sanitation sector in Brazil in terms of institutional constraints and considers the extent to which tripartite partnerships (TPPs) can be considered an appropriate "way out" for the governance sector's challenges in the country (section Discussion: On Institutional Constraints and Wicked Problems and Conclusion).

THEORY DEVELOPMENT: WATER AND SANITATION AS A WICKED GOVERNANCE PROBLEM

Complex and interconnected problems related to the provision of clean water and sanitation can be classified as "wicked problems." Wicked problems are difficult to define and address and have no fixed solutions (Rittel and Webber, 1973). Originally, wicked problem scholars argued that there was no template to follow when tackling these problems. But four decades later, second-generation wicked problem scholars started to acknowledge that arrangements can be identified, all based on a more solid understanding of the way ecosystems of collaborating actors can create novel governance arrangements (Crowley and Head, 2017). Wicked problems are systemic and require a deeper understanding of the institutional constraints and how the institutional setting can influence new approaches and possible solutions. Wicked "opportunities" can then be created by overcoming institutional constraints, expressed in this study through institutional complementarities, voids, and logics.

In recent decades, the water and sanitation sector has experienced growing social complexity that evolves from conflicting logics, making the feasibility of the sector primarily a governance issue (Franco-Torres et al., 2021). Water and sanitation governance must encompass a wide diversity of policy areas, water policy formulation, a sectoral fragmentation of tasks at different levels of government, between ministries and public agencies, a diversity of actors—government, private market, and civil society—that face conflicting goals and logics. Numerous issues related to water are the result of population growth, economic activities, climate change, pandemics, which makes water governance a highly complex system (Vannevel and Goethals, 2021).

Governance, seen as a (complex) system, needs to capture multiple elements involved in providing goods and services, such as the diversity of actors, roles, logics of interactions, and the dynamics of sharing responsibilities (Pahl-Wostl, 2019). Governance processes might take different forms and modes, while conflicts tend to occur at the interface between state, market, and civil society (Van Tulder and van Mil, 2020).

Dealing with complexity requires governance at different hierarchical levels. Water governance needs to be approached within a systemic framework, requiring the understanding of the key drivers of water management (Akhmouch and Correia, 2016). Water governance takes place at different levels, ranging from the national or supranational level to the regional or local level. The management approach can vary a lot depending on the scope, from climate change, that transcends territorial boundaries and are usually addressed on a global scale, to national water resources management, and even more particular to regional and local management of drinking water supply services. Institutional arrangements and different governance models must span the full range of regions, national and supranational levels. Water governance can bring fundamental issues and dilemmas of scale to modern environmental management and governance (Moss and Newig, 2010).

Akhmouch and Clavreul (2016, p. 2) delineated water governance as "encompassing political, institutional and administrative rules, practices, and processes through which decisions are taken and implemented, stakeholders can articulate their interests and have their concerns considered, and decision-makers are held accountable in the management of water resources and the delivery of water services." The OECD definition on water governance offers a broader view as "the set of administrative systems, with a core focus on formal institutions (laws, official policies) and informal institutions (power relations and practices) as well as organizational structures and their efficiency" (Romano and Akhmouch, 2019, p. 2).

The type of challenge to be faced determines the combination of governance modes that define more or less effective approaches. Hybrid forms of governance have been suggested as a possible approach that combines the strengths of different modes and allows combining complementary forces of different actors through a mix of policy instruments such as hierarchical regulation, economic incentives, and voluntary and participatory approaches (Pahl-Wostl, 2019). Effective governance is a normative concept, and purposes need be negotiated among different stakeholders (Young, 2013).

The existing governance models do not reflect the current reality of the water and sanitation sector and even less the increasing complexity of the sector and the need to search for new solutions. It is urgent to clarify what would be the constraints that could be hampering the establishment of proper solutions for the water and sanitation sector, as our analysis proposes on tripartite partnerships. We brought the institutional theory, shaped by different logics, lack of complementarity and regulatory voids in this attempt. We addressed institutional constraints at the national level of water governance that affect the implementation of partnership arrangements (tripartite governance model at partnership level).

We define governance of water and sanitation services as the whole system, with their supporting structures (institutional organization, with networks and hierarchies of interactions between institutes) and the combine content (e.g., policies, laws, norms, plans, programs, and management instruments) and the technical decision-making process that set the scene for management of services and that could encompass the promotion of new approaches such as partnerships.

But what should our focus be when addressing wicked governance problems? The complexity of water and sanitation problems can be addressed by (1) distinguishing the relevant components of the institutional constraints in water and sanitation that define a weak governance setting, (2) applying second-generation wicked problem approaches to assess the degree of "wickedness" of water and sanitation, and (3) considering as a reference collaborative approaches that have proven successful nationally (in Brazil) and, due to the diversity of solutions, in international cooperation programs between developed and developing/underdeveloped countries, that in this study refer in particular to Dutch partnerships programs. From the interviews and document analysis we identify elements of institutional constraints of the local contexts and how they are handled through the local governance level and the role of partnerships in this endeavor. The partnerships contracts involve not only the improvement of the existing physical facilities, but local capacity building through behavioral change and communities' mobilization and also the creation of an enabling environment, by policy development and institutional structure development and strengthening sustainable financing models. Empowering the actors and enabling the environment, it will ensure the continuity of service delivery, as well as the institutional structure to underpin it.

This is not a comparative study and by considering the Dutch example it was possible to obtain categories, from different dimensions for a deeper understanding on how cross-sector social partnerships can be managed across different contexts. Institutional analysis is proposed as an approach for dealing with the complexity of wicked problems. We consider that the institutional logic at a societal level pervades the organizational field and influences the governance of the cross-sector arrangements. According to authors Khanna and Palepu (2010), developed country operators in emerging markets may take the institutional context as given, or they can actively work to change it. In this sense, the efforts of the Dutch partnerships are concentrated, as can be seen in the structuring of programs aimed at different areas as the basic sanitation sector, where one of the common goals is tied to the development of local capacity. This can be seen in the challenges imposed in terms of goals in the TST project (The Special Treat project) project, where we conducted some interviews and which involve enabling and creating institutional environment, by policy development, institutional structure development and financial model, and the development of an educational program to create awareness of the local population and greater awareness in terms of citizenship.

Figure 1 explains the basic framework developed to cover relevant components of an institutional approach to the water and sanitation challenge. The structure of the analysis is based on the premises that a weak institutional setting can be associated with institutional constraints—complementarity, voids, and logics—which in turn aggravates the wickedness of water and sanitation governance problems. Defining institutional constraints makes it possible to discuss how to increase the effectiveness and coherence of the institutional arrangement of the sector and to enable the establishment of the innovative approaches as partnerships to help to mitigate the problems.

Institutional Constraints

Institutional constraints in any governance context stem from the interactions between multiple actors and logics—defined as different standards of conduct (Friedland and Alford, 1991; Thornton et al., 2012). The institutional structure defines the formal and informal rules through regulatory and normative arrangements and compliance mechanisms to control the application of these rules (Djelic and Quack, 2003; Thornton and Ocasio, 2008); from three different societal spheres (state, market, and civil society) and to qualify the tensions that organizations are exposed to when they come together. Some logics are shared and provide the basis for collaboration, whereas others present conflicting perceptions and practices (Jooste and Scott, 2012), generating institutional voids. The interplay of institutional logics can result in (1) institutional complementarity and/or (2) institutional voids.

Institutional Logics

Complementarity logics—synthesizing collaboration and competition—can be achieved when national, regional, or sectoral institutions create more balanced forms of behavior and social coalitions (Hall and Gingerich, 2004). Water and sanitation challenges involve societal complexity, in which all relevant stakeholders are involved. Each stakeholder potentially adds, from their own institutional sphere, a complementary form approach and a logic to deal with the matter (Van Tulder, 2018).

Institutional Complementarity

Through considering the institutional complementarity allowed us to analyze how institutions come together to create new organizational forms, or when they contrast with each other due to certain incompatibilities. Complementarity arises when a particular set of national, regional, or sectoral institutions creates balanced forms of behavior, combined with a broader set of other factors like the influence of public and social coalitions and socioeconomic conditions (Hall and Gingerich, 2004).

Lacking institutional complementarity in the water and sanitation sector can be identified through the plurality of entities, the duplicity and overlapping of the roles, the contradictions in rules and the lack of integration among parts of the system.

Institutional Voids (Gaps)

Institutional voids can arise from the relationship between formal rules and their purposes (regulatory voids), or from the lack of effectiveness in their implementation (enforcement voids). The emergence of voids in emerging markets is distinct, where economic growth usually advances faster than institutional structures. Sustainable development in emerging markets depends on the simultaneous growth of relevant institutions (Rodrigues, 2013). The inability of institutional systems to match different and simultaneous demands results in institutional gaps (Rodrigues, 2013). In the Brazilian water and sanitation sector institutional voids appear due to regulatory ambiguities, inadequate enforcement mechanisms, and weak governance system.

All relevant stakeholders—state, private sector, and civil society—are needed to be involved in innovative approaches, enhancing the effectiveness of institutional arrangements, and leading to mitigation of the problems. One of the central arguments in the analysis of institutional complexity is that the involvement of different actors usually brings conflicting institutional logics, which can lead to contradictory actions by actors (Greenwood et al., 2011). In contrast, second-generation wicked problem theory argues that each stakeholder potentially adds a complementary approach and logic to deal with the matter (Van Tulder and van Mil, 2020) expanding beyond individual capabilities when acting together, emphasizing the requirement of more complex interventions (partnering and multi-stakeholder arrangements) to deal with complexity of the problems (Austin and Seitanidi, 2012).

Water and Sanitation as Wicked Problem?

The literature on wicked problems and systems change distinguishes several relevant dimensions that denote sources of complexity (Waddock et al., 2015; Alford and Head, 2017; McConnell, 2018). Relevant insights that shed further light on the nature of linkages and the dynamics at play can be clustered

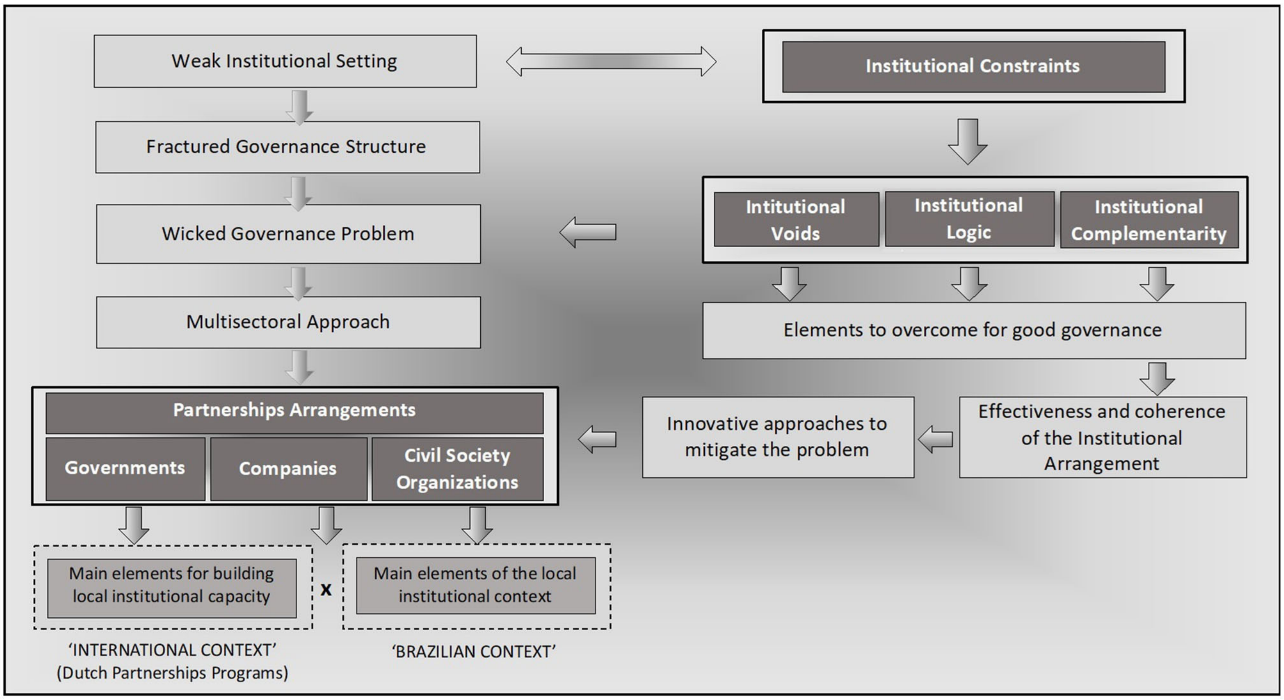

FIGURE 1 | An institutional approach to address weak institutions and wicked problems.

along five general classifications of complexity (Van Tulder and van Mil, 2020).

- ***Structural complexity*** shows how systemic is the problem and is characterized by the existence of a massive number of elements. More dimensions come into play (political, economic, social, legal, technological, and environmental) at different levels (micro, meso, macro).
- ***Generative complexity*** increases when the interconnectedness between elements of the phenomenon intensifies. Interacting elements can unfold in unpredictable ways; cause (root) and effect are not easy to distinguish and tend to sprawl different effects across time ("now" versus "later") and across boundaries ("here" versus "there").
- ***Dynamic complexity*** involves variety in pace and direction in the evolvement of—and between—different elements or parts of the phenomenon. Urgency, momentum, and inertia can exist simultaneously, as can be seen in the discussions on climate action.
- ***Communicative complexity*** is created if information is (a) actively molded to accommodate the interests of some, (b) influenced by the perception, behavior, preferences, emotional connectivity and receptivity of people, (c) is not fully understood and cannot be verified due to a lack of transparency, (d) not reliable and reduces trust in the messenger, or (e) leads to further fragmentation, individualism, and polarization.
- ***Societal complexity*** exists when the number and diversity of stakeholders involved or affected is extensive. This dimension is mirrored by the variety of and differentiation in "logics," interests, perceptions, behaviors, and identities, and by diffused responsibilities related to roles, loci of power, control, means, and spheres of influence.

Approaching Wicked Problems Through Partnerships

Wicked problems cannot be solved by single solutions but require collective and collaborative action in which all three societal spheres are equally represented and are able and willing to work on solutions to the collective interest of all (Van Tulder and Keen, 2018). Partnerships can develop collaborative links to improve the level of integration and coordination between different stakeholders (Lane and Robinson, 2009). Tripartite partnerships (TPPs) can better combine complementary institutional characteristics and logics between public and private, profit and nonprofit, governmental, and non-governmental, to provide public goods (Van Tulder and Pfisterer, 2014; Van Tulder and van Mil, 2020). TTPs offer "collaborative advantages" in involving stakeholders from different societal spheres—state, market, and civil society, based on the assertion that "no single actor has sufficient potential to address the issue unilaterally" (Van Tulder and Pfisterer, 2014, p. 113). TPPs can address wicked problems and sizable institutional voids as they help to minimize the individual failure of the societal sectors involved, instigating a greater level of complementarity and engagement between them. They have been more effective than bilateral arrangements (public-private between governments and business) by developing innovative approaches to mitigate conflicts between societal actors, achieve a fairer distribution, and address common pool dilemmas more effectively.

Wicked problems require pooling and reinforcing the complementary strengths of each sector: (i) governments in developing proper laws and sufficient regulation, (ii) companies in providing goods and services to the population, and (iii) civil society in reaching the neediest part of the population by providing security and stability. Hybrid governance solutions often lead to compromise, weakened accountability, and low transparency, resulting in sub-optimal approaches (Van Tulder and van Mil, 2020). Filling the institutional voids requires societal sectors to bear the responsibilities beyond their primary influences and transcend their individual influence scope (Clarke and Fuller, 2010). This means collaborate and align the compromise on their own longer-term interests. TPPs represent a governance approach capable of tackling perverse problems such as water and sanitation, especially in contexts of weak governance systems.

METHODOLOGY

To explore whether second generation wicked problem theory and related partnering approaches can help identify and address institutional constraint in water and sanitation challenges in Brazil, we engaged in qualitative research using data from semi-structured interviews with key informants from Brazil basic sanitation sector.[1] We interviewed key representatives from the government, private sector companies, and civil society organizations, at national, regional, and local levels and at the partnership level.

We conducted 68 interviews (80 h) with a semi-structured script with managers, consultants, and experts from medium to senior levels (**Table 1**). The interviewees were selected a priori (intentional sample), and we used a snowball process to reach the most senior representatives in the sector. We did 18 preliminary interviews for initial approach (nine in Brazil and nine in the Netherlands) and 50 in-depth interviews for deep research (32 in Brazil and 18 in the Netherlands). Most interviews were face-to-face and took place during the year of 2017 and 2018. All interviews were recorded in English and Portuguese and were transcribed in their original language and translated to English.

As secondary data, we used documentary sources from government and organizations' websites. Partnership data were also made available as contractual documents, reports, official documents, publications on institutional websites. The use of multiple data sources enabled data triangulation. The in-depth data collection involved multiple sources of information, not only interviews and partnerships documents, but also public access documents on partnerships and on the three sectors involved—government, market, and civil society, reducing potential bias.

Partnership level interviews were conducted with people involved in a partnership in Brazil, SISAR Project (Integrated Rural Sanitation System), and a partnership in Ghana, The Special Treat Project (TTP). SISAR project is one of the few solutions in Brazil for water and sanitation supply systems to rural areas in one of the most populated semi-arid regions in Brazil (northeastern, state of Ceará) and in the world (FUNCEME, 2017). It has a configuration that resemble a TPP. SISAR has been operating for over 20 years and has been achieving important results considering the low effectiveness challenge shown in rural water supply systems. The interviews with people from SISAR offered important insights to understand the constraints to the development of the initiatives of rural water supply systems in a developing country context. Three states in Brazil have developed similar solutions to deal with the challenge of providing water supply and sanitation to rural areas. The SISAR (Integrated Rural Sanitation System—SISAR), in Ceará state, the CENTRAL (Central of Community Associations for Maintenance of Water Supply and Sanitation systems), in Bahia state and Piauí—SISAR in the state of Piauí (Castro, 2015). We choose SISAR project due to the results obtained, achieving a higher rate of attendance to the rural population.

The Ghana project was selected by a snowball process initially indicated by an interviewee from the public sector in the Netherlands. After a careful analysis of other nominated projects, we chose the Ghana project because its tripartite partnership structure, with different types of partners, from different societal spheres and also because of the partnership's own objectives, particularly those related to creating an enabling environment, through policy development, institutional arrangement and sector governance. The Special Treat Project (TTP) belongs to the Ghana Wash Window—Sustainable Water Fund (GWWFDW) call 3 2014. The Ghana-Netherlands WASH Program (GNWP) was funded by the Ghanaian and the Dutch government and has RVO (Rijksdienst voor Ondernemend Nederland—The Netherlands Enterprise Agency) as the responsible for its managing the subsidy program (RVO, 2019). The project aims at improving the living conditions of people in small municipalities of Nsawam-Aodoagyiri, Ga Central, and Ga West by treating fecal sludge (Ghana Wash Window, 2014). Interviews and document analysis were used as data source for the research about the Dutch partnerships' initiatives. The documents from the partnerships were mainly about to contractual documents, reports, official documents, publications on institutional websites. Documents were also obtained about other entities involved in these programs, mainly official documents and publications available on institutional websites.

We engaged in a content analysis by considering the actors' interpretation and understanding of the problems. We codified and categorized the respondents' interpretations based in the main aspects of the content.

By conducting a document analysis and a preliminary interview analysis, we identified, a priori, broader categories to be researched, which helped to structure the interview script for deeper follow-up research. A semi-structured script was used to obtain new elements that emerged during the interviews (Patton, 2002). The interview script aimed to obtain participants'

[1] Water and sanitation systems comprise different activities and arrangements that cover the whole cycle to provide the services. In this study, we use the following terms: (i) basic sanitation services as a reference for all water and sewerage services; (ii) water services for all water supply systems, and (iii) sanitation (or sewerage) for all wastewater services.

TABLE 1 | Interviewees by type of organization and management level.

Interviewees/country	Interviewees	Number		Management level
	Total	Organization type		
		CSO/PSO/GOV	Partner-ship	
1. Initial approach				
Brazil	9	9	–	Senior Management; Senior Consultant; Middle Management
Netherlands	9	9	–	Senior Consultant; Senior Researcher; Senior Management; Senior Advisor; Middle Management
Total (1)	18	18	–	
2. Deep research				
Brazil	32	24	8	Senior Consultant; Senior Researcher; Senior Management; Senior Advisor; Middle Management; Consultant; Management Assistant
Netherlands	18	13	5	Senior Consultant; Senior Researcher; Senior Management; Middle Management; Consultant
Total (2)	50	37	13	
TOTAL (1) + (2)	68	55	13	

CSO, Civil Society Organization; PSO, Private Sector Organization; GOV, Government Entity.

perceptions of the main categories: Wicked Problems (sources and nature), Institutional Constraints (complementarities, voids, and logics), and Partnerships Approaches (TPPs). The scripts comprised four main strands: (i) conception of the problems on water and sanitation sector; (ii) main characteristics of the institutional setting of the sector's governance; (iii) partnerships approaches and stakeholder roles and responsibilities; and (iv) trends for partnerships.

In Search of a Benchmark: The Dutch Collaborative Experience

Evidence of the value of TPPs can be found in the Dutch example. Many partnership programs had already been developed by the Dutch Government in underdeveloped and developing countries in the water and sanitation sector. The Netherlands has traditionally been known for its expertise in the water sector and is arguably the most successful delta economy in the world. One-third of the country is below sea level, and it is a world reference regarding the development of water and sanitation technology. The Dutch government relies on partnerships arrangements whenever faces a challenge about water. Most of the advancements and solutions were based on TPPs—a delicate balance between public or semi-public institutions, commercial companies, and civil society. The Dutch Government has also embraced the concept of public-private partnerships (PPPs) since the early 2000s as part of foreign policies linked to sustainable development programs in Africa and Asia. These programs have been particularly successful in weak institutional environments and one of the reasons is the acknowledge importance in adapting to local institutional circumstances and created new (proto) institutions to fill in institutional local voids (Lawrence et al., 2002). Dutch PPPs involve cooperation between government, businesses, civil society organizations (CSOs), and knowledge institutes. The Dutch Ministry of Foreign Affairs designed policies for these partnerships and implemented by the Netherlands Enterprise Agency (RVO). Many WASH (water, sanitation, and hygiene) programs are carried out by CSOs and the Dutch and local government and with the participation of private water companies (GWW, 2018).

The Dutch approach seeks innovative solutions and systemic change with a long-term vision, strengthened by strong ties with local partners and reinforced by Dutch embassies and Dutch entities (PPPLAB-PPPLab Food Water, 2018). The partnership programs focus on structural poverty reduction, sustainable economic growth, and self-capacity growth. They have a premise to build local institutional setting capacity by creating an enabling environment, comprising policy development, institutional development, and sustainable financing models (FDW-Sustainable Water Fund, 2014, 2018; RVO, 2014). Interviews with Dutch representatives were held to identify the main dimensions and to configure the categories of a general theoretical framework to a first interview script. Also, to obtain their experiences in implementing TPPs in developing countries contexts. The interviewees reported two key aspects, considered critical for the continuity of the services provision after the implementation phase of the projects: (i) local capacity building, through training and education in behavioral change and mobilization of local people (communities); (ii) development of a favorable institutional environment to support post-construction local service providers to maintain the services level, and keep the commitment and engagement of public and private local entities.

According to the interviewees, for the partnerships to become a viable solution, a greater institutional support is needed, to guarantee the engagement of all stakeholders in the process (service provision). The Dutch partnerships programs represent an innovative approach aiming at empowering the users target group, encouraging local private sector participation and promoting capacity building at local governments level to improve water management systems. Also, the financial sustainability model of the projects seeks to reduce the dependency on grants from foreign donors (**Table 2**). The construction of an enabling environment is one of the key aspects to ensure the sustainability of partnership arrangements (Amjad et al., 2015). This requires a system of regulation, policies and the development of programs in a comprehensive framework, defining and detailing the roles and responsibilities of all stakeholders (De Palencia and Pérez-Foguet, 2011; Al'Afghani et al., 2019).

The main characteristics of the Dutch partnerships' programs were reported as the necessity of creation of a local environment that incentives community organizations. Partnerships deal better with the institutional constraints by promoting a greater balance between the actors. The Dutch partnerships programs were taken as reference on how to overcome the institutional constraints through partnerships approaches. Lessons can be learned on how to deal with the governance problems that the water sector has been suffering in Brazil.

Although the Dutch example emphasizes the strengths of a considerable part of research regarding partnerships from the global north (Glasbergen, 2011; Van Tulder and Pfisterer, 2014), analyzing the experiences in the global south, like in Brazil, could be an important step toward to the understanding of the impact of institutionalized structures in terms of constraints. Also localizing the theoretical debate that can helped to reflect on the characteristics, limitations and possibilities of the Brazilian water and sanitation sector's governance arrangements and to understand why the partnerships are barely used in the country, even in the face of the wickedness of the sector's problems.

FINDINGS: BRAZILIAN WATER AND SANITATION CHALLENGES

Brazil is the fifth-largest country by territory in the world and sixth largest by population (211 million). The water resources are concentrated in the sparsely populated Northwest (Amazon Basin), while the populous coastal cities are in the less endowed Southeast (São Paulo and Rio de Janeiro states). Brazil is a continental country with huge regional disparities due to geographic conditions, climate zones, income, demographic distribution, and cultural issues. The differences between water and sanitation service indicators among the regions are enormous. The problem is more severe in the north and northeast regions, which are considered the country's poorest areas.

The big challenges for the universalization of the services in Brazil are concentrated in peri-urban areas, slums, and many informal settlements (high density of people) and in rural areas (low density of people). In rural areas the problems can be even greater, like in the northeast and northern regions, where the natural resources are extremely scarce. The provision of services in these vulnerable areas is a complex task that needs the consolidation of formal and informal infrastructures to fulfill the requirements of each territory (Narzetti and Marques, 2021a).

Regulation should set the patterns and norms to guarantee access to quality services for users, ensuring compliance with the standards established by health organizations and preventing the abuse of economic power by stabilizing affordable tariffs to guarantee the sustainability of the provision of services. The regulatory system must ensure the achievement of a universal service level by defining a balance between actors and avoiding discrimination of the vulnerable population (Narzetti and Marques, 2021a). However, it is in these regions of high vulnerability that regulation and public policies are neglected, not suitable to local conditions and even worse, as in the case of Brazil, following regulatory norms to urban areas that generate innumerous voids in the sector management.

Since the PLANASA (National Water and Sanitation Plan) was extinctic in 1980s (end of military government) not much attention was given to sanitation in the country. The federal government enacted the Brazilian Sanitation Law in 2007 (Law 11.445, 2007), known as the basic sanitation regulatory framework, and settled policies for the provision of basic sanitation services. Through the National Sanitation Plan (PLANSAB), the government set the goals to universalize water and sanitation services by 2033. PLANSAB was initial published in 2013 and revised in 2019, when the goals were defined (Narzetti and Marques, 2021a). The current institutional setting places the responsibility of water and sanitation services at the municipal level (Federal Constitution Brazil, 1988, Article 30, V). This setting represented an opportunity to customize policies closer to local circumstances but, on the other hand, raised challenges regarding management capacity at the municipal level. The municipalities can render the services directly or grant these to a public (at the state or municipal level) or private company. The distribution of service providers, according to scope and legal-administrative nature is 93% public sector companies (26% municipal companies and 67% state-owned companies) and 7% private sector companies (SNIS, 2019).

Major water governance reforms in the regulatory and managing system were taking place in 2019–2020, causing tension and insecurity in the sector. A new regulatory framework (NRF) for basic sanitation in Brazil was sanctioned in July 2020 (Law 14.026, 2020) aiming at bringing uniformity to the regulatory system and the universal standardization of basic sanitation services by December 2033. The NRF also increased the incentives for private sector participation to improve the necessary investments for the universal access. The new law brought further attributions to ANA (former National Water Agency, now called National Water and Basic Sanitation Agency), a federal government autarchy linked to the Ministry of Regional Development, in addition to its current scope of managing water resources, adding a challenging task of centralizing, and standardizing at national level the regulation of the sector. Currently, there are ∼73 regulatory agencies operating in the country, 1 national, 34 municipal, 13 inter-municipal and 25 state, however, only 52% of the municipalities are supported by these regulatory agencies (ABAR, 2019; Narzetti and Marques, 2021b). It was attributed to ANA the responsibility for coordinating the regulatory agencies of water and sanitation services at the national government level, being responsible for

TABLE 2 | Dutch partnerships programs strengths: main elements from interviewees statements.

Institutional constraints	Interviews main elements
Governance and Regulatory System (Complementarity); Enforcement (Voids); CSOs Participation (Logics)	Community management system protect by law as an approach for water services delivery in rural areas and small communities.
	Formal definition of the roles of CSOs and communities' organizations in the water services sector; Institutional strength.
Governance and Regulatory System, Integration (Complementarity); Enforcement (Voids); Stakeholders Participation (Logics)	Framed institutional setting to incentivize the innovative approaches as partnerships.
Governance and Regulatory System, Political Engagement (Complementarity); Enforcement (Voids)	Political environment support to the establishment of partnerships programs countrywide (government engagement).
	Create conditions to scaling up a sustainable, urban wash approach in other cities of the country.
Enforcement (Voids); CSOs Empowerment (Logics); Integration (Complementarity)	Local support (managerial and technical) for the local services providers (from federal and state governments).
	Programs for building managerial capacity at local level/communities (social rights, citizenship).
Governance and Regulatory System (Complementarity); Enforcement (Voids)	Establishment of a governance system and accountability; Law enforcement.
	Development of a structure legal and policy frameworks.
CSOs Empowerment (Logics); Integration (Complementarity); Enforcement System (Voids)	Enabling environment through capacity building and organizational development of local entities.
CSOs Empowerment (Logics); Integration (Complementarity)	Enabling environment through behavior change campaigns and awareness at local community level, mobilization to improve sanitation and hygiene.
CSOs Empowerment, Stakeholders Participation (Logics); Governance System and Integration (Complementarity); Enforcement System (Voids)	Enabling environment through network development.
Enforcement (Voids); Governance and Regulatory System (Complementarity); Stakeholders Participation (Logics)	Capacity building of local authorities and other key actors concerned with governance and management of water and sanitation.
Private Sector Participation (Logics); Integration (Complementarity)	Development of a sustainable financial model.

Source: Interviews transcripts.

standardizing their operation and aligning their performance parameters (quality of service, operational and commercial efficiency), also economic regulation matters and the definition of a pattern for the contract's contents nationwide (Narzetti and Marques, 2021b). ANA will carry out decisions on regulators autonomy, distribution of regulatory processes, transparency and predictability in decision making.

The new law also determines that state governments must compose groups of municipalities (called regional blocks) to collectively contract the services and implement municipal and regional sanitation plans, making the contracts also more financially attractive. Although the new law was expected to bring changes to the institutional setting and the regulatory framework of the basic sanitation sector, it seems to promote even more centralization in the state government's hands, also leaving aside a relevant issue, being to increase managerial capacity at the municipal level.

The NRF brought no expected changes for rural basic sanitation and for vulnerable areas, worsening the constraints for the universalization of services since has indicated the responsibility for the universalization in these areas to other policies, such as urbanization, housing, and poverty eradication. There is no specific regulation for the rural sector and vulnerable areas, only the definition of social tariffs and cross subsidies programs, but with no specific regulatory direction for universalization for the poorest.

SISAR—A Brazilian Partnership Approach

Drinking water in rural communities represents one of the biggest challenges for developing countries as they receive little attention and priority from authorities. Its management and governance need to promote interactions among several actors at different administrative levels, and also with the local social actors' participation (Franco-Torres et al., 2021).

Rural areas represent one of the most vulnerable areas regarding to water and sanitation lack of provision in Brazil. The universalization of drinking water in rural areas in Brazil pose a great challenge to the sector due to the large territory and the dispersed allocation of communities in rural zones. According to the 2013 National Household Sample Survey—PNAD (IBGE, 2013) there were ∼31 million inhabitants living in rural areas and isolated communities and only 22% had access to adequate sanitation services. The rest collected water from fountains and wells largely unsuitable for human consumption. Only 34.5% of households in rural areas of Brazil were connected to water supply networks. Numerous communities still depend on supplies by water tank trucks from the nearest reservoir. The interviewees reported the necessity of create a strong enabling institutional environment, that recognizes and gives support to the small communities and their solutions for the provision of services at the local level. It also necessary to increase private sector participation that could provide greater financial and technological sustainability to the projects. SISAR managed to significantly increase rural coverage of clean water to the local population (World Bank-World Bank Group, 2017).

SISAR, is a nonprofit civil society organization, considered one of the few Brazilian partnerships initiatives operating in the sector with a similar configuration of a TPP. It is based on a community management model (users) and has a participatory management model to supply rural communities with drinking water and sanitation facilities in the State of Ceará, in northeast Brazil, considered one of the most vulnerable areas regarding to basic sanitation services provision in the country. SISAR focused on improving the quality of life for the rural population through projects and training on water & sanitation, health, and the environment. In partnership with user groups and affiliated community associations, municipalities, the state water operator (CAGECE), the state government of Ceará, and the German bank KFW and the World Bank.

The SISAR project was developed through the institutional support of CAGECE, that defined the sanitation plans, provided technical and managerial support, and developed a legal framework by engaging the project under the same regulatory entity at the state level. Rural sanitation does not have a specific regulatory system in Brazil, and they have to adapt the rules from the urban areas. The support from a state company provided legitimacy for the partnership, emphasizing the predominance of state logic. City halls exert a strong political influence on local communities, where water bargaining for votes is still a frequent practice. This makes it difficult to strengthen and expand the partnership model to cover 100% of rural areas in the state. SISAR, with support from CAGECE, strives to improve the level of participation of local communities in the system and bring a greater number of municipalities to participate in the partnership.

Institutional Complementarities

Through the interviews it was possible to identify many elements that configure the wickedness of the governance and regulatory system in Brazil. **Table 3** shows main elements regarding to the lack of institutional complementarity between public entities, emphasized by a fragmented (pulverized) governance system, and a decentralized regulatory system and complex to manage. Also reported was the weakness of management at municipal level, which, by Constitution (Federal Constitution Brazil, 1988), is the responsible entity for the management of the services.

We identified four main categories related to the lack of complementarity in the governance and regulatory system: (i) the plurality of the system, (ii) the duplicities and overlaps on the system, (iii) the lack of integration on system, and (iv) the political interferences (**Table 3**). Weighted the roots of the lack of institutional complementarity are composed as follows: 33% Plurality; 24% Lack of Integration; 24% Political Interference; 19% Duplicity and Overlaps. Plurality was the theme most attributed as a cause of lacking complementarity.

The *plurality* of the regulatory system is related to the diversity of entities involved at different levels (national, state and municipal governments, individuals, communities, and companies) and other societal spheres (government, private market, and civil society).

The configuration of the basic sanitation sector in Brazil involves different government levels, creating a complex institutional setting (World Bank-World Bank Group, 2016) and resulting in a fragmented governance structure that gives rise to many voids in the regulatory and enforcement system. Although, under the Constitution (Federal Constitution Brazil, 1988), the entity responsible for water services is the municipalities, for these services to be offered to the population there is a broaden chain of sharing co-responsibilities with different government levels entities participating: (i) the federal level that has the resources, (ii) the state level that operates the water and sanitation systems through contract with the municipalities, and (iii) the municipal level that owns the systems and is responsible for providing the services to the population under their jurisdiction (Federal Constitution Brazil, 1988).

The home for the water and sanitation services sector in Brazil is shared between the Ministry of Regional Development (through SNS—National Secretariat of Sanitation) and the Ministry of Health (through FUNASA—National Health Foundation). SNS serves municipalities with over 50 thousand inhabitants or members of metropolitan regions and integrated development regions (MDR-Ministry of Regional Development, 2020). FUNASA supports rural areas and small municipalities (up to 50 thousand inhabitants).

In Brazil, by law, municipalities are responsible for the regulatory bodies. Regulatory entities can be municipal agencies, state agencies, or a consortium between municipalities. Each municipality (5,570 in total) can create its own regulatory agency or contract an existing one at state or municipal level. The sector is fragmented in 73 regulatory agencies with municipal, intermunicipal, district or state operations and at national level (34 municipal, 13 intermunicipal, 25 state and 1 at national level) (Narzetti and Marques, 2021b). The agencies regulate about 2,906 municipalities or 52% of Brazilian cities (ABAR, 2019). These agencies regulate water supply services as well as sewage collection and treatment, solid waste management and urban drainage, alone or together.

Duplicity and overlaps in regulatory entities' roles and responsibilities lead to a multiplicity of rules and approaches for control and supervision of the services, sometimes inconsistent between each other, causing legal insecurity and mistrust of the system. Each regulatory entity can dictate its own rules, resulting in different and sometimes contradictory criteria among entities. An example given by one of the interviewees was the Brazilian water and sanitation operator of the state of São Paulo—SABESP, who must comply with eight different regulators at state and municipal levels.

The *lack of integration* was associated with the gaps in the macro guidelines at the country's regulatory system at a federal (national) government level, making it difficult to establish an integrated management structure in the sector and leading to a segmented public policy system with many inconsistencies and conflicts between rules. In the NRF this will be one of the main roles of ANA, define a standard of rules at the national level and promoting regulatory uniformity and integration between different entities at different levels (national, state, municipal and intermunicipal).

TABLE 3 | Institutional constraints—institutional complementarities in the governance and regulatory system: categories and main elements.

Categories	Main elements
(i) Plurality	**(i.1) Water management fragmentation**: Fragmented governance system (different entities at Federal, State and Municipal levels); Segmented public policies.
	(i.2) Decentralized regulatory system: Pulverization (spraying) of the regulatory agencies (at state, municipal and municipal consortiums levels). High number of entities involved.
	(i.3) Complex governance and regulatory systems: Different and inconsistent rules applied between regions; Widespread solutions (that do not adapt to specific contexts); Difficulty in decoding and implementing the different rules; Plastered system.
	(i.4) Weak managerial capacity at municipal level: Low legitimacy and weakness at municipal level to act as responsible for the provision of services (Gap of support from a central government entity).
(ii) Duplicity and overlaps	**(ii.1) Roles' overlapping and ambiguities**: Weak structure for definition and distribution of responsibilities; Duplicity in roles; No clear definition about the role of state-owned operators.
	(ii.2) Multiplicity of regulatory rules and conflict of interests: Conflicting regulatory rules; Contradictions in rules; Different regulatory entities at State and Municipal levels; Structure's Redundancy.
	(ii.3) No clear interactions between government entities: Lack of trust at government agencies; Low legitimacy at municipal level to enact and implement the water and sanitation local rules; Space for ambiguities; Supremacy of state operators.
(iii) Lack of integration	**(iii.1) Lack of a central regulatory authority**: Lack of a macro regulatory macro guideline at federal government level; Lack of support from a central government body; Weak integration between regulatory system agencies.
	(iii.2) Regulatory conflicts: Conflicts of interests between state regulators and state operators; Space for opportunistic actions.
	(iii.3) Lack of concertation: Lack of coordination to promote greater articulation between stakeholders; Low interconnections and weak division of responsibilities between main stakeholders and also with stakeholders from other sectors; Poor communication between government agencies; Lack of complementarity.
(iv) Political interference	**(iv.1) Political imbalance**: Different political strength between municipalities and state government entities; Political dependency of municipalities in state-owned water operators; Political power concentrated at state level; Political power at state level creates difficulties for the participation of private sector's companies.
	(iv.2) Political articulation between government spheres: Subordination of municipalities to the state government; Political clientelism; Water as an exchange good, especially on rural and small/peri urban areas.
	(iv.3) Culture of short-termism: Influence of electoral cycles (create difficulties for the implementation of long-term water and sanitation infrastructure projects). Short term election (political) cycles influence; Lack of regulation to avoid political interference; Difficulty in structuring a long-term strategy for longer term investment and initiatives.
	(iv.4) Conflict of interests at government level: State regulatory agencies and state-owned operators; Privileges to state operators.
	(iv.5) Negative effect and misalignments between government entities: Actions motivated by political interests; Protection of public enterprises—mainly state-owned; Political will and priorities from the state government; Lack of criteria to define priorities among municipalities within the state.

Source: Interviews transcripts.

The provision of basic sanitation services, especially by local governments in developing countries, is hampered by *political interference* (Bardhan, 2002). Brazil is characterized by a legacy of political clientelism, an exchange system based on political subordination in trade for providing public services as water and sanitation (Kitschelt and Wilkinson, 2007). Political interference occurs mainly in the political articulation between federal government, state enterprises, and municipalities. The protection of public enterprises, statewide and municipal, overestimate their relationship, tightening the dependence of municipalities on state-owned companies, hampering the participation of private sector organizations.

The small municipalities are more dependent on state-owned companies to provide the services and political alignment is an important criterion for prioritizing among the municipalities to be served (Sampaio and Sampaio, 2020). The political clientelism in Brazil is based on municipalities' political subordination to the state government, and water has become an exchange good (Kitschelt and Wilkinson, 2007). The practice of exchanging water trucks for votes in the elections is observed in many poor regions of the country.

Political rather than business issues influence the performance of state-owned operators. As reported by interviewees, the Brazilian political cycle established the "culture of short-termism." Elections take place (at municipal, state, and federal level) every four years, resulting in discontinuity of the political support to the sector and the lack of management priorities, affecting public service provision.

The state regulatory agencies regulate the operation of the state-owned operators' companies in their jurisdiction, resulting in conflicts of interest and increasing the risk of capturing the agency by state political interests and making private sector participation even more difficult. The situation results in the same government entity at state level working as an operator and regulator.

Institutional Voids

Institutional voids identified by the respondents can be grouped into two categories (**Table 4**): (i) regulatory ambiguities and failures and (ii) the lack of enforcement structure and mechanisms to coordinate the implementation and application of the rules provided by the Sanitation Law (Law 11.445, 2007). Weighted statements of the interviewees regarding the roots of the institutional voids show the following composition: 39% Governance and Regulatory system and 61% Enforcement system.

In Brazil, the *voids in the regulation and governance* system are about the institutional structure of the sector. The basic sanitation sector regulation system is based on the agency model, and the regulators agencies can be at the state or municipal level. It also allows for various institutional arrangements, such as the formation of consortia between states and municipalities, or among municipalities for the regulation of services, or the delegation of this activity to the regulatory agency of another federated entity. In addition, the formats allow combinations of different forms of regulation, as through contract with the presence of a regulatory agency (ABAR, 2019). As reported by interviewees several entities became involved in the regulation function, without standardization and coordination among them, creating performance gaps in the structure. Also reported the low management capacity at the municipal level in dealing with the complexity of the system, increasing their dependency at state-owned companies.

Table 4 presents the interviewees' statements about the institutional voids in the system. The regulatory system lacks a macro-level alignment at the federal level to set a standard of reference norms and guidelines for all agencies operating in the country. There was no single regulatory entity to dictate the basic rules for the sector, resulting in a weak system with different regional/local criteria.

In Brazil, rural areas and small municipalities lack a specific regulatory system and they must attend the general rules for urban areas. Subsidy and tariffs policies are defined at local operators' level, resulting in different standards and criteria throughout the country.

The lack of central coordination result in ambiguity in institutions' roles, generating bias and conflicts of interest. This is the case of the state regulatory agencies, that also regulate the state-owned operators, resulting in privileges and protectionism to them, inhibiting private sector participation.

The new regulatory standards, containing guidelines at national level, for the regulation of public basic sanitation services in Brazil is being prepared by ANA (National Water and Basic Sanitation Agency) until 2022 according to the new legal framework (Law 14.026, 2020).

The roots of *enforcement voids* were reported in the form of insufficient enforcement mechanisms to implement the country's Sanitation Law. Also, the poor coordination among stakeholders aggravates and make more difficult to decode and understand the system. This has led to low legitimacy of the system, low adherence to the rules, and in a high-risk perception over the sector.

The Federal Water and Sanitation Law (Law 11.445, 2007) stated that municipalities must establish fundamental principles and guidelines by developing a local plan for basic sanitation and supervise its implementation. The fragmentation of regulatory agencies, without the alignment of a central institution, leverages the lack of managerial and technical capacity of municipalities to meet the demands of the sector. Only 52% of municipalities have an established regulatory entity (statewide, municipal, or consortia), and only a third has a sanitation plan. This is a serious concern for the sector, as it is legally responsible for the design, implementation, and governance of sanitation policy.

The federal government has allowed countless postponements for the municipalities to deliver the Municipal Basic Sanitation Plans (PMSB), resulting in a loss of credibility of the system. The lack of a government structure to support the municipalities in drafting sanitation plans was one of the biggest pointed bottlenecks of the sanitation sector.

In 2013, the federal government adopted a national plan for basic sanitation (PLANSAB), according to the Water and Sanitation Law (Law 11.445, 2007), aiming for 100% access to water by 2033 and 92% access to sanitation services. The plan required a €100 billion investment over 13 years (2021–2033), an average of €7.7 billion a year, far below the average value achieved in the last decade (€2 billion). The respondents qualified the PLANSAB goals as unrealistic, compromising the legitimacy of the sector. The NRF kept the previous Federal Government's goals to achieve 99% of water access by 2033 for the Brazilian population and 92% to sewage treatment and collection.

Institutional Logics as an Explanation for the Found Patterns?

The interviews reported (i) the state-centered logic and (ii) the low appreciation of civil society as the main cause of the lack of balance between the stakeholders that participate in the water and sanitation sector. **Table 5** presents the categories and the main elements attributed to them. The statements of the interviewees regarding institutional logics presented the composition: 55% State Center Mode and 45% Low Appreciation of Civil Society. The state center mode was the theme most attributed to institutional logics constraints.

The *state-Centered Logic* was reported about the configuration of the sector, mainly on public companies' hands, leading to a low private sector participation and low competitiveness in the sector. The public service providers represent 93% of the companies operating in the sector (26% municipal and 67%). The private sector represents 7% (SNIS, 2019).

In Brazil, the governance of the water and sanitation sector is based on a hierarchical and corporate state logic with an emphasis on a market and commercial decision-making form. The system's operation is centralized in governments companies with a strong link between state-owned enterprises and municipalities, reducing the opportunities for private companies to participate. According to the interviewees this strong centralization strengthens the political articulations between state-owned enterprises, state governments, and municipalities that results in protectionism and privileges to state-owned companies.

The *low appreciation of civil society* was attributed to the lack of citizenship identity, mainly in the poorest layers of the

TABLE 4 | Institutional constraints—institutional voids in the governance and regulatory system: categories and main elements.

Categories	Main elements
(i) Regulatory voids	**(i.1) Lack of a central regulatory authority**: Lack of a central body at a federal level to dictate the basic principles and the macro policies to the sector. Lack of a comprehensive regulatory system.
	(i.2) Ambiguity on the roles of institutions and responsibilities definition: Tragedy of Commons; Legal insecurity providing space for privileges; Conflict of interests at state government level.
	(i.3) Low legitimacy of the system: Gaps between policy system and the enforcement mechanisms.
	(i.4) Lack of standardization on the legal and regulatory framework: Definition of tariffs and subsidy policies at local level (disparities between different regions in the country).
	(i.5) Parts of the system without regulation or with a weak regulation system: Lack of regulation for rural areas and small municipalities.
	(i.6) State-owned companies' protectionism: Privileges for state enterprises (Different contracting regimes between public and private operators).
	(i.7) Low private sector participation: Weak legal structure for incentivizing private sector participation.
	(i.8) Accountability for water and sanitation services at Municipal level: Lack of support to municipalities from a central government body.
(ii) Enforcement voids	**(ii.1) Lack of an enforcement structure to guarantee the application of sector's laws and rules**: Lack of a central body to support and coordinate the implementation; Poor mechanisms for coordination and implementation of Sanitation Law—Lack of enforcement structure to help at municipal level; Ambiguity about government entities responsibilities; Different demands due the regionals diversities; Lack of a subsidy program at a national level considering the regionalities.
	(ii.2) Governance fragmentation: Water and sanitation sector is under coordination of Ministry of Regional Development and Ministry of Health.
	(ii.3) Low Capacity at Municipal level to assume the responsibility: management and regulation systems; Lack of support from federal government level.
	(ii.4) Low legitimacy and adherence to the law system: Unreal and unattainable goals in the National Sanitation Plan; Successive delays in the implementation of the national/municipal sanitation plan; Lack of commitment and efforts to pursue the unattainable goals; Low capacity of the Municipalities to structure the municipal sanitation plans; Discredit with the Sanitation Plan.
	(ii.5) Contract standardization: Different contracting modalities for service operators (different levels of demand between public and private companies).

Source: Interviews transcripts.

TABLE 5 | Institutional constraints—institutional logics: categories and main elements.

Categories	Main elements
(i) State center mode	**(i.1) Government (State) as the main agent**: Public configuration; Political articulation between government entities; Protection of state-owned companies; Water and sanitation sector is organized under public configuration.
	(i.2) Emphasis on public-private relations: Predominance of a managerial logic—market and commercial.
	(i.3) Low private sector participation: 6% of the population served with water services; The structure of the sector does not favor the participation of private sector companies.
	(i.4) Low level of competitiveness in the sector: Sector stagnation.
(ii) Low appreciation of civil society	**(ii.1) Low participation of Civil Society on the sector**: Crisis of social participation in Brazil; Lack of the exercise of citizenship rights.
	(ii.2) Lack of empowerment (capacity gap) of Civil Society: Low political activation and engagement; Low awareness about water and sanitation problems; Lack of institutional strengthening; Need for a higher degree of professionalization.
	(ii.3) Need to build capacity: Lack of knowledge on what directs their actions and interests.
	(ii.4) Lack of civil society identity and citizenship: political forces restrict participation, dominance of political forces; Need to increase civil social engagement; Break the disbelief in civil society.
	(ii.5) Low image of civil society: Difficult image reversal (background facts); Lack of reputation and trust on civil society organizations (disruptive practices); Government bias regarding CSOs.

Source: Interviews transcripts.

population and the low level of trust and reputation on them, when organized on an individual form or around a CSOs due their involvement in disruptive practices in the past. According to the interviewees is urgent for the country to build capacity at local communities' level, being necessary to better understand what directs their actions and what must be done for their organization to take place.

The Sanitation Law (Law 11.445, 2007) is ambiguous about the role of civil society in the water and sanitation sector. The law describes social control as a fundamental requirement, but also defines social participation as optional and with a consultative character.

In this study, civil society comprises private organizations representing local populations, communities, and associations of communities, all nonprofit driven entities engaged in public utility services such as water and sanitation. According to the interviewers, in Brazil, many small communities (low income) are too poor for cost-effective water and sanitation supply and participatory management models to supply the population of rural areas and small communities are virtually nonexistent.

The local population needs to be informed about their rights within the political community they belong (Castro, 2011). According to the respondents, it is necessary to build a sense of citizenship in the country, asserting the population's political rights, reducing their political inertia and domination by political forces, and increasing their awareness in actively participating in the decision-making processes in the sector (SNSA, 2011).

DISCUSSION: ON INSTITUTIONAL CONSTRAINTS AND WICKED PROBLEMS

Water services governance in Brazil involves different government bodies, at federal, at state and at municipal level, pressuring the system on how to integrate and coordinate them. A weak governance system is affecting the whole organizational structure of a sector. The sources of the institutional complexity were analyzed by examining the institutional complementarities, voids and logics that hinder the establishment of more appropriate solutions. Partnerships have key elements to deal with governance complexities, by combining different logics and interests, promoting complementarity and balance between stakeholders.

The plurality in the governance system in Brazil is causing redundancy and roles duplicity, contradictions and incoherence in rules and policies leading to many institutional voids. The main causes of governance complexity are difficult to be diagnosed and we suggest three main causes for the Brazilian water services' sector: (i) as a result of lack of complementarity between different stakeholders, resulting in lack of integration, duplicity, pulverization, mismatch between policy and management and segmented public policies (institutional complementarity); (ii) as a result of a lack of a governance, regulatory and enforcement structure to guarantee the implementation of the law (institutional voids); and (iii) as a result of multiple government bodies, from different levels, crowing the policy landscape with different logics and divergent interests (institutional logics).

Institutional Complementarity

A governance system must provide robust public policies aimed at tangible goals, with a balanced institutional structure for distributing functions and responsibilities among stakeholders, monitoring, and evaluating the whole system (OECD, 2015). A strong governance system is necessary through policy integration and regulatory intervention to promote and align stakeholders. In environments of institutional plurality, governance is vital (Fligstein, 1991).

In Brazil, regulatory bodies are at state, municipal, and municipal consortia levels. There is no central body to dictate the main guidelines to standardize the system, resulting in multiple approaches for the function in different regions, generating contradictory rules. From the regulatory dimension perspective, the main problems include the plurality of the system, the duplication of roles, the contradiction in rules applied in the sector, and the lack of integration among stakeholders. Overlaps of roles and rules resulted in contradictions, making the system complex, and difficult to decode. From a political dimension perspective, problems include political interference and articulation at state-level government.

Institutional integration increases governance capacity to incorporate different perspectives and deal with collaboration as a necessary process to foment the participation of all stakeholders (Lane and Robinson, 2009). Many problems linked to the water and sanitation sector result from a fragmented structure, which lacks institutional integration between entities to enable state and non-state actors to participate in the decision-making. In Brazil, this resulted in many negative effects and misalignments among stakeholders, providing space for opportunistic behaviors as the political interference from the government side.

Institutional Voids

One of the big challenges associated with water and sanitation problems concerns the necessity of strengthening the role of governments as a central authority in the provision of regulation and policies for the sector, reducing the regulatory risks, and ensuring financial sustainability (Cosgrove et al., 2000). The lack of a macro-level alignment at the federal level to set a standard of reference norms and guidelines for the regulatory agencies operating in the country compromises the sector's effectiveness and generates many voids. A sound regulatory system should promote private sector participation following the interests of the public infrastructure sector.

In Brazil, the enforcement mechanisms are insufficient to implement the sanitation law throughout the country. The current mechanisms do not promote the necessary coordination among stakeholders, and the sector lacks a clear definition of responsibilities leading to low legitimacy of the system, low adherence to the law, and a high-risk perception of the sector, causing a great impact on the provision of financial resources for the sector.

The regulatory mechanisms cannot fully exploit the potentialities of all actors involved. There is a weak control system over basic sanitation plans, with ill-defined and unattainable goals. The national sanitation plan (PLANSAB) established unrealistic goals for the universalization of water and sanitation services for 2033, evidencing a huge gap regarding the current level of investments, without a clear plan of actions for the recovery of the investment level and the achievement of the goals, leading to a mistrust on the sector. A stable regulatory oversight system is one of the fundamental reforms needed to provide credibility and ensure a flow of resources to the basic sanitation infrastructure sector in Brazil (World Bank-World Bank Group, 2005).

Institutional Logics

The water and sanitation sector operates in Brazil under a state-centered mode. The main framework has a pre-conceived model with a strong emphasis on the relations between the public and private markets, where managerial logic prevails in the system (market and commercial). There is great emphasis on the political articulation between state enterprises, the federal government, and municipalities. The focus in protecting public enterprises, statewide and municipal, compromise the participation of the private sector companies.

The low representativeness of civil society in the Brazilian sector is aggravated by the concentration of arrangements in the state-based models, making it difficult to develop a more integrated and balanced approach. In the legal framework of sanitation (Law 11.445, 2007), civil society participation is marked by dubiousness, since at the same time, it encourages and limits participatory action.

The social and community empowerment of the population is necessary to create a participative political culture, promoting a more balanced distribution of power. They need to develop the practical community census and to learn the basics of self-organization to promote trust and social inclusion.

Addressing the Wickedness of Brazilian Water and Sanitation Problems

It goes without dispute, that water and sanitation governance problems are complex and full of interconnections that are difficult to prioritize. The wicked problems' theory provides a good support to classify the main elements that not only constitute a problem, but also indicating key points that help to direct the search for more effective approaches to deal with them. We qualify the problems by examining their sources of complexity (Van Tulder, 2018) and although in Brazil they match all the requirements to qualify as wicked problems, we consider three main complexity dimensions—structural, generative and societal, that represent the most prominent ones for classify them as wicked. The other two, dynamic and communicative complexities, can thereby be recognized as relatively universal problems related to the SDGs (Van Tulder and van Mil, 2020). The three dimensions helped us to classify the various elements obtained from the data, making it possible to link them to each one of the dimensions, ordering and qualifying their analysis. The complexity dimensions are presented in **Table 6** and although we focus the discussions on 3 of the 5 dimensions, we present the table with the elements also of the other two—Dynamic and Communicative complexity (**Table 6**).

Structural complexity is related to various dimensions (multi-dimensions) and levels (multi-levels) related to the problems (Van Tulder, 2018). In this study, different roots of structural complexities were identified on regulatory and political dimensions and involving different levels of government bodies and huge regional disparities. They pointed to the failures on the governance system (regulatory structure and policy management) of the Brazilian water sector to deal with them. The responsibility for water and sanitation services is at the municipal level, which sought in state operators to make up for their deficiency in managerial and technical capacity, becoming dependent on them. Also, the involvement of various government bodies levels (municipal, state, and federal) without a clear definition of roles brought complexity and insecurity to the sector's management (**Table 6**).

Generative complexity refers to the multi-causes and multi-symptoms attributed to the problems and their direct and indirect interconnections (Van Tulder, 2018). Water and sanitation problems unfold in unpredictable ways due to the innumerable externalities such as health issues related to the lack of basic sanitation, well-being, environmental security, and development. The main causes of the problems were pointed as fractured governance structure (plurality), the state centered logic, no clear division of responsibilities (direct and indirect) and a weak enforcement system to guarantee the application of the law (**Table 6**).

Societal complexity involves actors (multi-stakeholders) and responsibilities (multi-responsibility) with different values, logics of action, roles, power bases, and understandings, from different societal spheres (Van Tulder, 2018). The water and sanitation sector faces a complex interplay of conflicting stakeholders' interests (logics) at various government levels and with a low interaction of private sector and civil society. The societal complexity of the problems is demonstrated by the number and diversity of stakeholders involved in the sector and their distribution of responsibilities. Coordination among parties does not seem to occur efficiently in Brazil, and a balance between public and private sector participation and civil society participation is lacking. The number of regulatory bodies has resulted in a fragmented system, with no central guidelines for setting a standard of norms and rules. The various ministries and secretariats involved at the federal level result in lack of coordination (**Table 6**).

Brazil's water and sanitation problems are related to governance and regulatory systems failure. This has aggravated its wickedness and compromised the institutional setting capacity to support the necessary innovations. The findings reinforce the idea of wicked problems and imply possible solutions that require joint action of all stakeholders involved. Partnerships represent the organizational fit to better address wicked problems, as they could help fill the gaps by collaborative action. The governance system arrangement is important to promote complementary between stakeholders and form an institutional environment for cross-sector partnerships. The governance structure must add normative strength to a system, which is important in multiple and conflicting institutional logics such as the water and sanitation sector. A weak governance system can lead to a segmented and fragmented normative environment (Skelcher and Smith, 2015).

TABLE 6 | The wickedness of the Brazilian water and sanitation problems: dimensions of complexity.

Structural complexity			
Multi-dimensional	The systemic nature of the problem	Regulatory	Weak regulatory system and law enforcement
		Political	Political cycle influence/short term view ("shortermism")
		Financial	High risk perception/lack of funding/low private sector participation/long term funding profile
		Cultural	Low citizenship awareness/low appreciation of CSOs.
Multi-level	Different levels of impact	Federal × State × Municipal	Impact at development level
		Regionalities	Large regional disparities
Generative complexity			
Multi-cause	Identifiable roots of the problems	Different roots	Fractured governance structure/regulatory voids
			Law system/poor policy system/lack of a comprehensive policy system/enforcement voids
			Low capacity at municipal companies and CSOs
			State centered logic
			Complex distribution of responsibilities
Multi-symptom	Symptoms attributed to the problems	Externalities	Many negative externalities (health, well-being, economy, poverty, equality, others)
Societal complexity			
Multi-stakeholder	Actors involved from different spheres	Many actors involved	Many stakeholders involved/lack of engagement
			Government × Market × Civil society (complexity of the arrangements)
Multi-responsibi-lities	Sources of responsibility	Many sources of responsibility	Lack of Integration Federal × State × Municipal (lack of coordination, lack of concertation)
			Lack of complementarity
			Overlapping of institutions
Dynamic complexity			
Multi-directional	Nature of the interactions and interdependencies	Mechanism of coordination	Interlocking vicious circles, difficult to break Lack of coordination
Multi-paced	Dynamics of the problems	Sector inertia × Sense of urgency	Path dependence: Same trajectory (model) over time Sector's inertia is blocking the viability of new solutions
Communicative complexity			
Multi-frames	Competitive explanations and understandings	Public × Private × Social	Different views and explanations about the problems.
Multi-sources	Transparency and validation of information	Types of service contracts	Inequalities in the process of contracting State-Owned (Program Agreement) and Private Companies (Concession Contract)

Source: Interviews transcripts.

In Search of Solutions? Institutional Constraints and Tripartite Partnerships (TPPs)

Water and sanitation problems are composed of interrelated problems that materialize primarily at the interface between public and private interests. They are wicked problems and require collective action among different sectors of society, governments, the private sector, and civil society. They call for shared responsibilities and complementary actions. The partnering effort provides the most relevant—but not easy approach for the Brazilian water and sanitation sector. TPPs make use of complementary logics from different institutional spheres, raising common issues more effectively for dealing with regulatory and enforcement gaps. TPPs are usually associated with wicked problems, and although they have been operating in many developing countries, as the example of Dutch partnerships programs, they have been barely observed in Brazil.

Through the lenses of institutional constraints, it was possible to analyze the institutional setting of the water and sanitation sector in Brazil and understand the main characteristics that are hampering the establishment of TPPs in the country. The interviewees pointed to the necessity of a higher level of institutional integration in the sector's management. The different reactions of the interviewees to wicked problems also provided practical insights that could be contextualized through the use of institutional constraints theory.

CONCLUSIONS

High fragmentation of the water and sanitation governance structures hamper the establishment of a more integrated management system. In Brazil, we identified some causes of this fragmentation focusing on the institutional constraints linked to the lack of complementarity, conflicting logics, and regulatory voids that configure the wickedness of the problems in the sector, and help to explain the growing deterioration that sector is facing. The configuration of sector's governance in Brazil hampers the establishment of cross sector arrangements (TPPs) as illustrated by the SISAR model, where a great dependence on the public partner compromised the necessary engagement among other stakeholders. In contrast Dutch partnerships initiatives that also operate in relatively weak institutional setting, as the of developing countries, incorporated partnerships approach and were able to (re)construct and capacitate the local institutional environment, through policy and governance system development that integrated local populations and communities and also private sector organizations. We conclude that changing the governance configuration of the water and sanitation sector in Brazil depends mainly on a reformulation of the regulatory and enforcement system that promote a greater balance between the actors (from state, private market and civil society). Although the partnerships arrangements seem the right solution to help to solve the problems a wide scope of changes are needed, on which we provide in this some considerations based on institutional constraints. The development of an enabling environment to support and foster partnerships, by intervention in local capacity, should go through to empower civil society organizations that enable them to take a role and effectively participate in these arrangements. To extend competition between public and private operators and also improve the financing model would be necessary to maintain a strong regulation at a federal level entity to prevent price abuse and ensure the maintenance of quality of service. Partnerships programs in Brazil would focus on certain specific niches of the sector such as rural areas and low-income population areas helping to the achievement of the universalization goals in the services provision.

As a final remark, the new regulatory framework in Brazil for basic sanitation (Law 14.026, 2020) envisages substantial changes in regulation and will encourage competition and privatization of sanitation companies, seeking to attract private investments. The new law, however, leaves numerous gaps in relation to the institutional restrictions that we identified in this study: (i) Political interference; (ii) Lack of support at municipal level; Local managerial capacity building; (iii) Lack of governance, regulation and enforcement system for rural areas and small communities; (iv) Update of the water and sanitation goals (unreal) for 2033; and (v) Low appreciation of civil society, lack of empowerment and low participation level.

Recommendations for Future Research

This study has several limitations, opening the way for future research to complement and expand it. Future research could conduct an in-depth analysis of the Brazilian context and identify the possible routes to operationalize (tripartite) partnerships in the water and sanitation sector. Also, the discussion on what drives the actions of civil society for their organization to take place, what mechanisms could improve social engagement and participation, and lead to the institutionalization of participatory practices. Another recommendation for research would be to analyze the institutional constraints individually—institutional logics, voids, and complementarities. This analyze would enable a deeper discussion on the elements that compound their dimensions and would bring more arguments on how to better approach the wickedness of the water and sanitation problems in Brazil.

AUTHOR'S NOTE

The world is currently facing a water and sanitation crisis that represents a connected challenge for countries: it contains a multitude of causes and consequences, a multitude of actors and interests for which no one-size-fits-all solutions are available. The adequate approach to this type of complex—or wicked-problems is not to search for technological solutions only, but to consider new forms of governance and institutional logics. This study aims to explore the dimensions of institutional complexity on the water sector by investigating the institutional constraints—complementarities, voids, and logics—that make it difficult to discuss and resolve agency, administrative structure, and the relationship between three key institutional spheres of society: state, markets, and civil society. Institutional complexity contributes to fragmentation of water management and characterizes the wickedness of the governance challenge of the water and sanitation sector in Brazil. By looking at a developing country like Brazil, we were able to identify the root institutional and governance causes of uncertainty, while at the same time delineate approaches that could navigate change in less uncertain and ambiguous directions. We argue whether that a tripartite partnership approach can effectively address the wicked water and sanitation problems in Brazil.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Problemscapes and Hybrid Water Security Systems in Central Ethiopia

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Water management has followed a basin unit paradigm for several decades. This framing often inherits a pre-defined spatial and institutional boundary of analysis, one that largely fails to account for various externalities influencing water security beyond the hydrological unit. Moving away from this established basin-scale analysis, we present the concept of problemscapes, a systems approach for understanding how multiple physical and social drivers surrounding (and as part of) contextual water systems determine how they work and, ultimately, the outcomes in terms of the water security they provide. By first discussing the concept of boundaries for water paradigms, we argue that problemscapes can help us understand water security as a more dynamic and hybrid system by adapting these boundaries; enabling a clearer understanding of leverage points, interconnections and possible strategic solutions to longer-term water security challenges. We apply the method for establishing and utilizing a problemscape analysis across the Central Rift Valley, Upper Awash, and Abbay basins, as well as the capital city of Addis Ababa. The interactions in this part of Central Ethiopia are notoriously complex, with sets of critical water management issues at national and international scale, hybrid water security challenges across user communities, and contested management at different scales amidst multiple, and sometimes competing, ideologies. We show that *problemscaping* as an approach could support future planning decisions for long-term water security by enabling a systems perspective to emerge where complexity and connectivity between actors, institutions, and physical and social entities is considered.

Keywords: water security, Ethiopia, problemshed, problemscapes, water resources, water management, Addis Ababa

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INTRODUCTION

In the past few decades, water discourse has been increasingly dominated by water security, gradually eclipsing the more established integrated water resource management (IWRM) paradigm (Gerlak and Mukhtarov, 2015). The roots of the IWRM paradigm go back to the recommendations of the International Water Conferences in the Mar del Plata, 1977, coming into prominence after the United Nations Rio Summit on Environment and Development in 1992 (Mukhtarov, 2008). Post Rio, IWRM became a dominant paradigm of water management (Moss and Newig, 2010), reflected in the policy frameworks of many institutions (e.g., The World Bank, 2009; OECD, 2015; UN Environment, 2018). Water security, however, drawing from some of the foundational IWRM principles began its popular uptake amongst the water resources community at the start of the twenty-first century (Lautze and Manthrithilake, 2012; Varady et al., 2021). These paradigms now compete and complement each other in water management discourse; water security addresses some IWRM *gaps*, but also requires combination with integrative adaptive frameworks (like IWRM) to deliver solutions (Lankford et al., 2013). This paper argues that the main difference between these two paradigms is that water security takes a more focused systems-based approach, attempting to understand the dynamic web of connected relationships and sub-systems responsible for maintaining water system resilience. However, a large hinderance is, that as the water security paradigm continues to develop, it gains density in both breadth and depth. If we are to take the water security paradigm seriously as complementary to water management frameworks, we must manage this complexity conceptually and in action. In simple terms, making thinking on water security more practicable in real-world contexts. This is the aim of the problemscape approach presented in this paper.

A generalized overview of water security is presented in its various popular definitions [e.g., Global Water Partnership, 2000; World Economic Forum, 2011; United Nations University Institute for Water Environment and Health, 2013]. These tend to share largely physical themes such as: the ability to obtain and provide water of adequate use-quality to satisfy demand; ensuring sustainable supplies under changing planetary and social development scenarios; and nourishment and protection of water for both human and environmental development. Links with other resource dependencies have also been explored such as national, climate, food, energy, and human security (Lankford et al., 2013, Chapter 2). Despite these roughly agreed generalized themes, however, what it means to achieve water security has been found to vary across disciplines and geographies (Cook and Bakker, 2012). A likely explanation for this are the sets of global differences in socio-political and cultural contexts surrounding the water systems between countries, regions, communities, and individuals. This is something currently underdeveloped in water security planning, but crucial to action in the decision-making and policy arena. Using the problemscape approach, we reframe water security as a collection of hybrid contextual factors, determined by geographic, social, cultural, institutional, and political realities. Being especially mindful of the fact that these factors are in near constant flux and, are therefore, dynamic and constantly evolving.

The hybrid contextual factors determining water security (and water "securities" given its relative meaning for many different actor-stakeholders) transcend the physical geography of catchments and connect with the political economy and ecology of wider territories, whilst being more embedded within explanatory factors including culture, politics and ideology. This creates a broader understanding of water security that includes non-water insights for water challenges. The problemscape approach that this paper presents aims to conceptualize this hybridized representation of water security, rethinking integration and problem-solving in understanding water secure systems by centering its creation on a wider meaning of context. This emphasizes the inclusion of voice, knowledge, and belief systems of local users in problem-solving and problem boundary creation. Reassociating with a problem-facing operationalization of water management rather than theory-facing and in this sense is an evolution of the problem*sheds* idea, as initially described by Tony Allan in 1998 and reprised by Mollinga et al. (2007).

In this paper, we present our methodology for creating and analyzing problemscapes, deriving a practical method that can (re)present a water security complexity for strategic resource planning, risk mitigation, and tackling uncertainty. We create a problemscape for Central Ethiopia, focusing on elements of the Central Rift Valley, Upper Awash, and Abbay basins, as well as the capital city of Addis Ababa. *Problemscaping* being the process of creating and representing this hybrid water resource complexity and weighting the relative importance of different factors in determining water security (and insecurity) outcomes. The derived problemscape captures hybrid relationships that combine problem articulation and systems analysis, questioning the appropriate boundaries in which we choose to frame water security, accepting that these are more abstract and *fuzzy* in complex interconnected systems. It is important to note that this approach does not arrive at an optimal single solution or recommendation, rather it seeks to define and expand problems within a water security complex (where space is only one dimension) and to enable a deeper and broader understanding of the factors critical to long-term, sustainable water planning—crucially complementary to existing water management initiatives.

BOUNDARIES FOR WATER MANAGEMENT

Hard Boundaries

The dominant unit of water management is a *hard* boundary—the basin boundary. As a prime example of operational water management within this physical boundary, IWRM is widely implemented and has become the guiding factor for institutional development (Jaspers, 2003). The preference of the basin unit is largely due to consideration of the impacts of human interventions on local water budget components, so regional and basin scale analysis are favored (Ponnambalam and Mousavi, 2020). An extension of this focus means that technical management issues (e.g., organizational arrangements, financing, data) are often of greater focus than social issues, with efficiency (e.g., revenue, sectoral capacity, irrigation productivity) in physical and economic terms crowding out issues of equity and justice in human development (Mukhtarov, 2008). This, in turn, leads to questions of the benefits of using the basin boundary, specifically in terms of participation and accountability in water management (Cohen and Davidson, 2015).

Within the basin boundary, indicators of management implementation are however perhaps more easily measured. For example, those outlined by UN Water and the Global Water Partnership (GWP) (2007) and in the GWP Toolbox [Global Water Partnership (GWP), 2022] for IWRM—which are commonly adopted and promoted for workable water management. Even though this is a structured approach where success is relatively identifiable, the ambiguity of indicators that currently contribute to IWRM leave room for weaker interpretations of sustainability, suppression of water needs to land-use decisions, and consistent compromise between socio-economic growth and ecological integrity (Bakker and Morinville, 2013). Additionally, in 2015, the World Water Council observed that the implementation of IWRM was entangled in technical and institutional intricacies rather than embedded in problem solving (World Water Council, 2015). Arguably, these issues are products of IWRM, and its boundaries, being somewhat static and rooted in overly spatial conceptions of the water management problématique through largely ignoring interdependencies that exist outside of the basin unit.

As a summary of this hard boundary, we question its suitability for water security planning and practice. Whilst the traditional basin unit works very well for hydrological processes, other system phenomena rarely fit this mold. Essentially, basin processes do not operate at the same scale as economic or social systems and events occurring within these systems lose relevance or prominence due to unsuitable boundaries. This can be the case for macro representation of water management as well as micro events that take place in the decision-making arena; different dynamic scales between natural and human systems mean interfaces and interactions between the respective sub-systems often misalign and there are therefore asymmetries between water-sheds, problem-sheds, and policy-sheds (Cohen and Davidson, 2015; Ponnambalam and Mousavi, 2020).

Soft Boundaries

In attempting to move away from *hard* physical boundaries, other water management paradigms have orientated themselves around the boundaries in which systems interfering with water management exist rather than the basin unit—these can be understood as *soft* boundaries. The water security paradigm is an example of this; popular boundaries of water security analysis all surpass the basin scale (e.g., nation-state, supernational, and conceptual; Cook and Bakker, 2012) and the focus on interdependencies and relationships between social and physical processes means the paradigm operates within fairly dynamic and flexible water management boundaries. This is especially well-demonstrated in Lankford et al. (2013, Chapter 2) with the concept of a web of water security that employs political ecology in considerations of water independency to other interdependencies such as food, climate, energy, and equity. This concept operates with fluid international boundaries outside of the basin unit, giving an example of the extent to which food security in the UK is dependent on the water insecurity of communities in Peru or the West Bank. Whilst this creates a potentially hazardous boundless water management framing, the complexity of water security boundaries has arguably so far managed to capture the dynamic, systems-nature of the water problématique—perhaps leading to an increase in its popularity (Lautze and Manthrithilake, 2012).

As another example, socio-hydrology (e.g., Sivapalan et al., 2012) reflects interactions of processes by considering the boundaries for the non-stationarity behaviors of the two interlocking systems of socioeconomic phenomena and hydrological processes. This often includes two temporal scales: those concerning governing physical equations representing natural processes (e.g., mass balance equations, supply, demand) and those including socioeconomic systems (e.g., poverty, migration, income, education, gender, equity; Ponnambalam and Mousavi, 2020). Naturally, this means that the system boundaries and scale for socio-hydrological analysis can vary massively between studies. But what is important is that this perspective does not constrict itself to *hard* boundaries, instead it is the selection of suitable boundaries of processes and interactions that are of interest in a socio-hydrological analysis.

The socio-ecological systems (SES) framework takes this one step further by creating a process that is built on the co-evolution of the entanglement of social and ecological systems, including the dependencies that exist between the two. This creates a boundary of sub-systems, interactions, and processes, all existing amongst various levels of spatial, temporal, and disciplinary scale. The SES approach is specifically concerned with four core subsystems—resource systems, resource units, management systems, and users (Ostrom, 2009) with recognized second-level and deeper-level variables. Again, when applied to water resource systems, this demonstrates a water management paradigm that places itself outside of a fixed physical boundary. The concept of hydrosocial territories captures the spatially bound multi-scalar network actively and historically constructed through the interrelationship between society, technology, and water (Boelens et al., 2016). SES focuses on understanding the processes by which a particular hydrosocial territory becomes materialized, usually relying on qualitative methods and post-structuralist theory. Swyngedouw (2009) has highlighted how most socio-ecological conditions are shaped by the tension between social processes and the transformation of natural resources through a series of interlinked technologies, that can only be understood as integrating the political economy and the political ecology perspectives. *Soft* boundaries can therefore provide a very different framing of water security in comparison to *hard* boundaries.

Hybrid Boundaries

Disadvantages of *hard* boundaries for water management have been discussed in literature (e.g., Warner et al., 2014; Cohen and Davidson, 2015). But the basin boundary does, however, hold some analytical advantages being the natural hydrological boundary. Water management therefore must account for a *hybrid* boundary between natural processes and sociological phenomenon; boundaries should account for scales of processes, interactions and problems that transcend the hydrological cycle, especially as the realities of water management occupy a complex space that is hard to navigate through physical hydrological processes alone. This is particularly important for integrating contextual and cultural issues i.e., the problems that imbue human action with specific forms of agency—including building institutions (formal and informal), setting rules, and enforcing (or not) those rules. However, in the decision-making arena these complex *soft* boundaries can be inaccessible to those creating integrated solutions and action with stakeholders. Water security, therefore, requires a rooting in the *hard* on-the-ground realities of water management including characteristics of quantity, quality, and access, amongst others, in order to avoid the danger of boundless analysis.

Moving into a more complex understanding of what the reality of water security is, the problems faced, and how they might be understood and managed, requires conceptual navigation tools. In moving between physical and conceptual, we demand more from stakeholders and decision-makers in terms of understanding and processing. In this sense, the creation of a *hybrid* boundary of water security could help to unpack how context-specific factors are essential to achieving water secure systems, whilst ensuring that management is orientated toward on-the-ground challenges (i.e., problems) as they are experienced by local water users in a way that is accessible to decision-makers. This does not always manifest within the basin boundary, and so the suitable boundary of management is also treated as explorative, dynamic, and flexible. The presented problemscape approach attempts to create this *hybrid* boundary for water management, unifying two complex elements: (i) the conceptualization of water security as an evolution of the more static and physical understandings of water management defined during the IWRM era and very much focused on per capita availability; and (ii) a wider concept of water system management involving processes and intersections between water security elements that go far beyond the basin limits and, indeed, are to some extent limitless, which is central to the intermediary idea of problemsheds, discussed further in the next section.

THE PROBLEMSCAPE

The problemscape concept is related to problemsheds, a navigating device for framing the contextual nature of water knowledge (Mollinga, 2020). Crucially, in the context of water management, problemsheds are a socio-political construct that have multiple physical, geographic, and socially constructed dimensions (Hanasz, 2017). Problemsheds rest on the premise that the basin unit is a narrowly water-centered framing approach to water research and policy. It encourages water research to move away from reductive disciplinary framings in order to capture the multiple dimensions of water problems (Mollinga, 2020) by using issue networks as the unit of analysis rather than the basin; treating boundaries of water management as an open, empirical question instead of a pre-defined spatial, sectoral, and analytical hydrological basin boundary (Mollinga et al., 2007). A decade earlier, Prof Tony Allan used the concept to help explain how governments in the Middle East had ameliorated demand for water to ensure domestic food security through actively importing virtual water on global markets *via* trade in food staples (Allan, 1998).

In transitioning from problem*sheds* to problem*scapes* we explore an evolution where the foundations of the problemshed concepts are developed to make them more accessible in decision-making interactions for water security. The specific purpose of a problemscape being to guide decision makers and stakeholders through the complexity of contextual water management by structuring dynamic and interacting problems within a suitable boundary. Through this process we co-evolve a semi-framework that allows knowledge to be integrated and translated with stakeholders, a process whose importance is stressed by Ostrom (2009). Instead of reframing problemsheds, this requires a reconceptualization of relevance to the decision-making arena, addressing the challenge of development through the structuring of complex water security problems using a systems perspective in which articulations of physical, social, and political systems map the complexity of policy directions, decision-making environments and, ultimately, outcomes for water security. This expands on the influences of water security to management and landscape development and on those involved in this problemscape. The etymology of problemscape reflects this by moving away from the context of hydrology (-sheds) and toward area and structure (-scapes), hence altering the context of the issue network from actors in a policy issue to hybrid water problem structures. Similarly to problemsheds, the problemscape is not concerned with observable rigid relationships but the drivers and networks of problems.

It is hoped that this approach can foster better planning decisions for long-term water management by helping planners and practitioners engage with complexity. By attempting to structure complexity through *problemscaping*, we can offer a strategic perspective for water security on-the-ground. Although the outcomes of this active research approach are still under development and critique, we present the methodology and outcomes currently being developed through research and practice in Central Ethiopia. This provides an insight to how *problemscaping* can be utilized in complex environments, and how it will be carried forward for planning decisions in long-term water security management.

Methodology for Developing Problemscapes

Mollinga (2020) suggests that in beginning to define a problemshed, there are a few methods that can be adopted. The C(I)MO (context, interventions, mechanisms, and outcomes) configuration is one used by Mollinga (2020). C(I)MO explains a specific observed outcome, acknowledging that the same outcome can be created by multiple mechanisms. This is similar to the logic used in the Institutional Analysis and Development (IAD) framework (Ostrom et al., 2017) and DPSIR (driver, pressure, state, impact, response; Sun et al., 2016) method. C(I)MO, IAD, and DPSIR are all analysis tools that focus on bidirectional linear methods of contextual assessment, cumulative responsible mechanisms and drivers, and observed resultant phenomenon, as well as essentiality and causality in system interactions. The problemscape integrates some aspects of these various context-mechanism-outcome approaches; however, it differs by adopting a system approach to establishing the issue network as well as the eventual output. The problemscape methodology focuses on a process that places analysis in the center of the problemscape and works outwards. Through investigation of problem framing and constituent sub-system interactions, the process is inherently explorative for building problem situational analysis.

The problemscape methodology consists of three distinct phases (see **Figure 1**), put simply, firstly building the problem—and then the—scape. With the first two phases being concerned

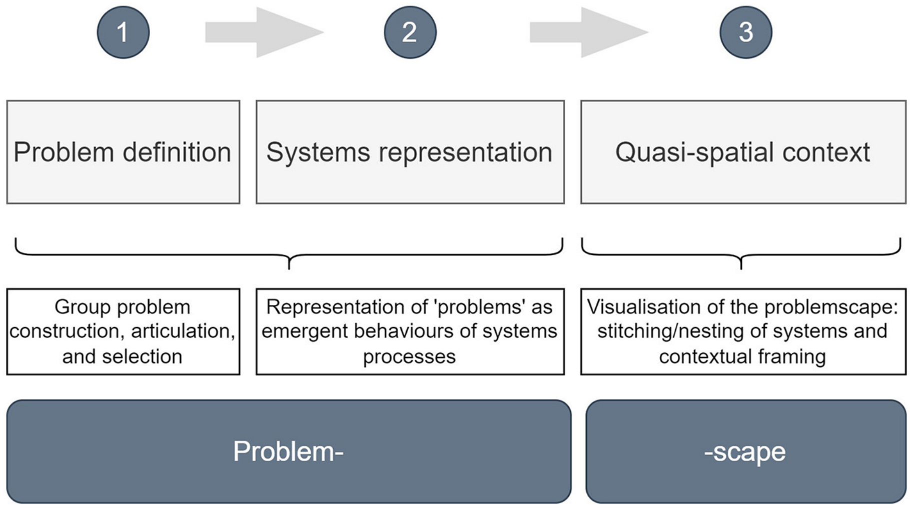

FIGURE 1 | The problemscape methodology.

with the problematization of water security, and the last phase introducing a quasi-spatial context to the analysis. The first phase, situational analysis, is conducted through problem definition, where problems can be derived from physical, social, or ideological processes or a combination of these with other factors. The second phase describes these problems as resultant emergent behaviors of problem components and sub-systems, essentially how and why these problems exist. Describing problems as emergent behaviors of their components and sub-systems is a way to represent causality and interconnectedness within the problemscape as a depiction of a structured reality. The third phase places these interactions into an area of quasi-spatial relevance in which real decision making takes place. This creates a problemscape with both a conceptual and physical transient boundary, which is proposed to help decision makers and stakeholders' understanding of vulnerability and risk associated with uncertainties as well as provide for social and managerial insights. The creation of the problemscape hybrid boundary, or perhaps better referred to as the acknowledgment of the fluid nature of the boundary, is a key outcome for *problemscaping*—the recognition of the state of the boundary itself being an important insight for planners and practitioners in the water security environment.

PROBLEMSCAPES EXAMPLE: CENTRAL ETHIOPIAN COMPLEX (CEC)

The area selected to represent the hybrid water security complex with the problemscape approach in this paper is Central Ethiopia and especially interactions between the capital city of Addis Ababa (also referred to as "Addis" in this paper) and three major surrounding basins: the Central Rift Valley (CRV), Upper Awash, and Abbay (see **Figure 2**). These foundational problemscape components (essentially where the outcomes for water security lie for different users—including the environment) are the roots of an entangled set of issue networks whose interactions in this area of Ethiopia are complex and increasingly political. There are overlapping water security themes between these such as land degradation, increasing agricultural activity, shrinking arable land, diminishing surface water resources, and rapid urbanization. Although the intensity of these themes varies between areas, each basin additionally has its own specific context and problems for water security. There are many ways in which the problemscape development could expand outwards from such a unit to embrace more complex water dimensions for Ethiopia, for instance at national and regional scale and suitable boundary conceptualization for a variety of stakeholders. However, in using these four areas, the water

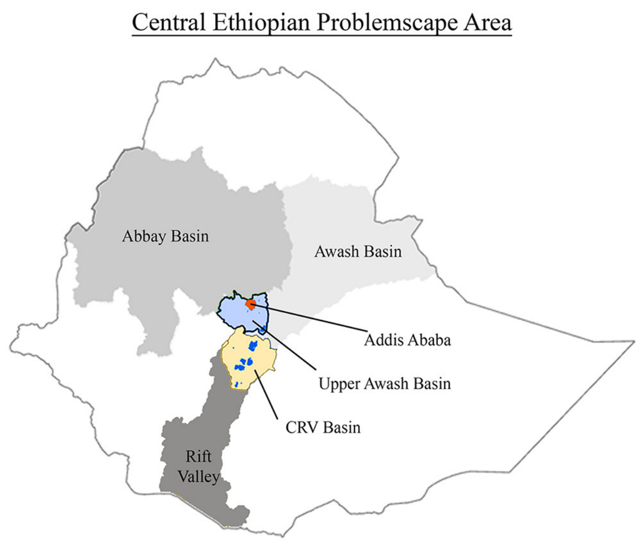

FIGURE 2 | The Central Ethiopian Complex (CEC) area.

management decisions for the Central Ethiopian Complex (CEC) can be mapped in the majority under consideration of the problemscape. With regard to hybrid water security, there are some hydrological and political-ecological connections in this area of Ethiopia which makes the idea of sharing water problems between areas obvious. However, risk is also shared, and in some cases intensified, when connections are seen outside of the hydrological influences and the aim of the problemscape is to demonstrate these and present them in a way that shows the interconnectedness of water security for the CEC. The problemscape of this area is therefore imagined as the cumulative areas of connected problems associated with the influence of water security on other systems, such as the economy, livelihoods, and environment, and hence these foundational areas form a vast network of interconnected actors and events as the problemscape develops.

The problematization of water security in the CEC is the first step in defining the problemscape, and is formed through problem definition and situational analysis, integrated with emergent behavior systems construction. A problem is understood systemically in this context; a product of actor interaction that produces a gap where the reality, or future reality, of a system is different to the desired state of a system, described by Checkland (1981) as "a sense of mismatch" of actuality. However, this "gap" is a socio-political perception by the problem owner between a situation and a normative principle or objective (Thissen, 2012), meaning that the agenda of the problem owner forms the establishment and recognition of the problem. It is important to recognize this characteristic of problem definition for this iteration of the problemscape. The water security agenda of the authors introduces a subjectivity to the system, that renders it only one of many multiple realties of the problemscape for the CEC.

Water security problems were co-developed with various experts in water security fields from the International Water Management Institute (IWMI) and the Water Land Resource Centre (WLRC), Addis Ababa, and attempt to provide the empirical observations of the problemscape. It is suggested that a more in-depth problemscape representation could be obtained with a more diverse range of problem identifiers, say stakeholder focus groups. The identified problems are listed below, these are relevant to the contextual assessment of water security in this area and so are chosen on this basis. The situational analysis that accompanies these problems follows a narrative approach. Through understanding the internal and external factors that contribute to the water problem discourse, we identify human and non-human actors involved as well as their impact to water security. The narrative approach is built on three cross-cutting processes based on the empirical water security observations; Addis Ababa's Urbanization, Agricultural and Land-Use Change, and Management and Organization.

CEC empirical water security observations:

1. **Water supply to Addis**—under stress due to expanding population demand, industrial development and drawdown of aquifers combined with highly variable precipitation between years.
2. **Water quality in the Upper Awash/Akaki basin**—essentially the Akaki-Upper Awash is Addis Ababa's major drainage system. Unregulated usage, return flows, and poorly managed sewerage leads to serious levels of contaminants from both domestic and industrial usage. Downstream, these same waters are used for productive purposes and foods irrigated by these waters are then consumed back in Addis and surrounding towns.
3. **Urbanization**—rapid and presenting added complexity due to the politics of urban expansion in and around Addis (including the impact of inner-city urban renewal on population movements to the periphery) and the encroachment of housing into farming areas.
4. **Land degradation**—national and international demand for food and wood fuel is causing mass deforestation to provide products and farmland. This is leading to severe land degradation in the form of soil erosion, soil infertility, and gully formation and becoming contributing factors in flash flooding and sediment transportation to surrounding lakes and reservoirs. Demand for wood (wood fuel and timber) has also led to eucalyptus plantations substituting for food production by farmers in key areas within the Abbay basin.
5. **Agricultural activity**—agriculture is the economic backbone of Ethiopia and is responding to increasing demand from a growing national and international population. As well as this, agriculture in the CEC is largely rain-fed and dependent particular seasonal patterns. Favorable soils and water availability from perennial sources has also caused agribusiness to expand rapidly in parts of the CRV. This is also due to proximity to export markets *via* Bole Airport and Djibouti Port.
6. **Flood risk**—the urbanization of Addis has created large areas of impermeable land in the city, which has increased the vulnerability of Addis to urban flooding from both flash and fluvial floods.
7. **Management and organizational structure**—the challenges of management in and around Addis Ababa are related to the expansion in size of the city's population, its complexion, the political system of administrative structures, the overlapping mandates between federal, city, and regional governments (some of which are in the same place), and the economic gravitational pull of the city and its hinterland.
8. **Competing water users**—the multiple water uses along with a diverse set of water users create competitions over resource use systems. The management situation in the CEC, in combination with water scarcity issues, has created tension, competition, and dysfunction between various water users and sectors in the area.

Addis Ababa's Urbanization

Arguably one of the biggest actors in this problemscape is Addis Ababa, the capital city of Ethiopia situated in the Upper Awash basin. In 2018, Addis was estimated to have a population of just over seven million people [United Nations Department of Economic and Social Affairs (DESA) Population Division, 2019] and is one of the fastest growing sub-mega cities in sub-Saharan

Africa [Addis Ababa City Planning Project Office (AACPPO), 2017]. Addis and its hinterland are not only the economic and political centre of Ethiopia, but also have a geographic spatial advantage being situated in the middle of the country and on the periphery of the major transport corridor to the seaport of Djibouti *via* the Awash Valley (northern part of the Rift Valley). This has caused Addis to become a socio-political arena as well as socio-economic magnet, attracting people from across the country as well as within the region itself (Terfa et al., 2019).

Addis' growing population and economic activity mean that the city's urban expansion has been significant over the past decade and large-scale housing development has boomed (Kifle Arsiso et al., 2017) as well as industry presence; 40% of large and medium scale manufacturing industries are located in Addis and its vicinity (Yohannes and Elias, 2017). This socio-economic growth—driven by both national hegemonic economic activity and important international and regional economic dimensions, not least because of the city's hosting status for the African Union—has driven an increase in water demand to service urbanization in the capital. According to Terfa et al. (2019) from 2005 to 2017 the urban area in Addis increased by ~36%. Furthermore, industrial and urban development have replaced green spaces with a covering of impermeable areas in the city (Abo-El-Wafa et al., 2018). This urbanization increases the impermeable surface area in Addis leading to rapid runoff generation and creating new exposure to risks as economic activities (including housing) expand to flood prone areas. Hence, adding to the susceptibility of Addis to extreme rainfall events, being vulnerable on two fronts of both fluvial and flash flooding due to poor drainage networks and upstream activity (Birhanu et al., 2016).

Another consequence of the rise in the urban population, is that water demand in Addis is predicted to increase from 110 million m^3 in 2012 to 233 million m^3 in 2025 (Kifle Arsiso et al., 2017). Current water supply comes from three water supply systems; the Legedadi and Dire reservoirs, the Gefersa reservoir, and the Akaki groundwater aquifer (Kifle Arsiso et al., 2017; **Figure 3**). However, the available surface water from these reservoirs is reducing largely due to sedimentation. The Legedadi was constructed 51 years ago and has lost 8.2% of its storage by sedimentation over 40 years (Orman, 2011). Recently, the main supply for Addis has shifted toward groundwater abstraction due to increasing demand from rising population and growing industries. This has resulted in the contribution of groundwater as a water source for the city increasing from 20 to 67% over the last 15 years, resulting in a predicted future decline in groundwater level of more than 20 m in the Akaki sub-basin aquifer of the Upper Awash (Birhanu et al., 2021). Furthermore, industries are reportedly resorting to ground water abstraction because water supply by the responsible government agency is inadequate. Groundwater has also been developed within the surrounding river basin, e.g., the Akaki river basin for city water supply (part of the Upper Awash). The shift from surface water to groundwater has also been speculated to have socio-political backing based on a set of complex land ownership issues, the historical roots of which are embedded in the national politics of identity. There are delays in the construction of planned surface reservoirs since all of them are situated outside of Addis, while shifting to majority groundwater abstraction means the water supply source is more diversified and relies less on surface waters originating in the Oromia Regional State and more from water sources within the city's boundaries.

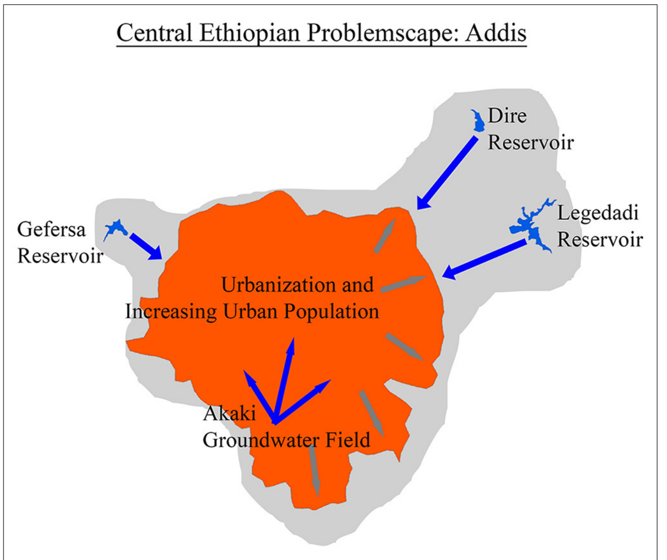

FIGURE 3 | Addis Ababa problemscape.

As well as contributing to the rise in water demand, and without significant increase in surface water production, the increasing urbanization, industrialization, and population acts in combination with the city's poor sanitation to cause severe pollution problems for the rivers that run through the city, namely tributaries to the Akaki river. The impact has been exacerbated by weak institutions and uncoordinated management structures that are unable to deal adequately with the challenges. Improper waste management practices in the city along with poor drainage infrastructure contribute to the disposal of waste in the Akaki river and the surrounding agricultural fields, thereby affecting the uses of the river and jeopardizing agricultural activities. Many factories have been built around the Akaki river, and contaminant-laden wastewater released from these factories also adversely affects the river water.

In rural areas where people use the river for different purposes, including agriculture and livestock, waste coming from the city is seen as a big challenge. The degradation of water quality of the Akaki river by both industrial and municipal waste from Addis has led it to become the most polluted river system in the country (Desalegn et al., 2006; Yohannes and Elias, 2017; Mersha et al., 2018). This high level of pollution is a result of discharging untreated industrial wastewater effluents into nearby waterways along with the widespread use of pit latrines in high population density areas due to only 6.5% of the population in the city being connected to the municipality-managed centralized sewage system [Addis Ababa City Planning Project Office (AACPPO), 2017]. Furthermore, the pollution from Addis has downstream consequences (see **Figure 4**). The Akaki passes through the

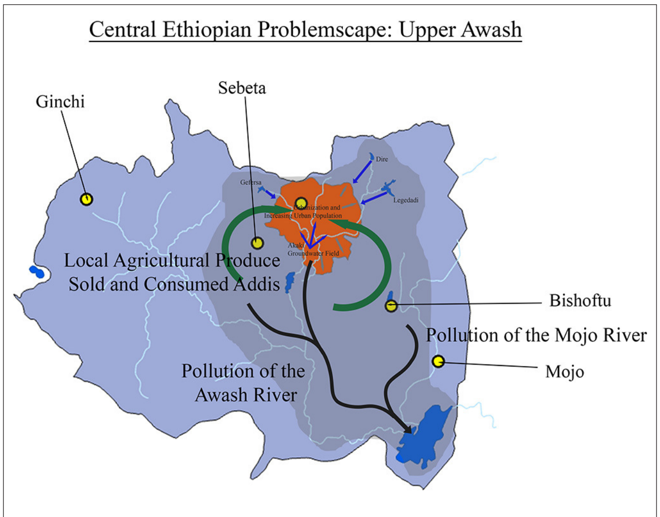

FIGURE 4 | Upper Awash problemscape.

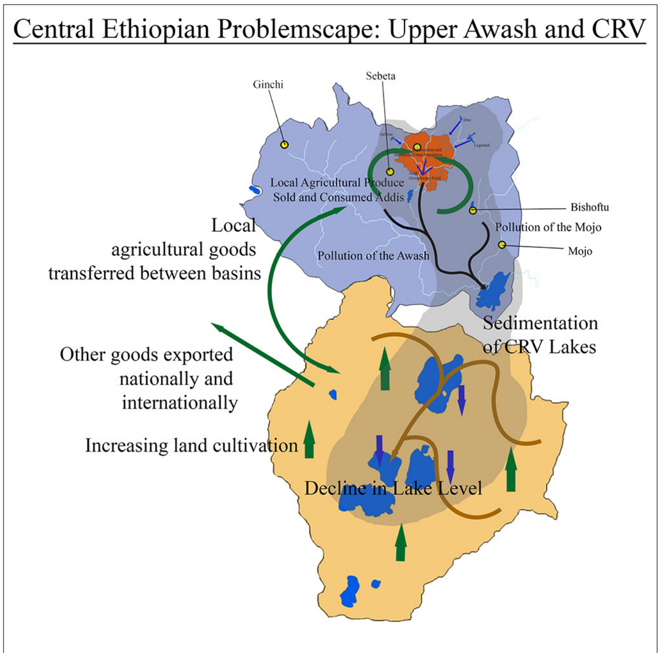

FIGURE 5 | Upper Awash and CRV problemscape.

downstream Aba Samuel reservoir before meeting the Awash river and consequently Lake Koka, where there is some treatment capability (in terms of dilution) but not at a high level. Therefore, Addis (through the Akaki) pollutes the Awash and surrounding towns. In addition to this, the polluted water is often used for livestock and crop growth, meaning the resulting consumables are also contaminated. For urban irrigation sites in Akaki, a study by Woldetsadik et al. (2017) found that "compared with the WHO recommendations and international standards, the fecal coliform and helminth eggs levels in irrigation water and lettuce samples exceeded the recommended levels." These products are then often sold in Addis and surrounding Upper Awash areas (e.g., Bishoftu), a cycle contributing to major health hazards in Addis Ababa and the surrounding regions [Addis Ababa City Planning Project Office (AACPPO), 2017]. As well as Addis, there are four other notable cities in the Upper Awash basin: Bishoftu, Mojo, Ginchi, and Sebeta. With Bishoftu and Mojo being part of the Mojo (Modjo) river system, not Awash. In addition to the non-point pollution from Addis to the Awash river system, the pollution of the Awash and Mojo rivers (both contributing to Lake Koka) are added to by the surrounding urban areas, and agricultural and industrial practices in the region (Tessema et al., 2020).

Agriculture and Land-Use Change

Agriculture has become Ethiopia's primary economic backbone, contributing to around 35% of its GDP (World Bank, 2020). This is molded by national and international market drivers from increasing demand, but most notably the agricultural potential of the CEC has been required to expand to support a growing population. Increases in agricultural activity have resulted in rapid land-use changes birthing a range of issues: land degradation, shrinking landholding, increased irrigation (water use), and pollution of lakes, rivers, and soil. This, moreover, creates competition for land and water amongst various sectors, exacerbated by water scarcity pressures on groundwater and surface water resources. Crucially, the agricultural activities in the CEC connect many regions economically, and semi-hydrologically, through virtual water trade in products. These relationships are shown in **Figure 5**.

The CRV basin, sharing the Ziquala mountain belt water-divide with the Upper Awash (Berhanu and Bisrat, 2020), is a closed basin with four major lakes (Ziway, Abyata, Langanao, Shalla). The basin is experiencing intensive agricultural development, mainly for cereals and livestock, alongside increasing population and industry presence (Getnet et al., 2014; Bekele et al., 2018). In the CRV basin, 85% of the population rely on smallholder mixed rain-fed subsistence farming (Bekele et al., 2018) making it extremely economically vulnerable to spatial and temporal shifts in rainfall patterns. As well as this, lakes in the CRV are experiencing sedimentation as a result of land degradation from large-scale land-use change; dependency of wood fuel and increased agricultural activity has resulted in loss of vegetation cover, deforestation (Garedew et al., 2009), and degradation of surrounding rural areas. Sediment is therefore being transported by heavy rain and building up in CRV lakes, also making lowland areas more susceptible to flash flooding. Lake Ziway is an example of this, whereby sedimentation (Desta et al., 2017), evaporation, and abstraction for irrigation and industry (Kebede et al., 1994; Pascual-Ferrer et al., 2014) have reduced the flow of the lake to subsequent downstream lakes. In particular Lake Abayata, as the terminal lake in the closed basin, has suffered as a result and reduced in size by more than 30% between 2000 and 2019 (Donauer et al., 2020). The reduction in lake capacity has an impact on local water resources for many sectors and the huge amount of water loss exacerbates water conflicts amongst diverse users.

As the terminal lake, Abayata suffers various water quality issues, affecting fish production in particular. Deteriorating water quality is also affecting the soil and irrigated vegetables around Lake Ziway. The quality of the lake is mainly being compromised by the intensive use of fertilizers for large- and small-scale irrigation practices in its watershed. The water used for irrigation shows high levels of alkalinity and sodium concentrations that damage agricultural land (Pascual-Ferrer et al., 2014). Among the large-scale irrigation users, the floricultures around Lake Ziway are major users of fertilizers (Hailesilassie and Tegaye, 2019). In addition to the anthropogenic sources of pollution, the basin is also characterized by low water quality because of its geologic formation. For instance, most of the rocky terrain in the CRV is of volcanic origin, leading to fluoride concentrations in groundwater sources of up to 200 mg/l in lower regions [the safe level is below 1.5 mg/l for drinking water; World Health Organisation (WHO), 2017]. Both water quality deterioration and physical water loss from the lakes in the CRV are contributing to water scarcity and creating heightened competition for water between users and sectors in the CRV, such as tourism, agriculture, and fishing (Hengsdijk et al., 2009).

This intensive agriculture is also seen in the Abbay basin, responsible for 40% of Ethiopia's agricultural products (Erkossa et al., 2014). The majority of the population in the Abbay basin crucially depend on rain-fed agriculture as a main livelihood (Mengistu et al., 2021). Additionally, poor land-use management due to increasing agriculture and deforestation has caused severe land degradation in the form of soil erosion, soil infertility, and gully formation (Yalew et al., 2016). As well as this, the basin is extremely vulnerable to climate change impacts such as increased warming and changes to temporal and spatial distribution of rainfall (Mengistu et al., 2021). The Abbay basin suffers similar issues to the CRV, with Lake Tana being subject to sedimentation from upstream land degradation, causing a reduction in capacity and altering the lake ecosystem (Wondie, 2010). There are also rapid changes in the landscape surrounding the basin as eucalyptus plantations abound in rural areas, with farmers switching to a more lucrative and reliable agro-forestry crop. However, unlike the CRV, the Abbay basin shares a hydrological connection with the Upper Awash; a hydraulic connection between the aquifer system of the Upper Awash basin and the two adjacent southern left-bank sub-basins of the Abbay (Mugher and Jema sub-basins; Berehanu et al., 2017). The role of the Abbay in this problemscape is mainly one of presence and influence. Considering the entirety of this basin introduces the transboundary politics of the Abbay, which is not covered in the decision-making conclusions of this paper.

Management and Organization

The aforementioned issues are all contained within the space of management and organization, the largest overarching issue network of the CEC. In general, water management, organizational structure, and laws, form an unclear landscape of responsibility and action for water security issues in the CEC. This is largely due to various political ideologies and conflicting political-economic and social frameworks; historical management regimes (e.g., modernization vs. socialist vs. state led free market) have created a management structure with conflicting ideologies that are present to this day. The various ideologies experienced by Ethiopia, and therefore the water sector, over the past several decades have created a complicated management system at national level for the management of water.

The political history of this area will not be covered in depth by this analysis. However, it is important to note some key ideological shifts and events in the last 100 years that have enabled the creation of the governance structure that exists now. Between the years of 1957–1973, national policy in Ethiopia was focused on economic modernization and the establishment of private operators. However, low institutional capacity meant that the water sector was generally underdeveloped with water supply to both rural and urban areas being insufficient. As well as this, land use began to shift toward irrigated agriculture for high value crops for export, industry, and urban consumption, hence beginning to introduce multiple water users and the potential for competing demand. During this regime, the basis of the economy—land—was under a private tenure system run by government and favored exploitative land institutions. The political economic outlook then shifted from a market-based economy to socialist oriented economic development policy for the years 1974–1991, the Derg era of Ethiopia. This shift in national policy meant that progress moved toward regional development and equity including self-sufficient production. The major political economic reform during this time is land nationalization whereby the State controlled the system of land tenure as well as further major expansion of commercial rain-fed and irrigation agriculture. Large scale state farms and state-controlled industries and economic sectors were important features of the regime. Alongside this, urban areas were growing and population increasing. However, because of intensive land use change, surrounding areas saw compounded land degradation and conflict between large irrigation schemes, small holders, and pastoralists. The years following 1991 to present have seen an ideological shift again, this time toward pro-market orientated policy within pragmatic frameworks of political economy, political ecology, power relations, and intersectionality. However, land has still remained under state control. National policy works in a state-led free market to accelerate economic growth and equity. For the water sector, this means that numerous narratives now exist as well as multiple complex institutional arrangements with unclear boundaries and unclear power relations. The pressure on water resources has also increased dramatically, with large increases in population and urbanization as well as an increased water scarcity and competition in some regions. This has created heightened tensions between water users such as the agricultural, industrial, municipal, and rural sectors. Additionally, irrigation on both the large and small scale is still increasing with a varied level of regulation.

Most importantly, after 1991, Ethiopia adopted an ethnic federal management system, meaning that the country is

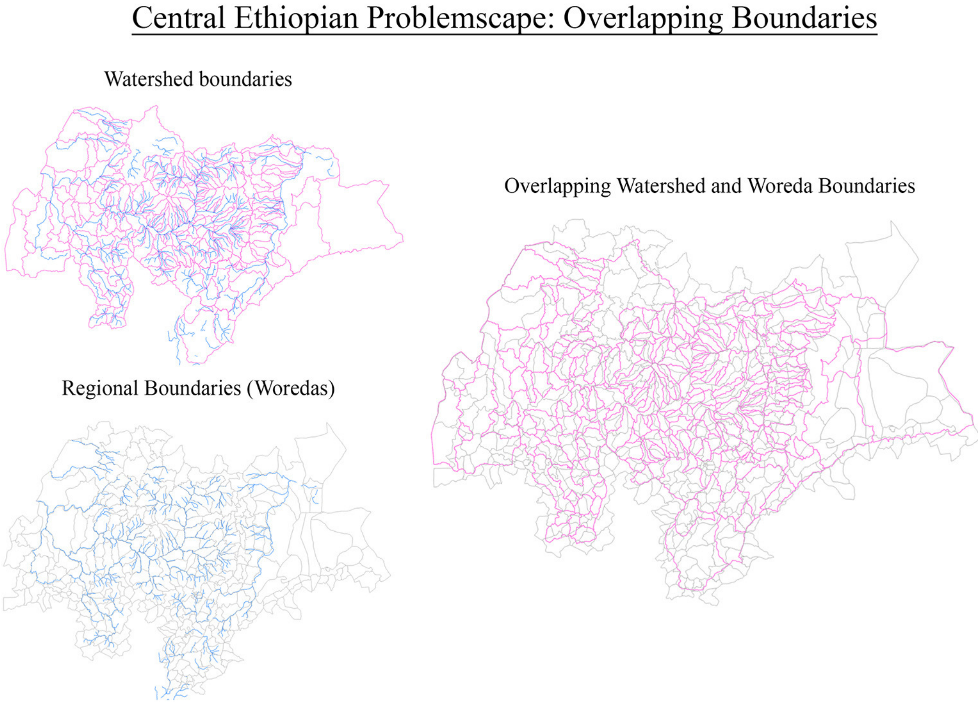

FIGURE 6 | Overlapping boundaries.

split into 10 regional states with Addis Ababa being one of two autonomous city administrations. Development efforts focused on the Woreda level, although control was continually centralized *via* the EPRDF—now prosperity party—coalition of parties system. Ethnic regions were given a measure of self-rule authority and the right to develop individual socio-economic development plans (Bekele and Kjosavik, 2016). The new ethnic federal boundaries cross-cut existing physical watershed boundaries promoting regionalism and localism by creating conflicting boundaries between watersheds, administration, and hydrology (shown in **Figure 6**). For water management this structure means that whilst the region follows a federal structure where federal bodies make laws (e.g., the ministry of water, irrigation, and energy), local bodies can also make laws (e.g., basin development authority). The local bodies' role and power are therefore confused with the mandates of the government. As an example, permits for investors often duplicate in different bodies, but some have more requirements than others meaning the investor is likely to go for the "easy" option to obtaining the necessary permit creating a power rift between various governing bodies. In the cases of large agriculture practices, permitting for water use and regulation is monitored by local mandate, albeit not strictly; however, for small holder farmers regulation is carried out less, and so abstraction from groundwater, lakes, and rivers is unmonitored. Collectively, these many small holdings generate a big impact on the water security of an area and the governance structure means competing mandates impede proper distribution of responsibility and accountability.

Visualizing the Problemscape

The narrative approach to analyzing Addis Ababa's Urbanization, Agricultural, and Land-Use Change, and Management and Organization provides some idea of connectivity and influence within the CEC. However, visualizing the problemscape is also important for demonstrating the spread of drivers and influences as well as interconnectedness between issues; being a graphical depiction of a structured reality. This is one of the main evolutions from the problemsheds concept, taking the conceptual representation of issue networks into an area of action that can be understood by decision makers and stakeholders. Furthering this as a tool for discussion with decision-makers and stakeholders, this visual depiction proves valuable in unlocking new ways of thinking about management and management problems, and also understanding challenges from many actor-based perspectives. However, an issue arises in the transient nature of the problemscape space. **Figures 3–5** depict the problemscape in an area of quasi-spatial relevance which aids spatial understanding, but not necessarily an understanding of the overlapping problems and the problemscape. Furthermore, we wish to move away from physical confinements that limit the transient nature of the problemscape. It is important, therefore, to recognize that spatial reference changes within the boundaries of various processes. In this sense, the problemscape is a transient area that has a variety of framings under fluctuating timelines. Whilst it may appear that some areas of the problemscape are fixed, this will only be due to temporal relativity where processes take place on varying time frames, i.e., the disparity between environmental, political, and hydrological cycles.

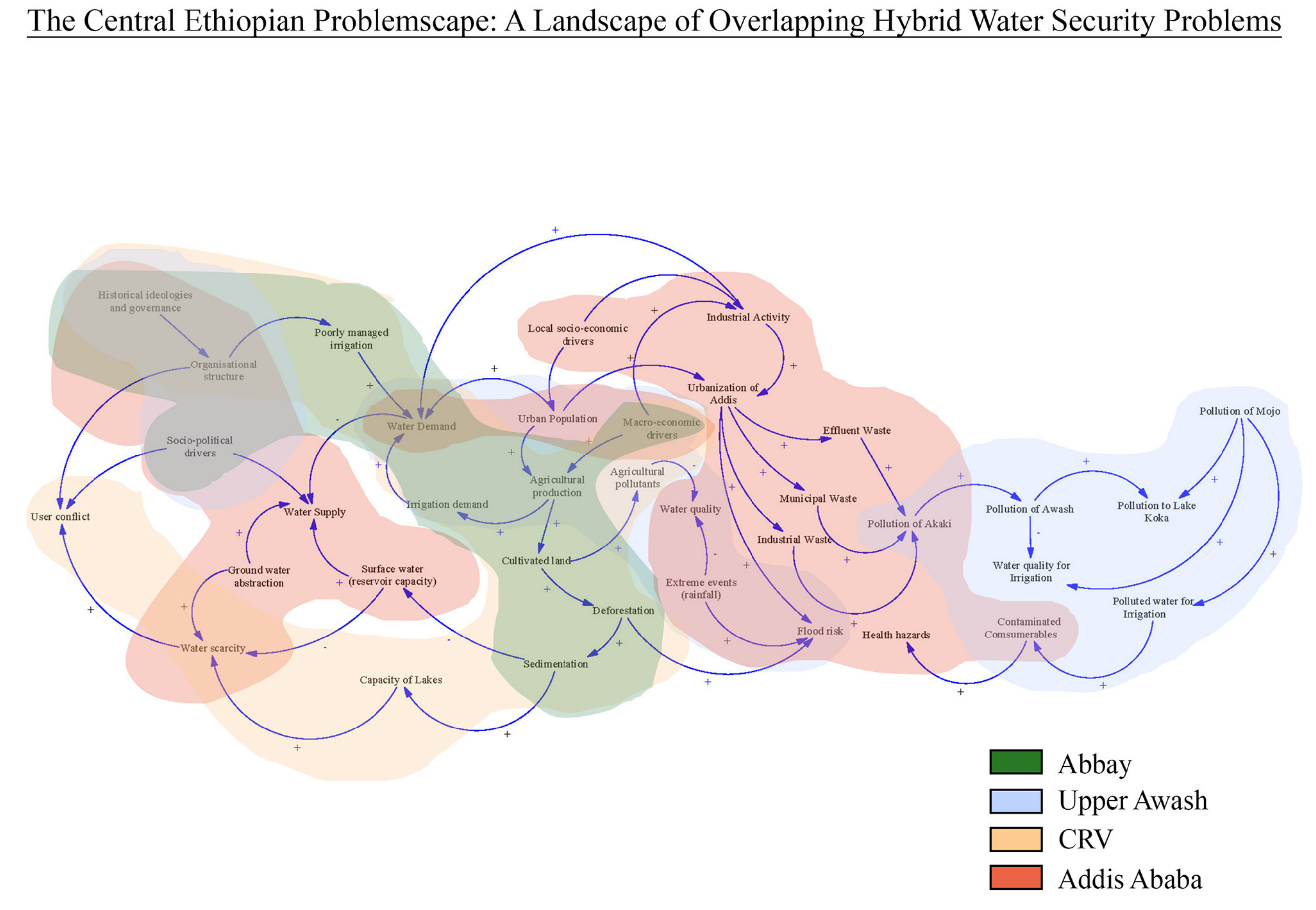

FIGURE 7 | The conceptual CEC problemscape.

A way to combat this is to show the problemscape as a conceptual system of connections between problems and areas of action. Building on the previous figures which demonstrate both interconnectedness and nestedness of the water security system of issues in this area. These are combined to form a problemscape of the entire area shown in **Figures 7**, **8**. This visualization of the nature and intensity of the problems represents the problemscaping process as seen from one perspective. The topography of the problemscape will, in all likelihood, change once viewed from say a local farmer or commercial water user. This process of depicting the "scape" and then using the visualization as a form of mental reflection of a particular actor perspective makes comparison between actor perceptions and depictions more interesting and potentially more dynamic as a tool to interrogate perspectives on problem-solving in a context such the CEC.

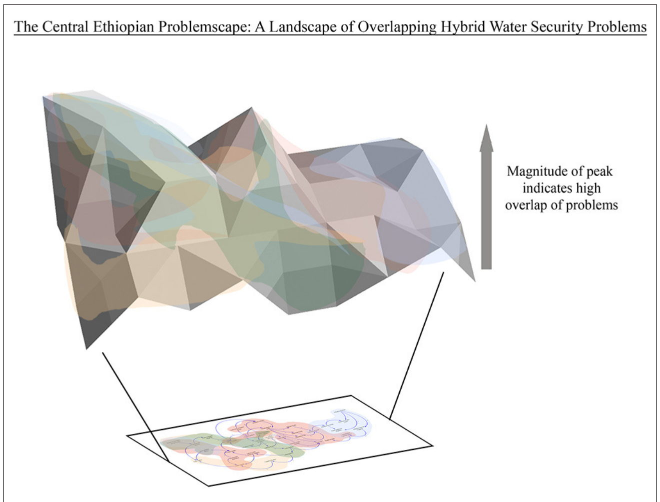

FIGURE 8 | The CEC problemscape landscape.

DISCUSSION AND CONCLUSIONS

The initial analysis and construction of the problemscape exposes the interconnectedness and hybridization of water security issues in the CEC area as well as the nestedness of scale and impact. It can be demonstrated that the CEC problemscape has a variety of water security interconnections, including hydrology, geography, sociology, livelihoods, ethnicity, history, administration, institutions, economics, and politics. In addition to this, it can be observed that the nestedness within the water security system of this area is not always proportional to the impact and scale. For example, Addis' water security issues are nested within bigger processes of the Upper Awash and influenced by even larger interactions between global markets and all three basins. However, the presence of Addis and its impact and influence become epicentral to the problemscape even under multiple framings. Spatially and politically, Addis is both highly sensitive to external change and a large owner of water security drivers. Addis is notably a high influencer in terms of physical impacts on the problemscape area (such as groundwater abstraction, domestic, and industrial pollution) as well as an area where uncertainties could create a high level of disruption (such as extreme rainfall)—and where political and administrative change could have major impacts on many relationships between factors determining the shape and dimensions of the problemscape. This is not a surprise, cities are often noted for their environmental, socio-political, and economical influence—and dominance in national political economics. However, it is also the area in which the majority of decision making takes place, where the management institutions reside, as well as the majority of industry and urban population. The second item revealed by the problemscape is the linkage of virtual water between all three areas. The farming of crops and livestock in the area have a direct impact on water security in some cases, but in others, the virtual connections link water security problems through conceptual connections. Such is the case for the links between Addis and its surrounding rural areas. Lastly, what is most interesting about the formation of the problemscape is that it is demonstrated that the points that appear to have the most prevalence in the CEC are those that are not basin confined. For example, macro and local economic drivers, organizational structure, and extreme events. The problemscape exposes these in a way that the basin unit may bury amongst other factors or more "visible" processes. This alludes to the need to find non-conventional solutions to water security problems, in other words, leverage points existing outside the original scope of the traditional water problem framing.

What the problemscape outcomes and process ultimately demonstrate are the vulnerabilities and uncertainties of larger water security problems—crucially, the interconnectedness of water insecurities outside of a basin boundary. Communicating this to planners and practitioners as a form of action research is predicted to be a useful tool to enable integration of water security research and development practice. For example, increasing water supply and sanitation resilience and demand management for multiple fronts. In addition to this, within institutions responsible for water supply in a big city such as Addis Ababa, *problemscaping* could be used to gain an understanding of the positionality of key actors and how this changes their own problemscape understandings and perceptions. This is currently being explored through co-development of the problemscape process with Addis Ababa Water and Sewage Authority (AAWSA). So far, focus groups from different departments are enabling us to refine the problemscape method and generate problemscape outcomes for water, sanitation, and hygiene in Addis.

The next steps for developing the problemscape concept are to understand agreements and disagreements between the systems representation—the variety of actor-stakeholder perspectives mentioned earlier—and to examine the problemscape from these different perspectives. These could be used in early attempts at mitigating conflict and negotiation solutions to disputes arising from resource competition and scarcities. Comparing problemscapes would also identify optimal leverage areas for integrated water security solutions—essentially hybridizing the discourse on water security. This requires the collection of multiple problemscapes from a range of diverse actors, which will also provide empirical evidence that demonstrates the variation of water security realities. Additionally, providing material that validates whether the practice of *problemscaping* over different geographies and contextual settings encourages collective interdisciplinary action for immensely complex water challenges. The degree of success for problemscapes improving water management perspectives for water security is still yet to be assessed; however, what is observed as being currently most valuable from this process is the exploration of non-water paths and non-linear insights for water security challenges. In addition to this, the use of both visual and conceptual prompts for navigating hybrid water security complexity in an area containing numerous interconnected issues.

To conclude, the concept of problemscapes not only provides a systems method for navigating water security complexity—and nurturing the notion of hybrid water security—but it also redefines what we mean and include when we discuss water security. In reality, the identification of effective paths of action that may really address water security risks and the viable implementation of solutions, even infrastructural ones, need a deep understanding of this complex hybrid contextual landscape. If anything, this concept demonstrates that water security cannot be seen as a simple concept, but rather a dynamic web of problems that touch a great many societal areas and contribute to the preservation of the many dimensions of water. The concept of problemscapes also reinforces that water security is almost indefinable in that it is contextual to every materialization in time and space. Solutions and solution frameworks must therefore reflect these key characteristics and avoid overly rigid application of a few conceptual dogmas. To further develop problemscapes, this approach needs to be tested in a portfolio of water security scenarios. Including, empirical evidence of improved water management perspectives from different geographies and contextual settings.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

XP: concept co-development, paper structure and initial write up, methodology, and figures. AN: concept co-development, application in hybrid water security systems, proof reading of whole document, and disciplinary comments, including various inputs where necessary. AH, MD, and MB: proof reading of whole document, and disciplinary comments, including various inputs where necessary. JA: proof reading and input to introduction (specifically boundaries of management) and discussion. All authors contributed to the article and approved the submitted version.

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A Sustainability Planning Framework and Methods for Rural Drinking Water in Satara District, Maharashtra, India

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Districts across India are progressing toward the national Jal Jeevan Mission goal of piped water supply and 100% Functional Household Tap Connections (FHTC) for all by 2024. While state and national data monitor progress toward tap water connection coverage, the functionality and sustainability of those piped water supplies are less clear. This study presents a Sustainability Planning Framework to assess rural drinking water conditions and needs at the village, block, and district scales. It employs a mobile app to survey five key aspects of sustainability: source water sustainability, water service sustainability, operations and maintenance financial sustainability, village institutional capacity, and asset management. Ordinal scores for these sustainability variables are analyzed and interpreted though GIS mapping to identify locations and types of village support needed. Scores are aggregated to create an overall village drinking water sustainability index. Important hydroclimatic, geomorphological, and socio-economic correlates of the drinking water sustainability index are also examined. This framework and methods can help districts in Maharashtra and other states analyze drinking water services, plan future investments, and make policy adjustments to ensure sustainability.

Keywords: rural drinking water, district planning, mobile app, GIS mapping, Jal Jeevan Mission, Satara, Maharashtra, India

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INTRODUCTION

According to the United Nations WHO and UNICEF (2021), approximately two billion people or 26% of the global population lacked access to safe drinking water in 2020. It is well-known that inadequate access to water supply and sanitation services impedes overall development and wellbeing of citizens, especially women and girl children who bear most of the burden of fetching water from long distances, storing, and using it carefully (Zwarteveen et al., 2012; Cronin et al., 2015). A World Health Organization (2012) study estimated global economic losses of about 1.5% of annual GDP due to inadequate water and sanitation services.

National and state governments in India are addressing these issues through ambitious drinking water programs and investments such as the national Jal Jeevan Mission, which strives to provide functional household tap connections to all by 2024. The sustainability of those drinking water systems and investments are key concerns in states like Maharashtra where more than 5.5 million new tap connections have been made since 2019, and an additional 4.2 million taps are envisioned by 2024 (Government of India, Ministry of Jal Shakti, Department of Drinking Water and Sanitation, 2022). Challenges of sustainability are compounded by the reliance on groundwater sources from hard rock aquifers in water-stressed areas of Maharashtra. In 2017, some 23% of Maharashtra's aquifers were classified as "semi-critical," "critical," or "over-exploited" (Government of India, Ministry of Jal Shakti, Department of Drinking Water and Sanitation, 2019). This situation is exacerbated by monsoon variability and climate change. After reviewing the evolution of rural drinking water programs in India, we highlight key planning challenges for drinking water sustainability in Maharashtra (cf. Kumar et al., 2016; Miller et al., 2019). To address these challenges, we develop a Sustainability Planning Framework and associated methods. A case study was conducted in Satara district in Maharashtra to demonstrate the utility of this approach (**Figure 1**).

Evolution of Rural Drinking Water Planning in India

Providing water for rural citizens has long been a priority for the Government of India and state governments such as Maharashtra (Lockwood and Smits, 2011; Schouten and Smits, 2015; Hutchings et al., 2017; Wescoat et al., 2021). State funded programs started in the early 1970s with the Minimum Needs Program, followed by the Accelerated Rural Water Supply Program. These were designed and implemented by state agencies, without much participation of local governments and communities. The 73rd Amendment to the Constitution of India in 1992 empowered local Panchayati Raj Institutions comprising rural governments at the district, block, and village levels. Drinking water and sanitation services were formally brought within the local government mandate in the 1990s, but state governments continued to design and implement major programs through their Public Health Engineering Departments. To strengthen local governments, the central government introduced the Sector Reform Program in 1999, starting with about 67 pilot districts. Reforms were expanded to the entire country under the Swajaldhara program in 2003. This set the trend toward decentralization of rural water management that has continued till date through the National Rural Drinking Water Program, and current Jal Jeevan Mission launched in 2020 (Sangameswaran, 2014; Verma et al., 2014; Murty et al., 2020).

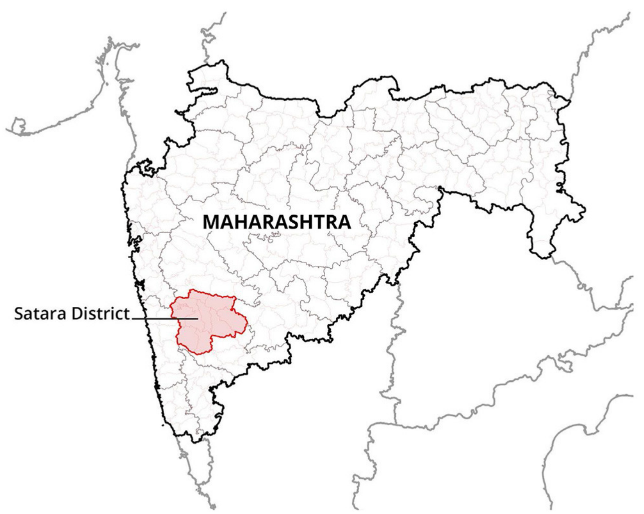

FIGURE 1 | Map of Satara (red) and surrounding districts (gray) in Maharashtra, India (Ranu Singh).

All state water programs, starting from Swajaldhara, have emphasized community participation in the development of Village Action Plans, led by Village Water and Sanitation Committees. Village Action Plans address local infrastructure needs, service delivery gaps, groundwater source sustainability, and operations and maintenance, which is a direct responsibility of village Gram Panchayat governments. Plans are approved in Gram Sabha village forums and consolidated at the intermediate block or *taluka* level of government. Districts comprising dozens of blocks and many hundreds of Gram Panchayats consolidate those local plans into a District Action Plan to prioritize investments and related capacity building. Districts in Maharashtra have a full-time Deputy Chief Executive Officer for water and sanitation, who has a support team of regular and contracted professionals. District Action Plans are amalgamated in turn into a State Action Plan, which establishes financial allocations to the districts from state and national sources. This planning process is thus a mix of bottom-up and top-down processes (Wescoat and Murty, 2021).

Earlier drinking water programs provided hand pumps, public taps, and stand posts at prescribed maximum distances from households. They aimed to satisfy a standard supply of 40 L per capita per day (lpcd), which was later increased to 55 lpcd for rural areas. Provision of piped water supplies and household tap connections was initially a relatively low priority. As per the Government of India, Census of India (2011), only about 18% of rural households in India had tap water from treated sources.

The recently launched Jal Jeevan Mission aims to cover 460 million rural households in India with piped water supplies and achieve a near-100% coverage with Functional Household Tap Connections that deliver at least 55 lpcd. Tap connection coverage is scaling up and has reportedly reached about 71% in Maharashtra (Government of India, Ministry of Jal Shakti, Department of Drinking Water and Sanitation, 2022). While coverage and expenditures are well-monitored, the *sustainability* of village water schemes has received less attention.

Key Sustainability Planning Challenges in Maharashtra

Expanding the Scope and Structure of Sustainability Planning

Planning is recognized as an important component of rural drinking water programs in India. The national Jal Jeevan Mission *Guidelines* (2019) call for Village Action Plans, District Action Plans, and State Action Plans. They mention sustainability, but do not indicate *how* to plan for sustainability. In Maharashtra, planning has likewise focused on capital expenditure to increase coverage. Despite large capital flows into the sector, there are growing concerns about sustainability, also known as "slipback," whereby "fully covered" habitations slip back into "partially covered" or "not covered" status, which is variously attributed to poor planning, execution, and/or maintenance (World Bank, 2008, 2014). The Government of Maharashtra wanted to understand these sustainability issues and develop a planning framework and useful tools for addressing them.

Shifting From Spreadsheets of Schemes to Planning for Sustainable Water Services

Districts in Maharashtra prepare Annual Action Plans that take the form of spreadsheets. Spreadsheets have two limitations for planning purposes. First, they tend to emphasize new infrastructure needs, which are important components of sustainability, but not sufficient. Sustainable water services also depend upon sound village financial planning for operation and maintenance, source water protection, cooperative local decision-making, and forward-looking asset management. These indicators were not captured in district spreadsheets.

Developing New Visualization and Communication Methods

The second limitation of spreadsheets, which have hundreds of rows and scores of columns, is that they are not easy to comprehend. They help list and sort potential projects, but they include no maps to visualize the geographic distribution of water problems, needs, and priorities. Nor do they have supporting text to communicate planning goals, criteria, and expected benefits.

This study worked with the Government of Maharashtra to address these three challenges by developing a Sustainability Planning Framework with new planning methods and tools for strengthening the sustainability of drinking water services.

Our Contribution: Sustainability Planning Framework and Methods

The Sustainability Planning Framework developed through an investigation of baseline levels of water service. The Jal Jeevan Mission strives to ensure safe tap water service of 55 L per capita per day. However, the volume of water delivered is not currently measured in most villages. In addition, water service varies seasonally between dry pre-monsoon months and the rest of the year. In some villages, concerns revolve around the adequacy of water sources and supplies. Others lack sufficient finances, O&M, or management capacity to sustain the systems constructed. Sustainability is thus a multidimensional objective that involves careful planning of system inputs, outputs, and outcomes. This study linked the assessment of drinking water services with sustainability planning.

Previous Approaches

The importance of this aim was made clear by a longitudinal study of East African countries, which drew attention to the deterioration of piped water supply schemes and reversion to substandard water services over a period of 30 years (Thompson, 2001, 53–58). Several sustainability planning methods and indices have been developed to address such scenarios. Some of them deal with urban utilities that use benchmarking indices based on financial, organizational, and human resource indicators, as well as water service levels (e.g., Asian Development Bank, 2007; CEPT, 2013; American Water Works Association, 2020). Benchmarking indices are also used to provide comparisons with peers, which is helpful when planning service improvements. In the rural context, Bandyopadhyay (2016) provides a broad review of drinking water sustainability issues and approaches in India. Hutchings et al. (2017) identifies successful models of rural drinking water systems and support organizations, described as "Community Plus" case studies in different regional contexts of India. Maharashtra qualifies as a "high-income developmental state" in their framework. WaterAid's (2011) sustainability framework highlights 12 principles that it employs as an external support organization. Miller et al. (2019) reviewed 218 studies of external support organizations for rural drinking water systems. Some studies employ sophisticated quantitative analyses of sustainability indicators. For example, Singh and Bhakar (2021) present a groundwater sustainability index in Rajasthan using an Analytic Hierarchy Process. Other studies employ cluster analysis, principal components analysis, and multi-criteria models, though those studies tend to involve small to medium sized samples of 10 to 100 water projects (Ibrahim, 2017; Molinos-Senante et al., 2019)—rather than the thousands of villages and hundreds of local staff in the Indian district context. Verma et al. (2014) present detailed chapters on source, service, and governance aspects of sustainability. The WASH Alliance FIETS model draws these aspects of sustainability together under the five broad categories of Financial, Institutional, Environmental, Technological, and Social indicators (FIETS) (WASH Alliance, 2021). Novellino (2015) analyzed the FIETS model's potential and limitations for assessing "slipback" (i.e., unsustainability) in the state of Gujarat, identifying specific drinking water variables for each of the five categories in the Government of India's Integrated Management Information System (IMIS) drinking water database. However, those data are stronger on physical progress, financial expenditure, and water quality than on water service levels, and are not readily accessible or mappable at the village level (Wescoat et al., 2016). The Jal Jeevan Mission has recently developed a mobile app to document rural drinking water sources, assets, and village Har Ghar Jal status (Government of India, Ministry of Jal Shakti, Department of Drinking Water and Sanitation, 2021a).

Our Approach

This study built upon approaches to sustainability in the literature above. On a conceptual level, it defined drinking water supply sustainability as a function of: (1) the water supply source; (2) water delivery service; (3) operations and maintenance finance; (4) village capacity; and (5) asset management. That is:

$$\text{Sustainability} = f(\text{source, service, O\&M finance, village capacity, asset management})$$

Working closely with state, district, and local water officials, the study identified specific methods, variables, and tools deemed relevant and practical for scaling up drinking water planning in the villages of a district. This collaborative process led to the development of a mobile app for data collection, consistent metrics for variable scoring and aggregation, GIS visualization of priority villages, and a template for planning recommendations described in the Section on Materials and Methods below. The section Results presents on results of the analysis and mapping in a case study of Satara District. Section Correlates of the Drinking Water Sustainability Index examines three important correlates of drinking water sustainability in Satara district that draw upon other state and national databases. The Discussion section weighs lessons learned while the Conclusions section underscores the major findings and implications of this sustainability planning approach.

Case Study District

This study is part of a wider investigation of district drinking water planning in Maharashtra. Among four case study districts involved in field research, Satara district had a high level of survey completion (86%), which enabled this analysis of drinking water services and sustainability (cf. Singh et al., 2019). It has a high level of Jal Jeevan Mission implementation—77.5% coverage with household tap connections (Government of India, Ministry of Jal Shakti, Department of Drinking Water and Sanitation, 2022).

Satara district is distinguished by a strong east-west gradient of annual rainfall that ranges from an average annual high of 5,000–6,000 mm/year (depending upon the database and period of record) in Mahabaleshwar taluka in the high elevation Western Ghats region of the district to a low of 400–500 mm/year in the semi-arid plateau lands of Man taluka on the eastern edge of the district. Overall, Satara district has an average annual rainfall of 1,200–1,350 mm/year, concentrated in the monsoon months of June-September with lesser amounts in winter. The district has high rainfall variability, and its semi-arid talukas experience drought declarations every 3–5 years. In 2018, the year before our survey, monsoon rainfall was 40% less than the annual average in the eastern Phaltan and Man talukas that carried over into drought impacts during the 2019 survey period.

This steep rainfall gradient reflects an elevation drop from ∼1,400 m in the western Sahyadri range to ∼400 m in eastern Phaltan taluka. Rapid runoff from streams in the Western Ghats is impounded in several large reservoirs. Precipitation on the central plateau recharges hard rock aquifers and local water impoundments. The district has five major physiographic regions: (1) the Sahyadri range of the Western Ghats that runs north-south; (2) the Mahadev dissected uplands running NW-SE; (3) the Koyna-Krishna River drainage in the southern part of the district; (4) the Nira River tributary of the Bhima River in the north; and (5) semi-arid plateau lands in the eastern part of the district. The district's dissected plateau lands are characterized by highly variable hydrogeological conditions, groundwater supplies, and drinking water sustainability [Maharashtra State, Ground Water Surveys and Development Agency (GSDA), 2011-2012, 2021; Government of India, Central Ground Water Board (CGWB), 2018]. The district has prepared a 240-page *Disaster Management Plan for 2020-21* (Satara District Collector, 2020) that addresses these drought and flood hazards.

Administratively, the district consists of 11 blocks that include 1,763 villages, or ∼160 villages per block (**Figure 2**) (Government of India, Ministry of Jal Shakti, Department of Drinking Water and Sanitation, 2022). Each village has an average of three small habitations (Wescoat et al., 2019). Planning for *all* villages in a district is thus a data-intensive process. Villages in Satara District have an average population of 1,518 permanent residents, and report having an average of 164 temporary residents and migrant laborers, locally referred to as "floating populations". Temporary residents are important for estimating fluctuations in village water needs, especially in pilgrimage centers and festival periods that respondents described as the most rapidly growing types of local water demand. Many residents migrate to work in block towns or cities like Pune and Mumbai (Dandekar, 1986). Villages near taluka block towns and industrial centers are becoming "rurban" or "peri-urban" with populations that have higher expected water services (Hui and Wescoat, 2018). The Census of India defines a rural village as a settlement that has three characteristics: <5,000 people; <75% of the male population in non-agricultural employment; and a population density of <400 people per square kilometer. Over time, however, this rural-urban dichotomy is breaking down, which will lead to higher expectations for water services.

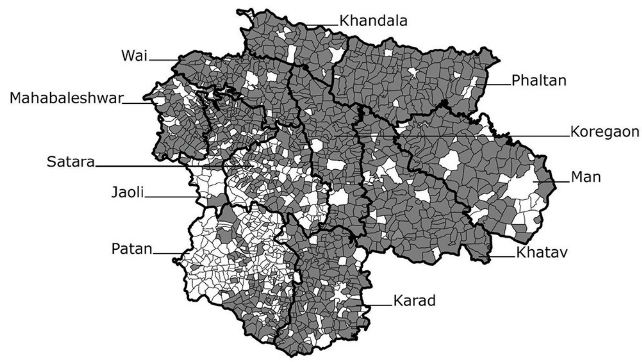

FIGURE 2 | Blocks and villages of Satara District (gray areas completed the survey) (Piyush Verma).

MATERIALS AND METHODS

After introducing the research process and challenges, this section describes the mobile app that was developed for village field surveys. Detailed discussion follows on the criteria adopted to score survey data for each variable. The section concludes with GIS mapping methods used to visualize and communicate research results.

Research Process

Reconnaissance interviews and field visits with district and village officials led to the design of planning methods and tools in four case study districts of Maharashtra, culminating in the Satara district study reported here. The research team gave presentations on drinking water planning approaches and methods, while district officials gave presentations on current drinking water conditions and projects that aim to address water scarcity, water quality, and peri-urban development. Multiple consultations were undertaken with water officials on types of water service data needed for sustainability planning. Currently, district annual action plans assess and prioritize several hundred out of more than a thousand villages in a district. The principle adopted in this study, however, was that conditions and needs in all villages should be considered as a matter of equity. Sampling is useful for identifying common needs, but it does not give each village an opportunity to be considered as part of an annual district plan. Villages vary greatly, even those in close proximity with one another. Surveying all villages sheds light on spatial heterogeneity and clustering of drinking water conditions and thus on opportunities for multi-village alternatives.

The initial village survey instrument used spreadsheets for transparency and real-time revision. After several iterations, however, a mobile app survey tool was developed in English and Marathi with drop down menus and radio buttons to facilitate field data entry. Local officials (*gram sevaks*) entered field conditions for each variable, which the app internally scored from 1 (very good) to 5 (very poor). The survey instrument and scoring are described in greater detail below.

Training and field testing ensured that local block officers, known as *gram sevaks,* responsible for monitoring village development programs, are able to collect reliable data with the mobile app. By comparison, elected village water officials and village heads (*sarpanch*) vary in their ability and objectivity. Training was conducted in district or block headquarters. Mobile app data entry required several rounds of checking to address incomplete, duplicate, or erroneous entries (which usually involved typed answers).

Data analysis examined each variable through charts, tables, and GIS maps. District officials were familiar with spreadsheet displays as well as bar and pie charts. GIS analysis was new. Each variable was scored from 1 to 5, and common intervals and colors were used in map legends to consistently represent conditions from very good (green) to very poor (red). Maps helped screen individual villages and village clusters that scored poorly, flagging them for more detailed field assessment and potential planning interventions. Follow-up actions can range from source water protection to improved scheduling, operations and maintenance, or financial planning support. In this study, survey results led to an emphasis on sustainability planning.

Mobile App Survey Questions

The mobile app survey was developed with the KoboToolbox open source platform. Data may eventually migrate to a new Government of Maharashtra or Jal Jeevan Mission drinking water monitoring and evaluation platform. The interface is attractive and easy to read in English and Marathi scripts. The survey consists of nine clearly identified sections (see the full drinking water supply survey in **Supplementary Materials**):

- *Village Name, Census ID, and Block Name.*
- *Water sources and piped water service*. This is the largest section of the survey. It includes source water availability in months of supply per year. Tap water service variables focus on availability in days per week and hours per day. Data were collected for both the pre-monsoon water-stress months of summer and wetter months of the year.
- *Operation and maintenance*. These questions focus on O&M expenditures relative to estimated costs, tariff levels, and percent revenue collection.
- *Village water management capacity.* Villages were asked about water operator training, and the performance of their Village Water Supply Committees.
- *Solid and liquid waste management.* These questions asked about the percentage of the village that have closed drains, open drains, or no drainage, which can be compared with data in the Census of India. As piped water supplies and tap connections increase, wastewater drainage issues may increase.
- *Water innovations.* Each village was asked about water innovations they have made. Some model villages are famous for achieving reliable water supplies and safe sanitation programs. The hypothesis behind this question is that there are many less well-recognized village innovations in each district.
- *Water source water classification.* The Maharashtra Ground Water Surveys and Development Agency examines village water sources for their sanitary condition and codes them as red, yellow, or green.
- *Water quality conditions.* Villages were asked about the presence or absence of major water contaminants. These conditions can be compared with more detailed state water quality lab results compiled in the national IMIS database.
- *Water supply asset management.* Villages were asked about the functionality and adequacy of key water assets, from wells to pumps, storage tanks, and distribution lines.

The full survey provides a rich profile of drinking water conditions in each village. It was deemed practical by state and district officials, and it was streamlined to the point where a knowledgeable *gram sevak* required about 30–40 min to complete a village survey. Each *gram sevak* is responsible for several villages, and thus has a deep level of local knowledge about those places.

Sustainability Criteria, Variables, and Scores

Five major criteria from the full survey were selected to develop the sustainability planning framework: (1) source water sustainability; (2) water service sustainability; (3) O&M financial sustainability; (4) village institutional capacity; and (5) asset management. In each case, responses were scored on a scale from 1 (very good) to 5 (very poor), so responses could be compared on an ordinal level across variables (see **Supplementary Table 1** in **Supplementary Materials**). Variable scores were averaged to generate sustainability indices. Future research may address variable weights and statistical distributions as well as mean scores.

Source Water Sustainability Criterion (1 Variable)

Villages were asked about the availability of their surface and groundwater sources in months over the past full year. Responses ranged from 12 months (very good = score 1) to 8 months or less per year (very poor = score 5). Parts of Satara district experienced a weak monsoon and drought in 2018 that contributed to a significant number of "very poor" scores in 2019.

Piped Water Service Sustainability Criterion (Average of the 5 Variables Listed Below)

Water service levels are increasingly important as India transitions toward universal piped water supply and functional household tap connections under the Jal Jeevan Mission. The following water service variables shed light on *functional* aspects of tap connections.

- *Percent household tap connections.* This variable ranges from 100% (very good = score 1) to <40% (very poor = 5). This variable is expected to change significantly with the current Jal Jeevan Mission commitment toward full coverage. Pre-Mission coverage is an indicator of potential sustainability of new tap connections, as are service level variables listed below.
- *Piped water supply in days per week (summer months).* Pre-monsoon summer months are a period of expected water scarcity. Many if not most systems experience some level of scarcity from April to June. Daily water supply during this period is deemed very good (score = 1) while supply 1 day per week or less is deemed very poor (score = 5).
- *Piped water supply in days per week (rest of the year).* Monsoon and post-monsoon months have more moisture and should have more frequent and reliable water service. Daily water supply is deemed very good (score = 1), while 1 day or less per week is very poor (score = 5). Systems with poor reliability during these wet months are assumed to have serious water service problems (i.e., beyond the problems associated with seasonal scarcity).
- *Piped water supply in hours per day (summer).* For each day of service, water is supplied to each zone of a village for a set length of time. In the rural context, 3 h or more of service per day is deemed very good (score = 1), while <30 min per day is deemed very poor (score = 5).
- *Piped water supply (hours/day in the rest of the year).* For moist months of the year, 3 h of service per zone is again deemed very good (score = 1), while <30 min per day is very poor (score = 5).

O&M Financial Sustainability Criterion (Average of the 2 Variables Below)

- *Percentage actual O&M expenditure compared to estimated costs.* Villages were asked about their actual O&M expenditures compared to their estimated costs. Spending 100% or more of estimated costs is deemed very good (score = 1), while spending <40% of estimated costs is deemed very poor (score = 5).
- *Percent revenue recovery.* Villages were asked what percentage of their annual water tariffs are actually collected. Some villages reported 100% or more of revenue recovery when actual costs were higher than expected revenues (score = 1); at the low end of the scale some villages reported <40% revenue recovery (score = 5).

Water Management Capacity Criterion (Average of the Two Variables Below)

- *Water Operator capacity.* Villages were asked about their water operator's training—from a fully-trained professional (score = 1) down to a part-time "valve-man" (score = 5).
- *Village Water Supply Committee (VWSC) performance.* They were also asked if their VWSC is active and effective (score = 1), irregular (score = 3), or not active (score = 5).

Asset Management Criterion (Average of Two Sets of Variables Below)

- *Asset functionality.* For each major asset (wells, pumps, tanks, and pipelines), villages were asked if the asset is fully functional (score = 1), semi-functional (score = 3), or not functional (score = 5).
- *Asset adequacy.* For each major asset, villages were asked if the asset is adequate for village needs (score = 1) or inadequate (score = 5).

Overall Sustainability Index for Screening (Average of the Five Criteria Above)

Scores for the five sustainability criteria were averaged to produce an overall Sustainability Index. This index is important for screening purposes: it flags villages and clusters that have the greatest overall needs and vulnerability. This screening method includes input, output, and outcome issues, which collectively shed light on drinking water system conditions and performance. The scores help screen villages for follow-up field verification and detailed project reports where warranted. Field assessment also helps correct *gram sevak* errors and changing conditions on the ground.

GIS Mapping Methods

GIS mapping is valuable for visualizing survey results for spatial planning purposes. It has not been used for rural drinking water planning in Maharashtra at the district, block, or village levels to date. Instead, district annual action plans currently take the form of spreadsheets of proposed projects with little supporting text and no maps. The GIS maps in this study used 2011 Census of India administrative boundary shape files. It began with the ArcMap platform and later shifted to the open source QGIS platform (Singh et al., 2019). Maps were prepared for each of the variables and indices in the Sustainability Planning Framework described above (see **Supplementary Table 2**–Satara GIS in **Supplementary Materials**). A common color ramp from green (very good) to red (very poor), and common equal interval scale were used to facilitate map comparison.

RESULTS

Village survey results were analyzed, mapped, and interpreted in novel ways. In addition to describing quantitative scores and spatial distributions for each variable, scores were interpreted for potential planning issues and implications. Take the example of source water supply, assessed in months of water availability per year: a high score of 1 may call for source water protection at wellheads and recharge areas to sustain that good condition throughout the year; an intermediate score of 2 or 3 may require source strengthening through well improvements and rainwater harvesting to attain 12 months of service; while a low score of 4 or 5 may require major new water supplies and schemes. Similar interpretations were developed for scores on each of the five sustainability criteria in the framework. The five criteria were then aggregated to produce an overall sustainability index to identify priority areas for planning intervention and support.

Source Water Sustainability

The first sustainability criterion is having a safe, adequate, and reliable supply of water. In the Maharashtrian context of monsoon climatology over hard rock aquifers, drinking water systems rely primarily upon groundwater sources supplemented by local surface water bodies for other domestic and animal needs. Irrigation also draws upon a combination of groundwater and surface water resources, which competes with domestic water uses in times of scarcity. Larger reservoirs serve municipal users, large irrigation systems, and sometimes nearby villages that do not have a reliable local source.

The source water sustainability criterion is defined as the number of months per year when at least one drinking water source is reliably available to the village. The map of source water availability displays a striking range and pattern of conditions (**Figure 3**). Many villages reported having a full 12-month supply, especially in the western and central areas of the district, though some villages dropped to 11-months of supply (e.g., in northeastern Phaltan taluka along the Nira River valley). Still others dropped down to 8-months or less in the eastern quarter of the district (e.g., in Man and Khatav talukas). This overall pattern reflects the rainfall and drought frequency gradients from west to east. In addition to the rainfall gradient, the dissected Mahadeo range that runs from NW to SE has exposed rock and thin soils that limit groundwater availability (Government of India, Ministry of Jal Shakti, 2013; Government of India, Comptroller Auditor General, 2018). These hydroclimatic and geomorphological conditions are discussed later as important correlates of drinking water service.

Even villages with very good scores have to *protect* source waters at the wellhead, watershed, and aquifer recharge scales. Increases in population, water demand, waste disposal, and land use intensification all impinge upon drinking water sources. Villages that reported fair scores of 2–3 need to *strengthen* their water sources, e.g., through rainwater harvesting, groundwater recharge, watershed conservation, and well improvements. Few villages reported having rooftop rainwater harvesting, though some successful examples were observed in hilly areas of the nearby Bhor taluka in Pune district to the north. Villages that have poor to very poor scores of 4–5 need to *develop* more secure supplies, as well as protect and strengthen existing supplies, either locally or through multi-village water schemes.

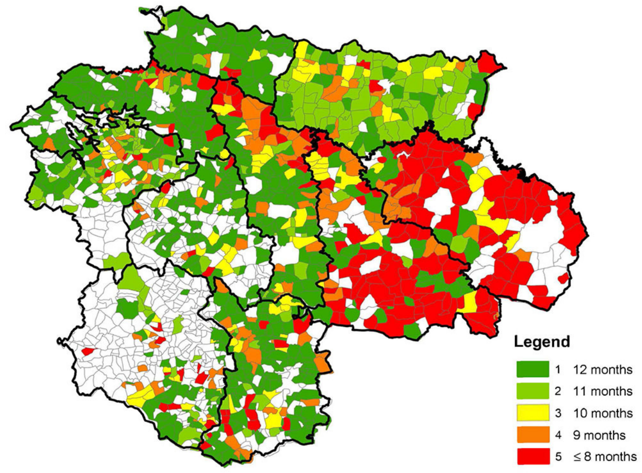

FIGURE 3 | Source water sustainability (months/year).

Water Service Sustainability

In addition to having a reliable year-round water supply, villages that have piped water supplies and tap connections need to achieve sustainable patterns of water service, defined in days per week and hours per day of reliable water delivery. Many villages have multiple water schemes. About three-quarters of the villages in Satara district reported having hand pumps; a third reported community taps; 30% have borewell pumps; a quarter have dug wells; and 10% rely on surface water bodies. Interestingly, only about 4% of villages reported using private water vendors. With the Jal Jeevan Mission, the trend is moving toward piped water supplies and household tap connections, so it will be important to start monitoring the sustainability of water service from new taps.

The piped water service sustainability criterion combines five survey variables: percent household tap connections; days per week of summer service; days per week in the rest of the year; hours per day of summer service; and hours per day for the rest of the year.

Villages reported an average score of 3 (61–80% coverage) for household tap connections, which is consistent with the current Jal Jeevan Mission estimate of 77.5% coverage (Government of India, Ministry of Jal Shakti, Department of Drinking Water and Sanitation, 2022). Our 2019 survey thus provides a good baseline for assessing the sustainability of new taps as coverage increases. It indicates which villages had a large or small proportion of tap connections prior to the Jal Jeevan Mission. Percent coverage is not simply a measure of progress toward universal coverage. Villages with less than full coverage have unequal—and presumably inequitable—levels of service that reflect the limited access of lower income and marginalized socio-economic groups (Birkenholtz, 2013; O'Reilly and Dhanju, 2014). Districts need to ensure that villages plan and provide for functional tap connections for all as a matter of equity.

For villages that had tap connections in 2019, the survey indicated where service was good or poor at that time. Poor scores show where new systems are also likely to face service

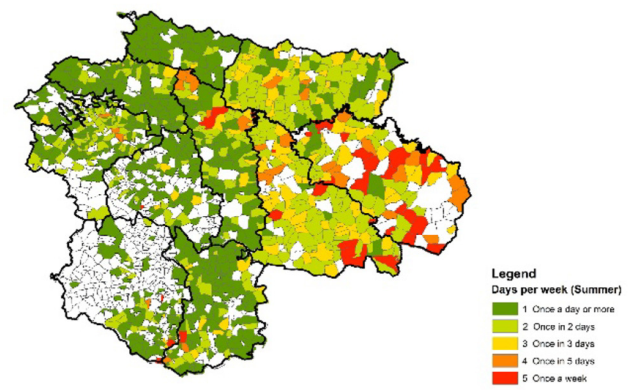

FIGURE 4 | Days of PWS per week (summer).

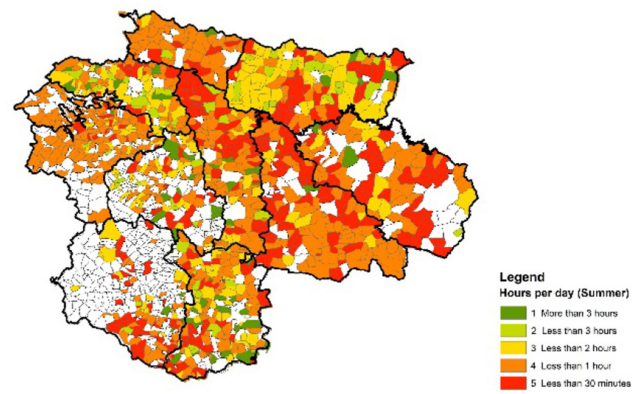

FIGURE 5 | Hours of PWS per day (summer).

sustainability problems. Discussions with district water officials in Maharashtra mentioned that service every day is deemed very good (score = 1), and service every other day is also good (score = 2). Less than that is fair or poor (score = 3 or 4). Service once a week or less is very poor (score = 5). On days when villagers do receive tap water, access for 3 h/day or more is deemed very good (score = 1), while access <30 min is deemed very poor (score = 5).

Water service varies over the course of a year. Even in favorable conditions, pre-monsoon summer months are water-stressed in Maharashtra, so it is important to distinguish summer water service from the rest of the year. A village that has good water service or better in summer, as well as the rest of the year, has a sustainable level of water service. Conversely, a village that has poor water service during the monsoon months is likely to have multiple problems that contribute to unreliable and unsustainable water service throughout the year.

Summer Tap Water Service

Satara district has an interesting pattern of pre-monsoon summer conditions where the days of water service per week are generally good (**Figure 4**)—but the hours of water service per day are low (**Figure 5**). Piped water service was available to most villages once a day or every other day, even during dry pre-monsoon summer months (**Figure 4**). Important exceptions occurred in the eastern villages of Man taluka. Those drought-prone villages received water only once or twice a week, which is not reliable or sustainable. A large number of villages in Patan taluka gave no response to this question, which may indicate low piped water coverage. While the overall pattern of weekly piped water supply was reliable for most villages that responded, there are areas of concern in both the western hills and eastern plains.

Hourly piped water service in summer months is limited in most areas of the district (**Figure 5**). One-quarter of the villages recorded <30 min of service per day, particularly in central and eastern areas of the district. The practice of supplying only 30 min of water per rotation occurs in humid and mesic as well as semi-arid regions. In humid areas, limited service may reflect increasing demand, scheme design constraints, or system management. While technically a full 30 min of service may be sufficient for a household's needs in volumetric terms, particularly in villages that provide daily service, it can be a borderline condition in the event of system disruptions. Homes have to store water in plastic tanks each day, and if served infrequently they have to make that volume last between rotations. One hour of service per day is a more common and reliable pattern, but even that can be on the margin of sustainability during drought periods or system disruptions. Over the long term, the pattern of frequent daily service but low hourly service in summer months is a risky situation. The district should strive to help villages attain at least 1-h service on a daily basis, and to sustain it through the summer months.

Overall Tap Water Service Index

A key aspect of the Jal Jeevan Mission is to provide *functional* household tap connections for all. The Jal Jeevan Mission dashboard indicates that the percentage of households with new tap connections is increasing, but it does not provide information on their functionality. This analysis helps fill that gap by surveying daily and hourly service levels, which collectively provide an index of sustainability. The five tap water service variables were averaged to create an index of village water service sustainability (**Figure 6**). These results reinforce expected concerns about poor water service on the eastern side of the district. However, they indicate mediocre tap water service across much of the district, with some poor conditions in the southern part of the district and even in humid hilly areas.

The mobile app survey included related questions that were not included in the numerical index. For example, it asked about water supply in liters per capita per day (lpcd), which is a standard criterion in India. That variable has a number of issues, foremost of which is that it is not currently measured. Schemes are designed to meet a certain lpcd standard and assumed to do so until scarcity makes it clear that the standard is not being met. Maharashtra's 40 lpcd standard was recently raised to meet the national standard of 55 lpcd. As many systems were designed for 40 lpcd, they may or may not be able to meet the higher 55 lpcd standard. Some drought affected villages in the eastern and

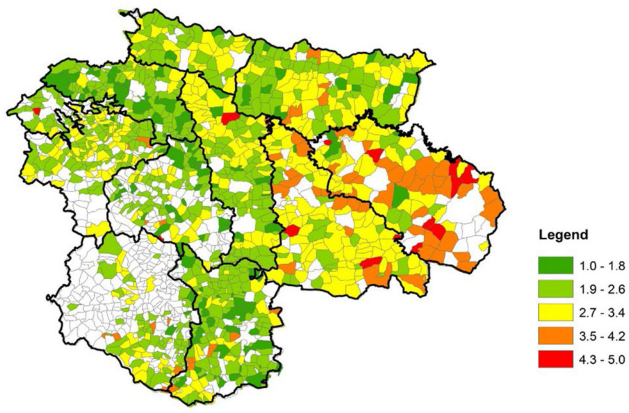

FIGURE 6 | Water service sustainability index.

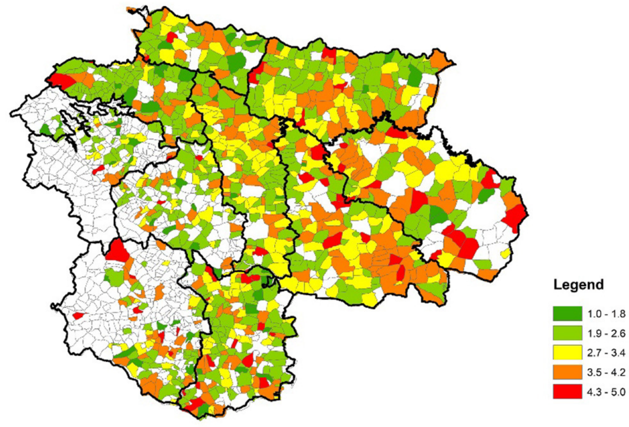

FIGURE 7 | Operations and maintenance financial sustainability.

northeastern parts of the district reported receiving <20 lpcd, which is a lower-bound threshold for districts to allocate public water tankers. Fifteen percent of villages reported receiving tankers at some point during the year. Other villages reportedly met the 55 lpcd standard, particularly in the western and central parts of the district. However, for the lpcd standard to be used with any confidence, basic measurement with water pumps, meters, or other water use estimation methods are needed. Only 100 villages (8%) reported having meters.

Sustainable Financial Management

Drinking water systems need reliable funding for operations and maintenance to be sustainable. All villages have water tariffs, some billed on a monthly basis and others on an annual basis. They vary in amount and adequacy for O&M and related financial needs. Revenue collection rates also vary. Even when collection methods are sound, the amount budgeted may or may not be adequate to meet the expenses required.

The mobile app survey asked several questions regarding village water finance. One set of questions asked about actual O&M expenditures compared to estimated O&M costs on a scale of 1 (>100% actual expenditures/estimated expenditures) to 5 (<40% actual expenditures/estimated expenditures). A second set of questions asked about water tariffs and tariff collection, the latter on a scale of 1 (>100% of tariffs collected) to 5 (<40% of tariffs collected). Cases where more than 100% was spent or collected indicated that a village was able to secure funds to address unanticipated as well as anticipated needs. These two variables were averaged to produce the O&M financial sustainability criterion.

O&M financial results in Satara District are impressive overall. **Figure 7** displays a generally high level of O&M expenditure and revenue recovery, even in some of the areas with source and service deficiencies. That is not always the case, as places with poor service often have inadequate revenues. Villages with acute O&M or revenue deficiencies in Satara District are more randomly distributed than other variables. They can be targeted for financial planning and budgeting support. These generally positive results may reflect a recognition of the importance of keeping wells and pumps repaired for the whole village, as well as distribution lines for those who have tap connections. There is still a possibility that O&M budgets are too low, which is addressed in the asset management section below.

In addition to revenues collected by villages through water tariffs, 14th Finance Commission grants (2015–2020) and 15th Finance Commission grants (2021–2026) make sizable funds available to villages for water and sanitation services. Under the 15th Finance Commission grants, a total of Indian Rupees 236 billion (equivalent to USD 3.11 billion in late 2021), are earmarked as grants to Panchayati Raj Institutions across the country (Government of India, Finance Commission, 2021). About 30% of these funds are specifically to be used for drinking water, rainwater harvesting, and water recycling, which contribute to the sustainability of drinking water schemes and services. Village access to and expenditure of these funds is important, but not easy to track.

Village Institutional Capacity

In discussions of rural drinking water sustainability, "capacity" and "capacity building" are often mentioned, both at the village and larger block and district levels. Two mobile app survey variables addressed the institutional capacity criterion: Water operator training, and Village Water Supply Committee (VWSC) performance. Very positive results were reported for village institutional capacity in Satara district (**Figure 8**). Most villages have a full-time water operator who is more than just a "valve-man", though few have professionally trained water operators. The need for the latter will increase as systems transition toward universal piped water supply and multi-village schemes. Most villages stated that their Village Water Supply Committees meet regularly and perform effectively. Satara district staff can thus focus on strengthening village capacity in the relatively small number of localities that have low 4–5 level scores. Future research should develop this criterion more fully, e.g., by assessing current levels of problem-solving and

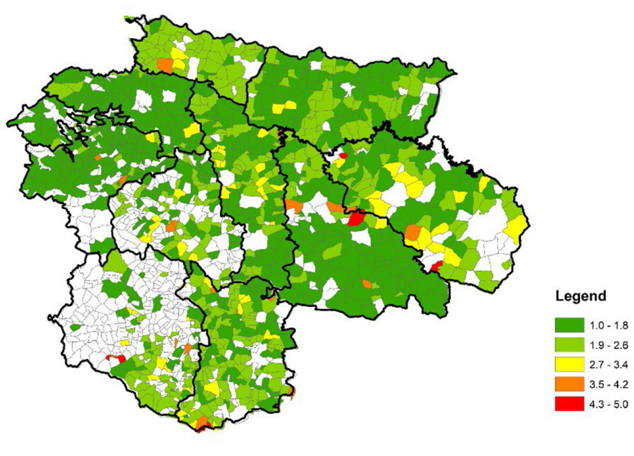

FIGURE 8 | Village capacity criterion.

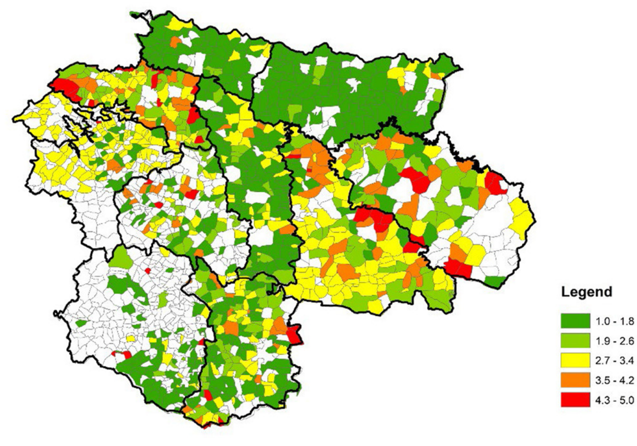

FIGURE 9 | Asset management index.

conflict management, especially in villages with major social-economic disparities.

Sustainable Asset Management

Asset management is crucial for long-term sustainability of water systems. It requires planning and budgeting for periodic replacement of deteriorating and obsolete equipment. It extends short-term O&M practices to longer-term and larger-scale strategic improvements. No villages that we have studied in Maharashtra have formal asset management strategies at present, which is the case for most small systems worldwide (though see US Environmental Protection Agency, 2003).

Villages do informally assess the condition of water asset and infrastructure needs. To identify these needs, this survey asked two types of questions regarding a common set of village drinking water assets (i.e., wells, pumps, rising mains, storage facilities, distribution lines, etc.). First, if the village has that asset, is it functional (score = 1), semi-functional (score = 3), or non-functional (score = 5)? Responses to this question speak directly to the Jal Jeevan Mission goal of functionality. They also shed light on the opposite process known as "slipback" to non-functional systems (Novellino, 2015). The main semi-functional to non-functional assets reported in the district were rising mains and sumps (with scores of 4–4.4), followed by water treatment plants. These are expensive assets to rebuild or replace, so it is important for district action plans to prioritize them.

The second set of questions asked whether the village regards each of the listed assets as adequate (score = 1) or inadequate (score = 5) in their village? This allows them to identify assets they would like to acquire or upgrade when resources are available. Interestingly, villages reported that the main new assets needed are water treatment plants. Most villages reported using some form of treatment, e.g., filtration or chlorination, but wanted additional treatment, possibly for hardness, nitrates, and biological contaminants that occur in the district.

Asset conditions and needs vary among villages, so scores for each asset on the common scale of 1–5 were averaged to yield an overall Asset Management Index, again on the scale of 1–5. This index differs from other maps in interesting ways (**Figure 9**). It identifies large areas of concern in the hilly western talukas (Wai, Mahabaleshwar, and Jaoli), as well as in Khatav taluka in the eastern part of the district. Northern talukas along the Nira River and southern talukas reported very good asset provision and functionality. A wide range of conditions from good to poor were reported in central parts of the district. Villages with very poor scores of 4–5 are relatively few in number, which suggests that infrastructure replacement is not as pressing as source water supply and service.

Support for multi-year asset management planning would help ensure that villages improve assets and secure funding for asset replacement to avoid slipback. This analysis represents a first step toward asset management. Future planning studies should help villages assess *when* assets need to be replaced, based on life-cycle and risk analysis; *how much* villagers prioritize different assets; and *how* they might plan to finance them.

Overall Drinking Water Supply Sustainability Index

The mobile app data analysis concludes with an overall Drinking Water Supply Sustainability Index that averages scores of the five criteria presented above. Only villages with scores for all five criteria were included. As variables included ordinal and interval levels of measurement, the index can be regarded simply as an ordinal scale, i.e., where lower scores are "better" than higher scores. It is not possible to say how much better or worse, beyond the consistent qualitative categories that they range from very good to very poor.

Figure 10 helps stakeholders focus on localities most in need of field attention in the next iteration of village and district annual action plans (Government of India, Ministry of Jal Shakti, Department of Drinking Water and Sanitation, 2019). It also identifies clusters of villages where larger multi-village programs and schemes might be considered. For example, Man taluka has clusters of villages in the very poor category, and Khatav

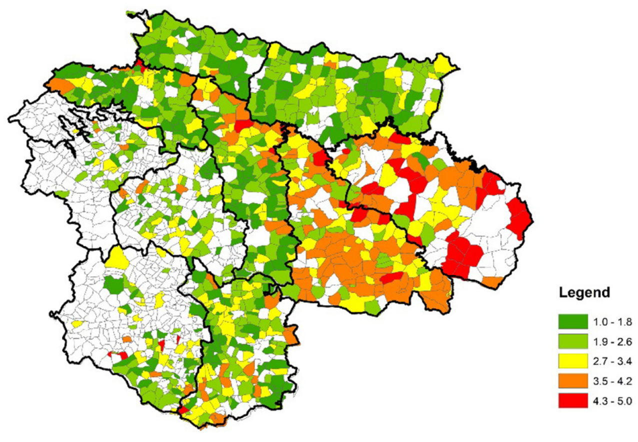

FIGURE 10 | Overall drinking water sustainability index.

taluka has a large cluster in the poor category where block-wide programs might be useful. Central, hilly, and northern talukas have relatively high or mixed scores where plans might prioritize individual village investment and support programs.

This overall sustainability index aggregates five sustainability criteria, but it does not analyze the likely interactions among them. For example, piped water service depends upon and is presumably correlated with the other four criteria. Failure of one aspect of the system affects the functionality and sustainability of the others. Future research should focus on interactions among variables, different variable weights, and aggregation methods. This study screened for conditions reported as very good or very poor, which helps direct follow-up field research to explain those patterns. We also identified several correlates of drinking water sustainability that are discussed in the next section.

CORRELATES OF THE DRINKING WATER SUSTAINABILITY INDEX

The literature review, village survey, and field research identified important correlates of sustainability, several of which can be assessed with national or state data. Three are briefly explored in this section: (1) hydroclimatic variability; (2) geomorphological conditions; and (3) socio-economic factors.

Hydroclimatic Variability

As discussed in the introduction, Satara district has a pronounced rainfall gradient (Mankar, 2008; Shaikh et al., 2017). Western blocks have high levels of rainfall, especially from Mahabaleshwar taluka which is anomalously high at ~5,700 mm/year, followed by Patan and Jaoli talukas at about 1,500 mm/year (Satara District, 2021). By contrast, the eastern blocks of Man, Phaltan, and Khatav receive an order of magnitude less rainfall on an annual basis (**Figure 11**). These eastern blocks also have high variability and frequent droughts, experiencing moderate or worse droughts every 3–5 years [Government of India, Central Ground Water Board (CGWB), 2018]. The 2019–20 study period followed one of those droughts, as indicated in **Figure 11**. Not surprisingly, these blocks also have some of the greatest sustainability challenges.

Droughts are a perennial concern in semi-arid areas of Maharashtra (McAlpin, 1983; Adamson and Nash, 2014) to which the eastern half of Satara district belongs (Jagannath, 2014; Udmale et al., 2016; Matkar and Zende, 2017). While no longer the cause of deadly famines, they periodically cause severe economic and nutritional distress for humans, animals, and crops. In the mobile app survey, 42% of villages reported water shortages that impacted their animal herds. District collectors issued drought declarations and promoted relief measures, culminating in the allocation of water tankers. The most frequent drought relief measures involved repairs to wells, followed by desilting of recharge areas and tanks, well deepening, and temporary irrigation well acquisition (cf. also Gaikwad and Pawar, 2020 on rainwater harvesting). The national Disaster Management Act of 2005 mandates that central, state, and district governments prepare district disaster management plans and identify hotspot areas for disaster events (Government of India, 2005; Satara District Collector, 2020). There is a need to integrate hydroclimatic and climate change hazards assessment with sustainable drinking water planning.

Geomorphological Constraints

In addition to its rainfall gradient, Satara District has pronounced landform, soil, and hydrogeological conditions that affect drinking water sustainability. Collaboration with the Maharashtra Ground Water Surveys and Development Agency led to the use of ground water prospect maps, village recharge maps, and geomorphological maps to understand these conditions. **Figure 12** displays major geomorphological patterns in the district. Most of the district is classified as a dissected plateau with a duricrust area in the western part of the district, through which the upper Koyna River has cut a steep valley (dark red). As noted in the introduction, the Mahadeo hills are highly dissected plateau lands with exposed rock and little or no soil cover (bright red). Dissected plateaus with thin soil cover are extensive in the northern and eastern parts of the district (orange). They have limited moisture holding capacity, though the map indicates that extensive surface water tanks have been impounded for seasonal water storage (blue). Only the major drainage valleys have moderate to deep soils conducive for agricultural settlement (yellow and green). While favorable for groundwater storage, these valleys also support irrigation that competes with drinking water supplies. The key observation here is that geomorphological conditions compound hydroclimatic constraints on drinking water sustainability in the upland and eastern parts of the district.

Socio-Economic Factors

Socio-economic factors also influence rural drinking water sustainability, though they are complex especially at the intra-village scale. The mobile app asked questions about village

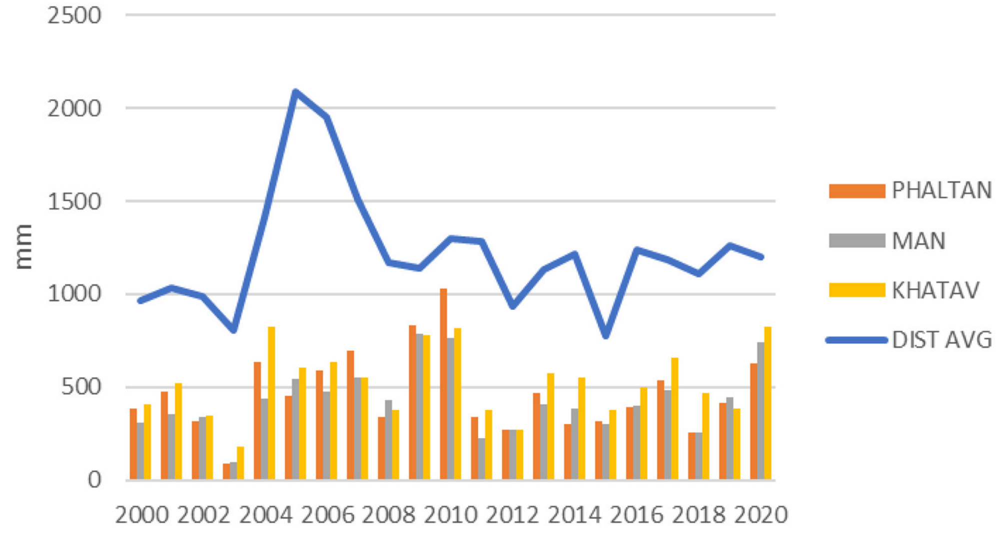

FIGURE 11 | Average annual rainfall in Satara district and in selected semi-arid eastern talukas, 2000–2020 (Source: Satara District, 2021 for 2002–2018 and Maharain.maharashtra.gov.in for the remaining years).

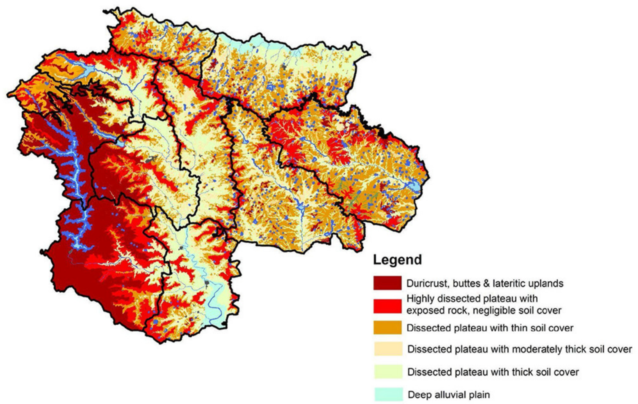

FIGURE 12 | Geomorphological patterns and constraints (GSDA data interpreted by authors).

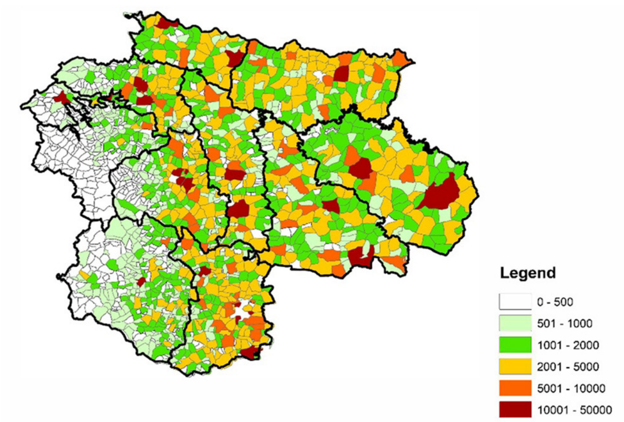

FIGURE 13 | Village population size according to major Census categories.

population. Those variables were supplemented by a GIS analysis of Census data on population and the social-economic variables of Scheduled Caste, Scheduled Tribes, and Agricultural Laborers, discussed below.

Village population size was shown to be positively correlated with water and sanitation services in a study of Pune district's peri-urbanizing areas, with some exceptions (Hui and Wescoat, 2018). **Figure 13** displays village population sizes in Satara district in relation to Census of India settlement categories. Very small villages with <500 people are concentrated in hilly areas that receive limited funding and support. At the other end of the spectrum, an increasing number of villages exceed the rural population threshold of 5,000 persons, which means that they will need to develop additional water sources to meet higher levels of service for their peri-urbanizing populations. A significant number of these towns are located in the central and high water-stress eastern zones of the district. In between are villages with highly variable populations due to seasonal migration, festivals, and tourism that pose challenges for variable demand management.

Drinking water programs in India must also address disparities in service for Scheduled Castes and Scheduled Tribes (Birkenholtz, 2013; O'Reilly and Dhanju, 2014; **Figure 14**). While their numbers are not large as a percentage of the total population of Satara district, there are important areas of spatial concentration along with many small habitations. **Figure 14** indicates that Scheduled Tribes are concentrated in the western hills of the district while Scheduled Castes have significant concentrations in the northeastern river valley of Phaltan taluka and eastern Man taluka, which are areas of

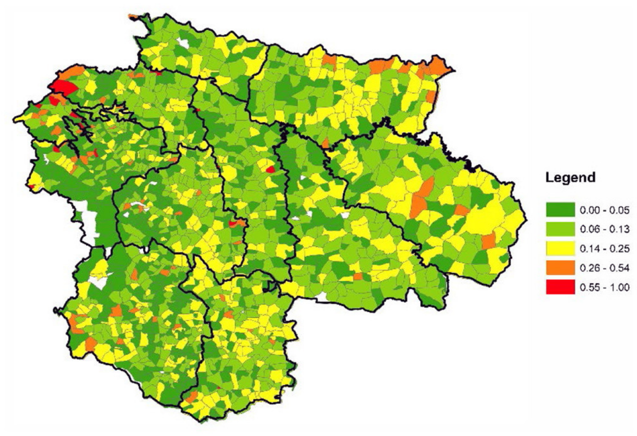

FIGURE 14 | Proportion of the population who are Scheduled Castes and Scheduled Tribes.

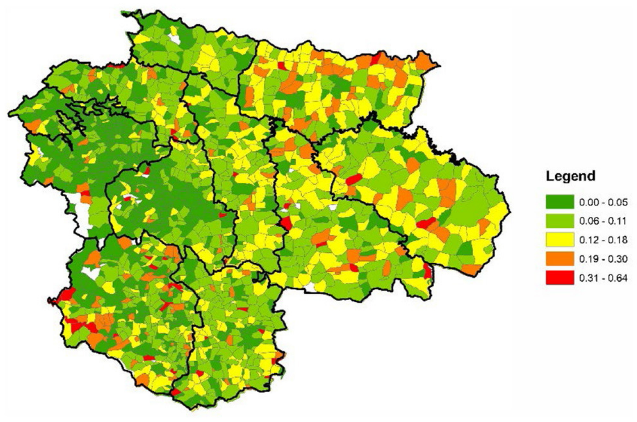

FIGURE 15 | Proportion of the population who are agricultural laborers.

relatively low drinking water service and sustainability. These areas also face physical water supply planning challenges in remote and hilly regions. Thus, in addition to prioritizing villages with large minority populations, village and district action plans need to address disparities in intra-village water access and service, and innovative approaches to water planning in remote and hilly areas.

Previous research has shown that the proportion of agricultural laborers is an indicator of socio-economic stress that can contribute to sustainability challenges (cf. Mohanty, 1999; Ramotra and Divate, 2018; Rathod, 2021). These occupations are less able to pay for new infrastructure, O&M tariffs, or asset management assessments. **Figure 15** indicates that the highest concentrations of agricultural laborers are again located in the northeastern Phaltan taluka, followed by eastern Man and Khatav talukas, with a cluster of red and orange villages in the southwestern Patan taluka. Financial support for villages with a high proportion of socio-economically disadvantaged classes is needed to ensure sustainable water service for all.

These environmental and socio-economic patterns reinforce the broad pattern of results observed in the mobile app analysis of sustainability variables and indices. Drinking water needs tend to be higher in areas of hydro-climatic and socio-economic stress—but not uniformly so. These—and additional—correlates of drinking water sustainability help interpret the mobile app survey results and suggest avenues for future research that are discussed below.

DISCUSSION

This study of rural drinking water developed a Sustainability Planning Framework and associated methods that addressed several key challenges in Maharashtra and posed lessons for future research. For example, the framework incorporated the state's current emphasis on water sources and schemes with greater emphasis on water services, measured in days per week and hours per day in pre-monsoon and post-monsoon months of the year. It considered water supply in liters per capita per day, but concluded that those values are not currently measured and that gross field estimates are not useful for planning purposes. As water metering and Internet of Things tools expand, volumetric measures of water service may become useful (Government of India, Ministry of Jal Shakti, Department of Drinking Water and Sanitation, 2021b). The mobile app did not include questions about rainfall patterns or landforms that affect groundwater sustainability because better data are available for those variables from the Indian Meteorology Department and Maharashtra Groundwater Surveys and Development Agency, as discussed in the correlates sections on Hydroclimatic Variability and Geomorphological Constraints. Future research will need to focus on quantitative and spatial data assimilation from mobile app, remote sensing, and government databases.

The mobile app survey was able to assess, analyze, and map three key criteria of sustainable drinking water services, which are not currently addressed in district annual action plans, notably: financial management; village institutional capacity; and asset management. The importance of those variables and inferences about them are presented in detail above. These results also raise some limitations. For example, an early iteration of the survey design in another district included additional questions about the equity of water service, e.g., to scheduled caste households. When all of the survey responses reported "no difference" in water service, they were assumed to be unreliable and were set aside. Partial proxies for socio-economic inequalities were inferred from three sources. First, the mobile app question about water service problems reported in remote and hilly habitations was deemed reliable, and it often corresponds with patterns of socio-economic marginality. Second, intermediate levels of water coverage and service (e.g., in Section Water Service Sustainability) were interpreted as proxies for socio-economic inequalities. Future research will need to address the complex socio-economic and institutional aspects of drinking water sustainability that are documented in local qualitative research, but have not yet been scaled up for district surveys of thousands of villages.

A third source of insight into socio-economic and environmental involved expanding the mobile app analysis to include several important correlates of drinking water service in Census of India and Maharashtra government data presented in the section on Correlates of the Drinking Water Sustainability Index. Those data supported the broad pattern of mobile app survey results, with nuanced observations about water service in areas with significant populations of scheduled caste, tribe, and agricultural labor. We recognize that much more can be done to assess the socio-economic profiles and dynamics of village water management. Again, an earlier iteration of the survey included a question about political aspects of local water funding, as they are important, but there was no consensus among district staff about how to reliably code political behavior related to drinking water systems. Future iterations of the mobile app survey can develop such variables, but they will need to be tested for reliable field data entry by *gram sevak*s. For example, the Jal Jeevan Mission has developed a new mobile app to document water sources, assets, and Har Ghar Jal villages. Until that time, the "screening" approach developed here, which identifies places with poor water service for more detailed local investigation provides a useful approach at the district-wide scale where thousands of villages are involved.

In summary, an important lesson from this drinking water planning study is that an initial question to be addressed in all villages of a district concerns current levels of water service. If water services register as "very poor," they can be prioritized for follow-up field assessment with close attention to local socio-economic and environmental factors. The sustainability of those services depends in turn upon local financial, institutional, and asset management. If one or more of them register as poor that provides a screen for focused field investigation and programmatic support.

CONCLUSIONS

This study addressed three key gaps in rural drinking water planning at the district scale in Maharashtra, India by developing a broad Sustainability Planning Framework and tools that complement and go beyond current spreadsheet methods. It has special relevance in the current context of the Government of India and state of Maharashtra's Jal Jeevan Mission efforts by shedding light on the *functional* dimensions of Functional Household Tap Connections for all.

The planning framework encompassed five major criteria of drinking water sustainability: source water sustainability, water service sustainability, O&M financial sustainability, village institutional capacity, and asset management. These recognized aspects of rural drinking water sustainability were analyzed individually and jointly. Jointly, they helped screen high priority villages for district attention and support. Individually, they indicated the types of support needed—source strengthening, improved service delivery, sound financial management, institutional capacity building, and so on. Future research should explore interactions among and different weights for these sustainability variables, based on district priorities and resources. It should also incorporate related water quality, socio-economic, and public health variables (Patel et al., 2009; Dhawde et al., 2018).

A second major contribution involves the methods and tools developed to assess drinking water needs in every village of a district, so that they all receive consideration, as a matter of equity. The mobile app tool, scoring, prioritization methods, and GIS mapping proved innovative and practical in this regard. These tools could be creatively enhanced by interactive engagement with stakeholders, e.g., whereby initial GIS mapping elicits new questions for follow-up field investigation and planning alternatives. Informal discussion of mapping results was undertaken in other case study districts and at the state level, but that could be advanced through rigorous experiments with map-based problem framing, screening experiments, and plan formulation.

Third, this research showed how each sustainability criterion can be specified along a consistent ordinal scale from 1 to 5, which includes interpretations of equity as well as coverage and sustainability. While a score of 3 or 4 may represent progress toward the goal of water for all, we argued that it also represents unequal and likely inequitable patterns of water service that require further field investigation and planning measures to correct. In addition to experimenting with stakeholder-defined variables, weights and interpretations, future studies could focus on methods for scaling-up the joint assessment of drinking water equity and sustainability at the district level.

These drinking water sustainability tools and methods can be used by districts for multiple purposes. This article discussed implications for near-term Annual Action Plans and strategic plans that require 3–5 years to execute. They can be used for sustainability monitoring tools for mid-course program corrections where warranted. By identifying types and patterns of poor water service, they help focus attention on financial, institutional, and socio-economic support. The tools developed are flexible, with the ability to add or remove indicators, and create new indices, particularly in socio-economic, environmental, and political domains, as described in the correlates and discussion sections of the paper.

As noted at various points, the study identified priorities for future research. Assessment of financial sustainability would benefit from closer analysis of access to and use of devolution grants and other funds for O&M and asset management. Village institutional capacity will be an increasingly important element in the context of piped water systems, as well as larger peri-urban villages that require skilled water operators, managers, and water supply committees. Villages in remote and hilly areas will need creative physical planning strategies that take advantage of watershed protection, rainwater harvesting, and innovative gravity flow and reuse systems. The state's current expansion of village observation wells, water budget analysis, and cooperative aquifer management will be important to incorporate in future studies, as will the multi-sector challenge of integrating rural drinking water planning with irrigation agriculture (which consumes ∼80% of water withdrawals) and municipal and industrial demand (Satara District Collector, 2019). Water treatment for successive reuse could facilitate some transitions. While no one set of tools is available to address the multiple use frontier for sustainable water planning, there are movements in that direction (Kumar et al., 2016; Shah and Harris, 2022). This study contributes a Sustainability Planning Framework with scalable methods for rural drinking water at the district level in Maharashtra and beyond.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/**Supplementary Material**.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Massachusetts Institute of Technology, Institutional Review Board. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

JW contributed to field research, paper conceptualization, analysis, and writing. JM contributed to conceptualization, analytics, and writing. RS developed the mobile app and contributed to analysis and writing. PV contributed to field research, GIS mapping, and writing. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2022.804845/full#supplementary-material

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Gap analysis and methodological framework to assess and develop water centric sustainable agricultural intensification pathways in Sub-Saharan Africa

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The sustainable agricultural intensification (SAI) debate, partly rooted in discussions over the Green Revolution, was developed in the 1990s in the context of smallholder agriculture in Africa. In many Sub-Saharan African (SSA) countries, production is still largely rainfed, with the prevalence of significant yield gaps and rapid environmental degradation. Projections indicate that climate and demographic changes will further intensify the competition for freshwater resources. Currently, SAI is centered around predominantly rain-fed agricultural systems, often at a farm and plot scales. There has been increased attention to the improved role of agricultural water management (AWM) to address the daunting challenges of climate change, land degradation and food and nutritional insecurity in SSA. Nonetheless, the supporting frameworks and tools remain limited and do not connect the sustainability assessment and the development of intensification pathways (SIP) along multiple scales of the rainfed irrigation continuum. This paper reviews the gaps in concepts and practices of SAI and suggests a methodological framework to design context-specific and water-centered SIP for the SSA region. Accordingly, the proposed methodological framework demonstrates: (a) how to couple sustainability assessment methods to participatory SIPs design and adaptive management approach; (b) how contextualized sustainability domains and indicators can help in AWM centered SIP development; (c) the approaches to handle multiple scales and water-related indicators, the heterogeneity of biophysical and social settings when tailoring technology options to local contexts; and (d) the principles which enable the SIP designs to enable synergies and complementarities of SAI measures to reinforce the rainfed-irrigation continuum. This methodological framework allows researchers to integrate the sustainability assessment and SIP design, and guides policymakers and practitioners in planning, implementing and monitoring SAI initiatives (e.g., Framework for Irrigation Development and Agricultural Water Management in Africa) across multiple scales.

KEYWORDS

agricultural water management, ecosystem services, sustainable intensification, food systems, multiple scales

Introduction

The world's population is expected to grow to 10 billion by 2050, in turn increasing the demand for agricultural products by about 50% as compared to 2013, in a scenario of modest economic growth (FAO, 2017). At the same time, in Sub-Saharan Africa (SSA), the projected population growth is higher, leading to intensified pressure on already scarce agricultural land and water resources (Conway et al., 2013). Worldwide, about 80% of the cropped area is dependent on rain-fed agriculture—this figure rises to almost 90% for the SSA region (You et al., 2011). Rain-fed agriculture is vulnerable to increasing climate variability leading to significant yield loss (AU, 2020). In the face of increasingly variable and uncertain rainfall, long dry seasons, recurrent droughts, and dry spells as well as floods, water is a key yield-limiting factor for rain-fed agricultural production systems, particularly in tropical semiarid and arid regions (Gleick, 2003; You et al., 2011; Conway et al., 2013; Nakawuka et al., 2018). In SSA the present yield level is only 24% of the potential yield (AU, 2020). Notably, an emergent major challenge is the production of 50% more produce under rain-fed dominated global agricultural systems (FAO, 2017; AU, 2020). The situation can be severe for SSA where the dominant system is rain-fed agriculture, with irrigation undertaken of only 6% of the total arable land (You et al., 2011; Conway et al., 2013). A rapidly increasing population (with a growth rate of 3%) in tandem with lagging agricultural growth has led to rising food imports, expected to swell from US$ 35 billion in 2015 to over US$ 110 billion by 2025. The import of agricultural products already accounts for about 15% of total African imports (AU, 2020).

Sustainable agricultural intensification (SAI) has been proposed (Conway et al., 2013; Steiner et al., 2020) as one option to address the increasing demand for agricultural production in SSA (AU, 2013). However, despite its merits—i.e., as illustrated by Pretty et al. (2011)—various forms of land degradation threaten the uptake of SAI. For example, Barrett (2008) and Sutton et al. (2013) have highlighted the linkages between excessive or otherwise inappropriate use of agrochemicals and environmental problems in many SSA areas (also note Assegide et al., 2022; Teklu et al., 2022); on the other hand, nutrient deficiencies and insufficient fertilizer application prevent productivity increases (Conway et al., 2013; Nakawuka et al., 2018). For example, in SSA (where subsistence agriculture dominates), continuous cultivation without adequate replenishment of soil nutrients leads to widespread soil nutrient mining, rendering people in poverty (Haileslassie et al., 2007). Many grazing lands are in a degraded state, affecting livestock productivity, household incomes, and environmental health (Haileslassie et al., 2007; Conway et al., 2013; Kemp et al., 2013). With the additional water resources required to sustain and increase production, there is a trade-off between the resulting agricultural benefits and the benefits foregone with alternative uses of the water (Cofie and Amede, 2015). These conditions are only prone to be further complicated in the face of climate change in SSA (AU, 2020). Overall, in many aspects, the planetary (e.g., biogeochemical flows) and local and regional boundaries (e.g., freshwater uses, land use changes) have been transgressed, with heightened vulnerability of agriculture and food systems to disturbances (Struik and Kuyper, 2017). In fact, recent studies (Steiner et al., 2020) indicate that in the worst-case scenario, the current food system can even collapse.

The commonly discussed priorities for SAI include increasing production on existing cropland by closing yield gaps (Steiner et al., 2020); the same is underscored by Conway et al. (2013), but with the addition of water for SSA in the definition. For achieving the intensification of agriculture, the increased and prudent use of water to close the yield gaps is vital (Cofie and Amede, 2015; van Ittersum et al., 2016; Nakawuka et al., 2018; AU, 2020). It entails improved agricultural water use efficiency (AU, 2013), diversifying and increasing the number of crops grown per year as well as a reduction in pre- and post-harvest losses. For livestock, the challenge is to increase productivity and the productive use of water per animal through better feeding (water productive feeds), effective animal breeding, and livestock health care, and a shift to more efficient animals—such as from cattle to poultry and fish or small ruminants—wherever possible.

However, a recent review by Haileslassie et al. (2020a,b) contends that the intensification of agricultural systems leads to the altering of hydrological processes, where multiple water values can be influenced (AU, 2020). SAI practices centered around agricultural water management (AWM), as posited by Cofie and Amede (2015) and AU (2020), provide an opportunity to address the current challenges and achieve food and nutritional security while improving upon or maintaining environmental sustainability (also note Rosegrant et al., 2013; MacDonald et al., 2016). Despite the differing opinions on SSA solutions given the diverse landscape, socio-economic settings, and technologies to pursue, a consensus is emerging that AWM-centered SAI needs to be built on context-specific sustainable intensification pathways (SIPs) (Godfray et al., 2010; Haileslassie et al., 2011, 2016; Conway et al., 2013; MacDonald et al., 2016; Nakawuka et al., 2018).

The current intensification practices and SIP design in the SSA region rarely include AWM in addressing challenges, ameliorating agricultural productivity and enhancing environmental integrity (Conway et al., 2013; Cofie and Amede, 2015). This lack of consideration is worrisome with the increasingly apparent impacts of climate change which affect both the demand and supply sides of freshwater resources as well as the size of arable land (Conway et al., 2013; Mutambara et al., 2016). Furthermore, rigorous efforts of trade-off management through targeting strategic entry points that leverage complementarity and synergies of interventions impacting the same water resources are typically deficient. Practical efforts to link sustainable intensification to landscape and food system (FS), along with targeted transformation from a piecemeal approach to one with an integration of genetic, environmental, and socio-economic practices, are in shortfall (Conway et al., 2013; Struik and Kuyper, 2017; AU, 2020).

The development of SIPs (Struik and Kuyper, 2017) requires the engagement of all stakeholders, an understanding of the state of the system, knowledge and technologies, the farmers' choice and vision, and a consideration of multiple models (Conway et al., 2013). In addition, a vital aspect is the recognition that farms of different sizes and systems can coexist in any location, use water in different magnitudes, and that more differentiation over time is driven by the interaction of demographic and economic change and political ambition (Masters et al., 2013; Struik and Kuyper, 2017). To ensure SIPs, for instance, new business models are essential for defining diverse options of agricultural technology to fit all farms at different scales and levels of resource endowment. The overarching objective of this study is to strengthen the current SAI planning process and practices by incorporating a systemic water lens. We first examine and synthesize the water-related gaps in science and practices of SAI by focusing on SSA; secondly, a methodological framework is developed to analyze the status of SAI to design sustainable water-centered and context-specific SIPs across multiple scales in SSA.

Methodology

In this study a narrative review type has been undertaken with a qualitative interpretation of prior knowledge. It has been innovatively synthesized to a methodological framework to assess the status quo of SAI measures and develop water centric SIPs. The published scientific literature is indexed in a variety of databases. To identify relevant literature from the same, we developed a search strategy, mainly in three databases—Scopus, Google and Google Scholar and Web of Sciences. Application of key words—sustainable agricultural intensification, sustainable agricultural intensification in Africa, intensification pathways, climate change impacts on water, irrigation in Africa, agricultural water management in Africa, rain fed irrigation continuum, food systems in Africa, water centric planning, agricultural intensification framework—was undertaken.

The search period was set to 2000–2022 and after a brief review of abstracts, 81 pieces of literature was screened as a priority. In many aspects, the literature was of international context; some was specific to SSA, either at the country or at the regional level. With the aim of comprehensive lessons, global, regional as well as country level examples were considered.

Figure 1 depicts the review framework deployed in this study, comprised of four interactive steps. It synthesizes the steps adopted and the key knowledge inputs in each step. The first step establishes the foundation of gaps assessment by exploring sustainable agricultural intensification practices globally and in SSA. Subsequently, SIP is defined and justified in the context of food system and water centric planning, specifically discussing the need for water centric pathways. The third step builds upon the previous ones to conceptualize and elaborate the SIPs. The final step encompasses stakeholder engagement to help validate the framework and obtain relevant feedback.

Sustainable agricultural intensification in a landscape context

Sustainable agricultural intensification has been advocated as a paradigm shift for SSA (Conway et al., 2013). Since many efforts and successful instances of approaches and technologies have focused merely on plot and farm scales (Pretty et al., 2011), there is a paucity of multiple scale planning and interventions which range from plot through farm to landscape. Despite water being advocated as a critical input for SSA agricultural transformation (Conway et al., 2013; Cofie and Amede, 2015), water-centric planning tools and frameworks have been found to be lacking in several different approaches.

Such gaps need to be addressed through a critical understanding of the spectrum of sustainable intensification discourse in the context of SSA and world experiences. Furthermore, sustainable intensification pathways, in the perspective of wider water and food systems as well as in the context of AWM, need greater exposition. The following section of this paper will systematically address these.

FIGURE 1
Simplified review framework synthesizing the steps followed and key knowledge ingredients in each step (SAI, sustainable agricultural intensification; SSA, Sub-Saharan Africa; SIP, sustainable intensification pathways).

Understanding the spectrum of the sustainable agricultural intensification discourse

Challenges and critiques of sustainable agricultural intensification

Sustainable intensification debate has its roots in the Green Revolution discussions. The concept came to be coined in the 1990s in the context of smallholder agriculture in Africa marked by low productivity levels and a degradation of natural resources (Cook et al., 2015; Struik and Kuyper, 2017). In general, sustainable intensification has variously been considered as a goal, a process (Firbank et al., 2018), a trade-off between economic production activity and ecological performance (Gadanakis et al., 2015), or a group of interventions (Godfray and Garnett, 2014).

In practical terms, however, SAI primarily means the delivery of more products per unit of resource while preventing the dwindling of natural resources and ecosystem services now and in the future (Conway et al., 2013; Garnett et al., 2013). Realizing these goals and reducing agriculture's environmental footprint necessitates precision farming as well as the presence of necessary support systems—policies, infrastructure, markets (for inputs and produce) (Mutambara et al., 2016), research and development, and ways to manage trade-offs (Struik and Kuyper, 2017).

SAI approaches are scale-dependent (Struik and Kuyper, 2017)—agronomy and input efficiency practices, for instance, are limited to the field and farm level in SSA (Pretty et al., 2011; Conway et al., 2013) while natural resources management, such as water, is typically manifested at a watershed, landscape, or regional level (Haileslassie et al., 2016; Weltin et al., 2018). Considering the same, a key aspect is planning and practicing SAI across scales in the SSA context. Some SAI approaches draw on the value-add generated through the pro-active embeddedness of the farm into the larger regional/landscape context, i.e., through coordinated actions, cooperation in supply chains, resource allocation or knowledge exchange. These indicate that observing SAI at multiple scales in SSA allows the integration of indicators that can be captured at different levels and in conducting a comprehensive assessment of the effectiveness of SAI approaches as its implementation evolves. In this respect, the usage of a hydrological boundary—hydrological response unit (HRU) as a basis to delineate the landscape boundary—could be a means to match the relevant landscape and water resources approaches and to enable AWM centered SAI assessment and SIP development across scales. Furthermore, the same is applicable to a river basin scale where several landscapes can be identified.

SAI practices in a landscape follow the shift in functional or structural components of landscape or both, with different degrees of a feedback loop between the two (Haileslassie et al., 2016, 2020b). Practices focusing on functional changes include precision farming, e.g., fertilizer micro-dosing in many SSA countries (Pretty et al., 2011), or crop-livestock integration (Haileslassie et al., 2007) as well as targeted decisions on the land use allocation basis the site characteristics and functions. Since water is an enabler and provides the interface of these functional and structural components, therefore, SAI practices and SIP development without adequate attention to water are prone to fail—production of enough quantities of food, feeding and meeting the nutritional needs of a young (60%) and growing SSA population and minimizing the negative impacts of food systems on the environment may all be compromised (Cofie and Amede, 2015). This is also critical in the light of pernicious climate change impacts (Mutambara et al., 2016; AU, 2020).

Allowing agricultural production to be increased without exceeding the earth's local and regional carrying capacity is one of the greatest challenges for SAI (Garnett et al., 2013; Firbank et al., 2018). In addition, another complication is the lack of consensus on the meaning and wider uptake of SAI (Pywell et al., 2015; Musumba et al., 2017; Xie et al., 2019). This is coupled with insufficient attention to the drivers influencing water use in agricultural systems and practices in the landscape along the food chain (including producers, manufacturers, distributors and consumers) (Godfray and Garnett, 2014; Hallstrom et al., 2015; Macfadyen et al., 2015). Trade-offs must be addressed when implementing different interventions, as the process of intensification does not improve the efficiency of all inputs at a time or aligns different actors in input, such as water use (Struik and Kuyper, 2017).

There are various criticisms (Cook et al., 2015) relating to SAI and its water-centered approach: (a) the current interpretation of SAI focuses mainly on production (supply); (b) more emphasis should be provided to resource scarcity such as water (Mutambara et al., 2016); (c) SAI is not viewed as a subsystem of a larger landscape and food system; (d) sustainability is defined too narrowly, with vital social and economic elements neglected, such as, livelihoods, equity, social justice, and economic viability; and (e) there is a focus on corporate-dominated food systems rather than transformation to a system delivering food and nutrition security for all. Notable, while these gaps are global in nature, they do fairly reflect the situation in SSA (Pretty et al., 2011; Conway et al., 2013).

The focus on production, with the consequent emphasis on "high-yielding varieties" has faced robust reproval; such approaches are more "productive" only in response to certain inputs such as fertilizers and water. The measurement of output, especially in rural societies, must consider more than just the marketable elements of crops. This critique also recognizes that the agricultural landscape in SSA is a multi-functional, multi-output system which produces not merely commodities (food, feed, fiber, agrofuels, medicinal products, and ornamentals), but also non-commodity outputs such as environmental services, landscape amenities and cultural heritage (Smith et al., 2017; Mekuria et al., 2021). The output of ecosystem services is analogous to multiple water values (AU, 2020) and entails the need for water-centric planning (Haileslassie et al., 2020a).

In addressing global food security, an excessive focus on yields (and supply) is restrictive since it fails to impart significance to equally important issues of access to food and governance of FS, including demand-side management which is critical in SSA. While Fischer and Edmeades (2010) emphasize the need to look at intensification within the context of the larger FS, it is practiced in SSA in a fragmented manner.

The position of sustainable agricultural intensification in the food system

Figure 2 illustrates the placement of SAI within a sustainable FS. SAI must be considered within a wider sustainable food system, as the need for food security is one of the major drivers of sustainable intensification. Furthermore, addressing multiple issues such as food waste, population growth and natural resources conservation (e.g., water) is critical (Fischer and Edmeades, 2010). Increasingly severe negative impacts on the FS are stemming from climate change, such as the hydrological regime being impacted (Mutambara et al., 2016). Interestingly, food systems are also culpable in this cycle, through direct and indirect emissions (Steiner et al., 2020). Thus, the SAI concept needs to be situated within a larger food system perspective to achieve the goal of increased production in tandem with environmental protection, in addition to SAI contributing to climate change adaptation and mitigation of these impacts. Some intensification interventions—those requiring a change in the structure or function of the landscape components in SSA (Haileslassie et al., 2020b)—are strongly linked to the water system and implicitly need practical interventions (e.g., improved governance of land and water) linked to the food system (Figure 2). Following a summary of SAI from the perspectives of its definition, practices, principles, and its

FIGURE 2
Sustainable agricultural intensification within a sustainable food system in an African or a low-income country (adapted from Fischer and Edmeades, 2010).

characteristics (Xie et al., 2019), reduction of food waste is suggested as an integral part of a sustainable food system (Figure 2).

Furthermore, while practicing intensification, food security and resource conservation is not guaranteed by ameliorated food production through SAI alone—it is vital to encompass multiple complex factors that determine accessibility to food at different scales. These include purchasing power, socio-political context, and access to distribution channels (MacDonald et al., 2016), all significant in the SSA context. Soil and water conservation in rainfed agriculture illustrates the same, since it does not guarantee sustainable intensification in a watershed as part of the conserved additional water can be used downstream by other farms in producing more food per unit land or for the industrial purpose to sustain food processing. The necessity of enhancing rainfed irrigation continuum in context of the FS is thus made visible.

In general, the SAI activities involving crop selection and livestock management for beef/dairy, as revealed by MacDonald et al. (2016), may require a change in consumption behavior. For example, at a global scale, shifting diets away from animal protein in favor of local crop-derived proteins has the potential to reduce irrigation water consumption by as much as 14%; substantially curtailing supply chain food losses and waste could reduce it by 12%. Diets, waste management, and governance are therefore critical determinants of the degree of crop production increase needed to ensure global food security (MacDonald et al., 2016). In addition, creating a set of robust criteria for deploying SAI in individual SSA countries through multi-stakeholder dialogues is crucial (Mutambara et al., 2016). Such dialogues must embrace representatives of food insecure/vulnerable groups and build upon local knowledge and priorities, and these criteria should provide at least equal weighting to sustainability issues and intensification. Also included should be the need for sustainable intensification to push beyond production and tackle key challenges in processing, consumption and waste, access and entitlements and markets, etc., as illustrated in Figure 2 (Mutambara et al., 2016). Furthermore, the SAI framework—focusing predominantly on the production side—must transcend agricultural production to encompass indicators and principles which support monitoring of natural resource allocation and equitable and efficient use, such as of water, within transforming landscapes (Pereira et al., 2012). This is also vital in capturing competing water demands between agriculture and other sectors and influencing the feasibility of sustainable agricultural intensification in a given SSA landscape.

Approaches to sustainable agricultural intensification

Within sustainable intensification, there are broadly considered to be three pillars (Godfray and Garnett, 2014)—ecological, genetic, and socio-economic intensification—not necessarily mutually exclusive, with diverse practices in each; this has been similarly emphasized within the SSA context (Conway et al., 2013). Some work suggests that there is no single generalizable model of *ecological intensification* practices, which are rather site-specific (Kremen et al., 2012; Lemaire et al., 2014). Such practices include the implementation of measures related to agroecology, organic agriculture, diversified farming systems, and some forms of conservation agriculture, agroforestry, and integration of crops with livestock systems (Haileslassie et al., 2007; Conway et al., 2013). Ecological intensification underscores the understanding and intensification of biological and ecological processes and functions in agro-ecosystems and extends its scope to landscape use and ecosystem service (Xie et al., 2019). Inclusion of landscape within ecological intensification corroborates the consideration of multiple and interactive scales to capture resources (such as water) to be a key input and intensification enabler. Such a multiple-scale approach can capture the sources and sinks of water and thus aid in practicing reasonable water allocation and judicious use. Water is a fundamental driver of ecosystem services. While the characteristics of ecological intensification—e.g., ecological process and ecosystem services (Xie et al., 2019)—reveal water-centered SAI to be important, its practical application could pose a daunting challenge.

Genetic intensification in SSA can range from "conventional plant breeding," "biotechnology," and "livestock breeding" which incorporates elements of plant and animal breeding technologies. An important goal for genetic improvement of crops is to adapt existing food crops to be resilient to increasing temperatures, decreased water availability in some places and waterlogging in others, rising salinity, and changing pathogen and insect threats as a consequence of climate change (Conway et al., 2013; Abberton et al., 2016). Genetic improvement through livestock breeding attempts to sustainably increase the productivity of livestock with little to no increase in the amount of land devoted to livestock fodder production and grazing (Steiner et al., 2020). Water saving may be undertaken in delivering livestock products and services, though the practice may vary. To enable improved water saving in SAI in SSA (e.g., for the livestock sector), a model that synchronizes livestock breeding, feed sourcing, and feeding is vital, given the high volume of freshwater input required to produce a unit of dairy and beef products (Haileslassie et al., 2011). Transforming the agricultural paradigm away from high inputs toward stability and environmental resilience of yields, alongside decreasing inputs, is a daunting challenge (Conway et al., 2013). However, it may be met with the accelerated application of genetic intensification tools coupled with judicious consideration of associated input packages such as water productive feed sourcing and feeding in SSA (Haileslassie et al., 2011; Abberton et al., 2016); in this context, water-centered planning can be critical.

Socio-economic intensification incorporates supportive enabling environments and building the social and human capital of smallholder farmers in SSA (Conway et al., 2013). The former combines macro-economic policies that favor markets and trade, the provision of inputs and physical and social infrastructure as well as institutions (Conway et al., 2013; Yami and van Asten, 2017). Social capital is the value generated through social networking, trust, and cooperation within and between people and organizations, as well as through culture and tradition. It is an important element for creating sustainable livelihoods and economic development in SSA (Conway et al., 2013; Rivera et al., 2019). Human capital or capacities, such as education, skills, and health, can foster productivity and improve livelihoods and food security, and play a critical role in economic growth and development since human actors are at the center of production, processing, distribution and consumption (Davis et al., 2007). Since agricultural education and training, extension and research are critical aspects of the capacity building of farmers, more investments are needed in education to improve the human capital in SSA (Conway et al., 2013).

Lessons learned from the Green Revolution have highlighted the higher yield and better food security garnered through an emphasis on a few intensification pillars such as high-yielding varieties, irrigation, mineral fertilizers, and agrochemicals (Conway et al., 2013; Struik and Kuyper, 2017). However, notable negative consequences include the depletion of water resources and the salinization of agricultural land in many parts of the world like Gujarat (Mutambara et al., 2016; Steiner et al., 2020) as well as SSA. To evade the same, SIP development and SAI implementation must account for AWM. Sustainable agricultural intensification efforts without practical integration of the three sustainability pillars and centering of critical resources, such as water, can deplete the resources leading to the collapse of the food system.

Measuring indicators of sustainable agricultural intensification

Sustainable agricultural intensification requires indicators and associated metrics for tracking progress, assessing the trade-offs, and identifying synergies (Pereira et al., 2012; Haileslassie et al., 2016; Smith et al., 2017; Xie et al., 2019). Furthermore, measuring and monitoring sustainability also provides an opportunity to exercise adaptive management (Haileslassie et al., 2020b), while the indicators used can assist in understanding the status of the SAI gaps elaborated earlier. A review undertaken of 60 publications (Smith et al., 2017), has organized the SAI indicators into five dimensions: productivity, economic sustainability, environmental sustainability, social sustainability, and human wellbeing.

Productivity has been articulated in a variety of indicators and metrics (Smith et al., 2017) including yield, efficient use of inputs including water (Pereira et al., 2012) and animal health. Commonly cited indicators of economic sustainability include agricultural income and crop value. Metrics of agricultural income at the field level include net income from agriculture (Castellini et al., 2012), disposable income (Meul et al., 2008), losses of agricultural income due to natural disasters, or changes in total agricultural income (Zhen et al., 2005). The profitability of a crop and the estimated labor required to grow a crop comprise the crop value metrics (Gafsi et al., 2006). One of the indicators included in the human wellbeing dimension is food and nutrition security (Kamanga et al., 2010). Biodiversity conservation, carbon sequestration, soil erosion, nutrient dynamics, soil biological activity, soil quality, and in many cases the productive uses of water are indicators of environmental sustainability (Thrupp, 2000; Phalan et al., 2011; Pereira et al., 2012; Conway et al., 2013).

Social sustainability is measured by indicators such as information access and gender equity (Phalan et al., 2011). Farmers' access to information can be gauged by their level of connectivity within the agricultural knowledge network, consisting of farmers and local experts (Hoang et al., 2006). It can also be measured quantitatively by administering a test to farmers regarding a set of agricultural practices. Gender equity in each SAI effort can be evaluated by the percentage of farmers participating in the project or adopting an SAI technology suitable for women. Equal access to resources for male and female farmers could also be an indicator of gender equity in SAI (Degrande et al., 2013). Furthermore, equity in the impacts of intensification efforts can be reflected in the distribution of labor, or the proportion of SAI-related work performed by male relative compared to that performed by women, along with recognition of other attributes of inclusion and gender. This can be applied, for example, to some aspects of common property resources management, demand-side gaps analysis and livelihood options (Fischer and Edmeades, 2010).

Despite the attempt to measure water resources sustainability (at farm and plot level and more so for production-oriented SAI), water in the perspective of ecological sustainability and across multiple scales and multiple uses is in fact, a far more critical indicator than what is suggested (Pereira et al., 2012; Conway et al., 2013; Haileslassie et al., 2016; Smith et al., 2017; Xie et al., 2019). Water is a fundamental driver of ecosystem services and as discussed earlier, indicators on water allocation across multiple uses—ecological, social, cultural, and economic (Haileslassie et al., 2020a)—are missing for the SSA region. In general, water is an intensification enabler and an interface of the functional and structural components of an ecosystem. Limiting its indicators to a single dimension (economic or ecological or social) will deter a true picture of sustainability from emerging, distorting the SIP.

Sustainable intensification pathways in perspective of wider water and food systems

SIPs are a means toward SAI in achieving food security, social inclusion and environmental sustainability goals. Sustainable intensification pathways can largely be considered as balancing trade-offs between intensification and sustainability across its key dimensions (social, economic, and environmental) and diverse scales (Haileslassie et al., 2016; Kumar et al., 2019). Such an approach can help minimize the probability of hitting a non-beneficial tipping point (Xie et al., 2019) which is a critical point in a situation, process, or system beyond which a significant and often unstoppable effect or change takes place. There is a need to focus on the socio-economic, ecological and genetic intensification in conceptualizing practical approaches to SAI for SSA (Conway et al., 2013). Knowledge on integrating these approaches into the landscape scale and water-centered planning is complex and often deficient.

Different farm types can coexist in a landscape in SSA countries such as Ethiopia, with numerous heterogeneities in terms of the level of SAI efficacy and its pathways within a landscape (Mutyasira et al., 2018), with several farm types in a landscape involving farms with high intensification-low sustainability, low intensification-high sustainability, low intensification-low sustainability and high intensification-high sustainability. While SIPs attempt to bring many farms to an intensive-sustainable status, identification of common pathways to this destination in the realm of such diversity is a significant challenge.

This complexity partly stems from the specific location of the farms in a landscape that influences the biophysical and climatic conditions and their access to water resources for irrigation. Farms situated in the upper landscape may need to focus on soil and water conservation-based intensification to reduce on-site erosion induced land degradation. This leads to a longer growing period (onsite), higher yields, and flow of water (surface and groundwater) to lower landscape positions. The process supports the idea of operationalizing rain fed-irrigation continuum across a scale, illustrating water to not only be a point of convergence of SAI measures but also a chief factor in linking lives and livelihoods across landscape positions (Kumar et al., 2019). The challenge arises in supporting this connectivity.

A smaller sized SAI plan may have linkages to a more homogeneous group of farms, reducing the issues of aggregation in developing the SIP (Mutyasira et al., 2018; Kumar et al., 2019). This means a multi-scale approach where farms are nested in farm typologies and farm typologies are nested in the landscape can help identify effective SIPs at a landscape scale for SSA. Such a nested approach requires both landscape-level and farm-level indicators that complement each other.

Much like its spatial scale, SIP is also time-bound. Change in external drivers, actors' behavior, or emerging issues such as climate change can shift the threshold points of sustainability. Thus, a systematic decision and continuous co-learning through an adaptive management approach to achieve sustainable intensification in SSA becomes necessary (Birge et al., 2016; Haileslassie et al., 2020b).

Designing sustainable intensification pathways

The principles of SAI are applicable to any production system and agricultural landscape and its associated value chains, whether it is conventional, organic, or some other system of agriculture. SAI can be implemented in farm enterprises of different sizes and degrees of market integration. It should be noted, however, that simplistic, universal prescriptions or recommendations cannot lead to successful SIPs (Lobell et al., 2009). Designing the right SIPs requires an understanding of the status of SAI in terms of the condition and trajectory of a system and the reason behind certain trends occurring in specific contexts, as illustrated by the priority indicators set by actors reflecting their challenges, opportunities, and ambition at different scales (i.e., landscape, community/local, and farm). A knowledge of the practice and *status quo* of sustainability indicators identified through stakeholder engagement is indispensable. A combination of qualitative and quantitative methods which explore the level of resources endowment and utilization, community livelihood and future expectations and political ambitions is essential (van Ittersum et al., 2013).

SIPs should not aim to imitate the natural ecosystems that have not been optimized for food, feed, fiber, or bioenergy production (Denison et al., 2003). Instead options should be derived from the sustainable use of natural systems, traditional systems, and "alternative" systems, from experimentation and traditional knowledge as well as scientific theory and empirical observation. These options need to be tailored to local conditions by the use of well-integrated research and development systems subsequent to a participatory approach. Although many principles for systematic SIPs development are generic, the scope for increasing eco-efficiency in agriculture varies widely.

Research on SAI has illustrated the pathways which combine the maintenance or increase of agricultural production on the same area of land and the contribution to sustainable development in a balanced way (Godfray et al., 2010; Garnett et al., 2013; Gadanakis et al., 2015). Four fields of action based on the spatial scale have been identified (Weltin et al., 2018), including agronomic development, resource use efficiency, land use allocation, and regional integration, whether these are SIPs or just fields focusing on productivity improvement. The first, agronomic development, ranges from adapted cropping such as crop rotations and intercropping to available land and water resources as well as climate patterns. Within a specific crop management system, practices can contain the choice of variety and crop management including techniques from tillage to soil conservation (Townsend et al., 2016). This field of action also looks at the use of novel technical solutions, new digital technology applications, the use of site-specific information and system data, and precision farming.

Sustainable intensification practices grouped under resource use efficiency center around the SIPs aiming to increase agricultural productivity either through the use of fewer inputs or with the higher production at a given input level (Weltin et al., 2018). Resources could be natural (green, blue and greywater, manure, residues, and animal feed), chemical (fertilizers and pesticides), and human (labor, knowledge and managerial abilities). The majority of approaches related to resource use efficiency (Weltin et al., 2018) pertain to fertilizers (fertilizer use efficiency and measurements of soil nutrient balances and losses), residues and water (marginal water use, integrated crop water management or rainwater harvesting). However, sustainable resource use on-farm may not generate sustainable intensification at a basin level. The approaches associated with human resources, such as knowledge management and labor productivity, are less frequently covered by the current SAI (Weltin et al., 2018).

The field of action of land-use allocation comprises of approaches that aim at improving the joint provision of various environmental services in the same landscape and/or to produce the same amount of food and biomass on less land or in a different organization of land (Weltin et al., 2018). Most of the literature surrounding the same concerns landscape design and its decline in the land sharing and land sparing SAI approaches (Shackelford et al., 2015). Both the dwindling land and water resources in SSA (Mutambara et al., 2016) available for increasing agricultural productivity through extensive agriculture, along with the need to conserve biodiversity and key ecosystem functions call for the holistic integration of productive and natural spaces at the landscape level and the Identification of innovative land-use practices.

The land sharing and land sparing intensification approaches like the integration of livestock and pasture, coffee plantations and native vegetation and birds are linked to coexistence on a specific landscape of agricultural production (Mastrangelo and Gavin, 2012). Such approaches also work with mixed crop-livestock systems on the landscape scale. Sustainable agricultural intensification practices grouped in this category generally increase the diversity within the agricultural systems, allowing for the improved regulation and maintenance of key environmental services such as water through a diversified landscape mosaic (Lemaire et al., 2014). This implies that certain land uses have a lower application of water and can enhance "natural storage" in the landscape. Hence the diversification at the landscape level can only benefit ecosystem services if suitably undertaken, for instance through water-centric planning and judicious implementation.

Regional integration covers elements such as knowledge exchange and innovation diffusion, the functioning of institutions, governance mechanisms and local networks (Mutambara et al., 2016; Weltin et al., 2018). Institutional changes such as taxation, land tenure policies, or access to credits, improved forms of leadership and governance are considered to be triggers for SAI practices (Southern et al., 2011; Bird, 2014). Such intensification practices play a significant role in cooperation and experience exchange between different actors including policy and decision-makers at the regional level for different purposes, such as common resource use, value chains and marketing strategies (Mutambara et al., 2016). Studies indicate that multi-level and multi-stakeholder networks in SSA can enable common resource use, redistribute inputs and close nutrient loops (Pretty et al., 2011), and emphasize not only the role of extension services (Pretty et al., 2011), but also the effectiveness of farmer-to-farmer learning (Baulcombe et al., 2009).

Numerous studies have looked at SAI and generic SIPs by considering emerging issues such as environmental externalities and climate change (Steiner et al., 2020). The focus is largely upon understanding the yield-limiting (soil, water and plant varieties), yield-reducing (pests), enabling environments (policies and institutions) and the complementarities and minimized trade-offs (among the package-ingredients and external factors) in proposing the pathways (Lobell et al., 2009; Bindraban and Rabbinge, 2012). According to projections, climate change is predicted to hit, in particular, water resources even harder and impact agricultural production and ecosystem services (Haileslassie et al., 2016; Mutambara et al., 2016). Keeping the same in mind, the new model for designing effective SIPs must consider water resources (Cofie and Amede, 2015); the following section elaborates on the same.

SIPs in the context of agricultural water management

Current predictions indicate declining water availability and the occurrence of more frequent and severe droughts and floods in the coming decades in many agricultural regions worldwide (Rosegrant et al., 2009). Agriculture is responsible for about 70% of the global freshwater withdrawals; notably, this figure can reach to more than 90% in some agricultural economies (such as SSA). Of the total world food production, 40% is derived from irrigated systems on only about 20% of the arable land area. More investments in improving water productivity in existing schemes and safely expanding irrigated agriculture are thus vital for sustainable FS, with a strong emphasis on policies and new technologies that ensure maximum efficiency and productivity while protecting critical freshwater resources and the environment (Rosegrant et al., 2009; MacDonald et al., 2016; Mutambara et al., 2016; Pretty et al., 2018; AU, 2020). Integrated solutions must balance the use of surface water and groundwater resources by different sectors (Gleick, 2003) while optimizing water productivity in the whole FS. Consuming less water for instance can also be achieved through wasting less food, consuming less water-intensive food, and augmenting the water use efficiency in crop-livestock systems; altogether creating practical linkages to a sustainable FS (MacDonald et al., 2016).

Of the total the cropped area, about 80% worldwide and more than 90% in the SSA region depends on rain-fed agriculture. Rain-fed agriculture is vulnerable to increasing climate variability which leads to significant yield loss (Mutambara et al., 2016). With factors such as increasingly variable and uncertain rainfall, long dry seasons, recurrent droughts, and dry spells as well as floods, water is a key constraint for rain-fed agricultural production systems, especially in tropical semiarid and arid regions (Gleick, 2003; AU, 2020). The challenge of 50% more production of food (FAO, 2017) in the rain-fed dominated global agricultural system is significant, with the situation for SSA being potentially dire (AU, 2020).

Sustainable intensification pathways in SSA in the context of AWM and water-centric planning recognize multiple values of water (Haileslassie et al., 2020a), enhancing water availability and expanding irrigation (full and supplementary) by optimizing consumptive and reducing non-productive water losses (Pereira et al., 2012; MacDonald et al., 2016). There is a huge potential for crop water management to sustainably intensify agriculture including multiple production and mitigation of crop failure risks related to dry spells. Along this line, many global policies, including the ones at the regional level in East Africa, concentrate on irrigation development to meet food demands (Nakawuka et al., 2018). Although this approach is important in different contexts, there are recognized limits in the scale of its expansion in many parts of the world. Only a small proportion of cultivable land in Africa (5.5%) is suitable for irrigation (Abrams, 2018) because of limited water availability and soil/topographical characteristics. Contrastingly, Altchenko and Villholth (2015) suggest that the total area of cropland irrigable with renewable groundwater ranges from 44.6 to 105.3 × 10^6 ha, which corresponds to 20.5–48.6% of the cropland over the continent; there is visibly diverse opportunity for AWM-based SAI in Africa (Nicol et al., 2015). Optimal climates are specific to each cropping system (Li and Troy, 2018), where irrigation provides a benefit; there are also other conditions where irrigation proves to have marginal, if any, benefits. It is also prudent to understand at which point and under which circumstances irrigated agriculture is more beneficial than rain-fed agriculture and the best way for the two systems to complement each other (Vanschoenwinkel and Passel, 2018).

Different farms should consider water management options across a wide spectrum ranging from purely rain-fed farms to purely irrigated ones (Vanschoenwinkel and Passel, 2018). Some farming, for example in East Africa, is noted to be moving toward somewhere in between rain-fed and irrigated agriculture, i.e., practicing supplementary irrigation and water conservation measures (Nicol et al., 2015).

Access to green and blue water for agriculture (Vidal et al., 2009) is not simply addressed by opposing rain-fed and irrigated agriculture—agricultural systems have often not been strictly rain-fed or irrigated. Irrigation farmers typically also use green water and at times rain-fed farmers, if possible, also use blue water, even in the absence of formal irrigation systems (Vidal et al., 2009). Farmers have predominantly always dealt with a green to blue water continuum, struggling to extract the best product value from the same. Moving along the continuum, the impact on hydrological processes intensifies, with varying accessibility for other actors and sectors. Furthermore, the inclusion of greywater has become increasingly important in areas dealing with physical water scarcity in SSA (Vidal et al., 2009; Mutambara et al., 2016); this further complicates the SIP design.

In nurturing the rain-fed and irrigation continuum through principles and practices of SIP planning, the significance of water-centric planning in pursuing SAI in SSA and globally is paramount. This is revealed by the following factors:

i) The agricultural landscape is a system hierarchy stretching across plots, farms, watersheds and basin, operating within the same hydrological system. Water flows create intra- and inter-system linkages; therefore changes in one part of the landscape affect water availability and attendant livelihoods and ecosystem services (provision, regulation, support, and cultural) in other parts. Water-centric SIP design ensures desirable water quality and quantity while maximizing agricultural production in the upstream areas. This leads to mitigation of impacts, and provision of reliable water supply to the downstream areas.

ii) Climate change is projected to reduce renewable surface water and groundwater resources significantly in the driest subtropical regions such as SSA (Mutambara et al., 2016). Competition for water among different uses and users will only be amplified, threatening water, energy, and food security (Boretti and Rosa, 2019). Water-centric SIP design can ensure judicious use and optimum allocation.

iii) Farmers in SSA have not managed well in adapting to increasing water scarcity in the face of climate change, especially on the exploration of ground water (Mutambara et al., 2016). Africa's intensification efforts are in part triggered by Sustainable Development Goals (SDGs) (Pretty et al., 2018), with water at the heart of many of the Goals. It is a key input, identified to be a resource cross-cutting several SDGs and their respective targets—no poverty (SDG1), zero hunger (SDG 2), good health and wellbeing (SDG3), gender equality (SDG 5), climate action (SDG13), life below water (SDG14), and life on land (SDG 15). Achieving the targets under each of these goals in a region as water scarce as SSA without water-centric SIP becomes a major obstacle.

iv) Global water demand will grow significantly over the next two decades in the industry, domestic and agriculture sectors. While industrial and domestic demand will outpace agricultural demand, demand for agriculture will nonetheless remain the largest, increasing by 60% by 2025. These figures could be even higher for SSA given the young population and the high growth rate (Boretti and Rosa, 2019). In total, this entails the need for judicious use of water ensured through water-centric SIP.

v) Water is the major yield-limiting factor globally and in SSA. Meeting a 50% expected increase in food demand will not be possible without a water-centric SIP design. Within SSA, meeting future cereal demand will not be feasible with the existing production area through yield gap closure alone (van Ittersum et al., 2016). A yield gap analysis for 10 countries in SSA revealed that in addition to yield gap closure, other more complex and uncertain components of intensification are also indispensable. These include increasing cropping intensity (the number of crops grown per 12 months on the same field) and sustainable expansion of irrigated production area (van Ittersum et al., 2016). Similarly, Agenda 2063 of Africa Union proposes to increase water productivity from rainfed and irrigated agriculture by 60%, harvest at least 10% of rainwater for productive use and recycle at least 10% of wastewater for agricultural and industrial uses (AU, 2013). Considering the same, AWM-centric SIP can unlock Africa's potential to ensure food security.

The proposed methodological framework for sustainability assessment and development of water-centric sustainable agricultural intensification pathways

Conceptual framework

Sustainability assessment is a complex appraisal system that supports decision making and policy formulation in the broader social and environmental context. It transcends purely scientific evaluation (Sala et al., 2015; Xie et al., 2019)—there have been several attempts, for the last decades, to develop a sustainability assessment framework (Sala et al., 2015; Smith et al., 2017), on top of efforts to categorize sustainability assessment practices. Some look specifically at the tools applied (Gasparatos and Scolobig, 2012), while others focus on the broader process employed and the aims and scope of the assessment (Hugé et al., 2013). There are gaps in terms of the understanding of SAI status quo, designing SIP and employing adaptive management.

AU (2020) initiated a framework for irrigation development and AWM in Africa (IDAWM), which is structured around four strategic AWM areas or agricultural water developmental pathways. It includes AWM in rain-fed farming; farmer-led irrigation; scheme development and modernization; and unconventional water use for irrigation. IDAWM is a high-level direction of development, therefore does not include a detailed methodology, details on implementation and on the ways that different plans can complement each to bring additional benefits.

Critiques highlight the failure of the SAI assessment and SIP development efforts to address: (a) how sustainability concept and assessment methods evolve in time and space with emerging agricultural techniques and a better understanding of global challenges such as climate change and the limitation of freshwater resources (Mutambara et al., 2016); (b) methodological principles and elements to couple agricultural sustainability assessment with SIP development; (c) the means to integrate the different pillars of sustainable agricultural intensification; (d) how the best indicators of sustainable agricultural intensification are anchored in the overall FS, and (e) how to operationalize the multiple scales approach of agricultural sustainability assessment and SIP design to capture the performances of different attributes, which is unlikely at a single scale.

We argue that a framework that outlines how to move from agricultural sustainability assessment *per se* to the development of SIPs is crucial to enable complementarities and synergies of interventions and address existing and emerging challenges.

The water-centric framework proposed here (Figures 3, 4) aims to ensure comprehensiveness, flexibility, and robustness in the evaluation and planning of SAI. The framework is constructed from four building blocks: (a) targeting sustainable agricultural intensification dimensions (Figure 4A); (b) understanding the *status quo* of SAI measures (Figure 4B); (c) defining SIPs to bring desired change and manage the trade-offs (Figure 4C), and (d) principles and approaches of SIP design which enable synergies and complementarities of interventions (Figure 4D).

Figure 4 is an integral part of Figure 3 and it illustrates: (a) the approaches to address landscape and farm level heterogeneity; (b) the approaches operationalizing the sustainability assessment and the development of SIPs at multiple scales; (c) links with weak performing indicators with changes needed (SIPs) in time (short, medium and long term), space (landscape positions) and social context (farm type/income level/tenure); (d) combination of sustainability assessment, SIP development, and adaptive management. The following sections discusses each of these components.

Defining sustainability dimensions to understand the performance of sustainability indicators and the changes needed

In SAI assessment, the starting point is deciding on sustainability dimensions which form the basis for indicators co-identification. The sustainability dimensions (Figure 4A) in the water-centric framework build upon earlier work from Haileslassie et al. (2016). The relative importance of sustainability dimensions is pliable and should be fixed in discussion with actors such as local decision-makers and the community. Particular attention can be given to emerging threats (e.g., climate change or a global pandemic like COVID-19), opportunities and political ambitions. The sustainability dimension must place at the forefront the concerns which need special attention in the perspective of local communities—the first entry point to design the SIP. For this study, a water-centric approach was deployed since water management is a challenge in most cases in many SSA countries.

Understanding the status quo of SAI measures: A critical step following the sustainability dimensions is to understand the *status quo* of the SAI measures (Figure 4B). This involves the identification of an inclusive matrix and indicators in a participatory manner. SAI indicators are an important tool to inform the design of SIPs by offering a basis. The same enables a better understanding of current conditions, goals, identifying trends and targeting changes needed in SAI practices; furthermore, it aids in comprehending and monitoring the progress made in both relative and absolute terms. Indicators can also help in evaluating and selecting alternatives, given that they are concise and easily interpreted—thus, they too can offer an entry point to enable water-centric SIP planning.

It is important to distinguish between indicators as landscape units, structures, functions or processes and as measures, i.e., properties of a phenomenon, body, or substance

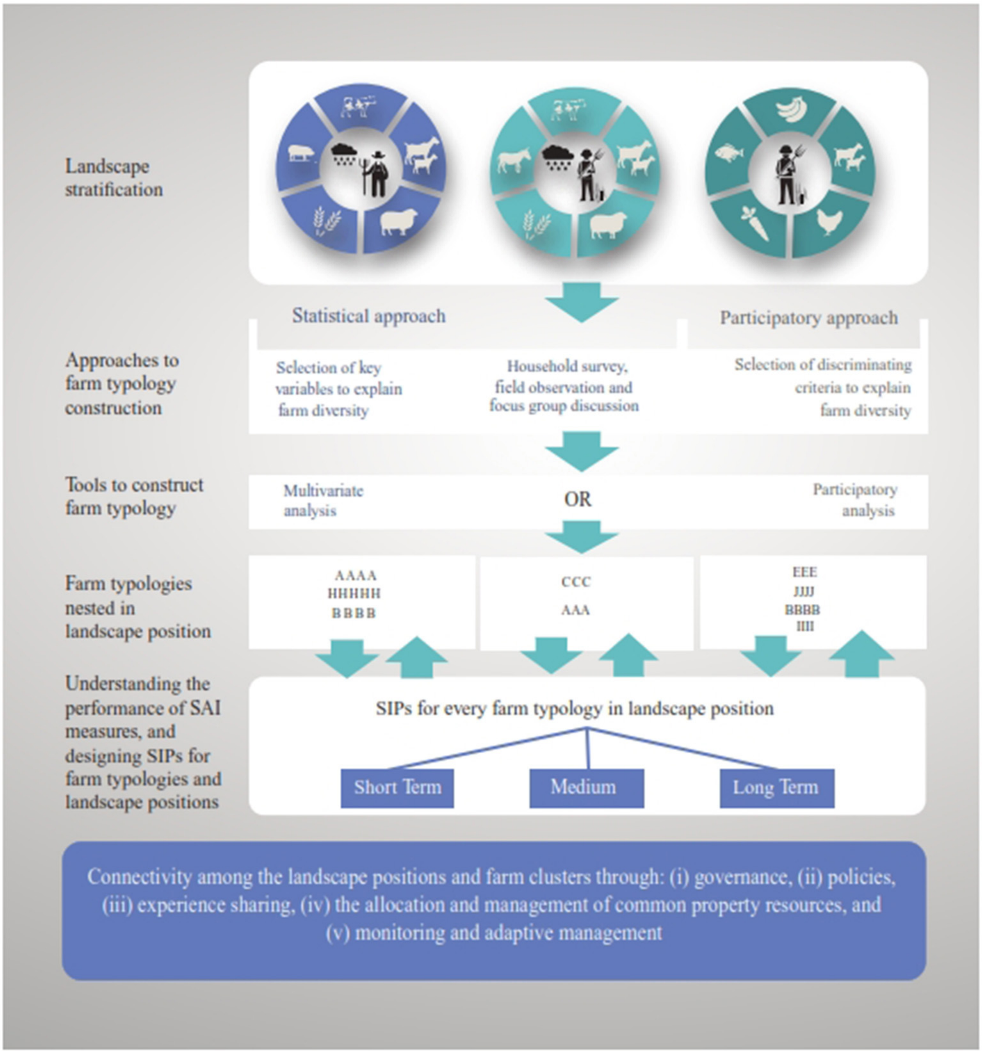

FIGURE 3
Schematic diagram illustrating how to operationalize the multiple scales approach in sustainability assessment and SIP planning.

to which a magnitude can be assigned, and between descriptive and normative indicators. Generic indicators and matrices contributing to each of the target dimensions can be identified using previous studies (Pereira et al., 2012; Haileslassie et al., 2016; Smith et al., 2017). Since every potentially available indicator cannot be utilized, so an element of simplification while maximizing unique and relevant information, is essential. Balancing of indicators for sustainable intensification of crop production at the field and river basin levels is also recommended (Chukalla et al., 2020), confirming the significance of multiple scales and water-centric SAI.

Subsequently, the above must be contextualized basis the desk work, key stakeholder consultations, and expert knowledge of the site (Figure 4B). Table 1 describes an example of generic indicators proposed to understand the *status quo* of a water-centric SAI assessment. During the first visit, farmers will be asked to co-develop additional indicators. Participatory pairwise ranking approach can be used to prioritize indicators. Indicators that do not reflect end-users' interest and ambition, as well as the SIPs based on the same would not be adopted much.

Much like to the sustainability dimension, the indicators can be used as an entry point to address the erstwhile gaps in the SAI practices (Heink and Kowarik, 2010). For instance, the relevance and level of integration of environmental, genetic, and institutional intensification and elements of the sustainable food system such as governance, NRM and demand management could be explored. While water use efficiency and access to water may be essential indicators (Pereira et al., 2012) at the farm and landscape level, practices reinforcing rain-fed irrigation continuum (e.g., off- and *in-situ* water harvesting) and bringing

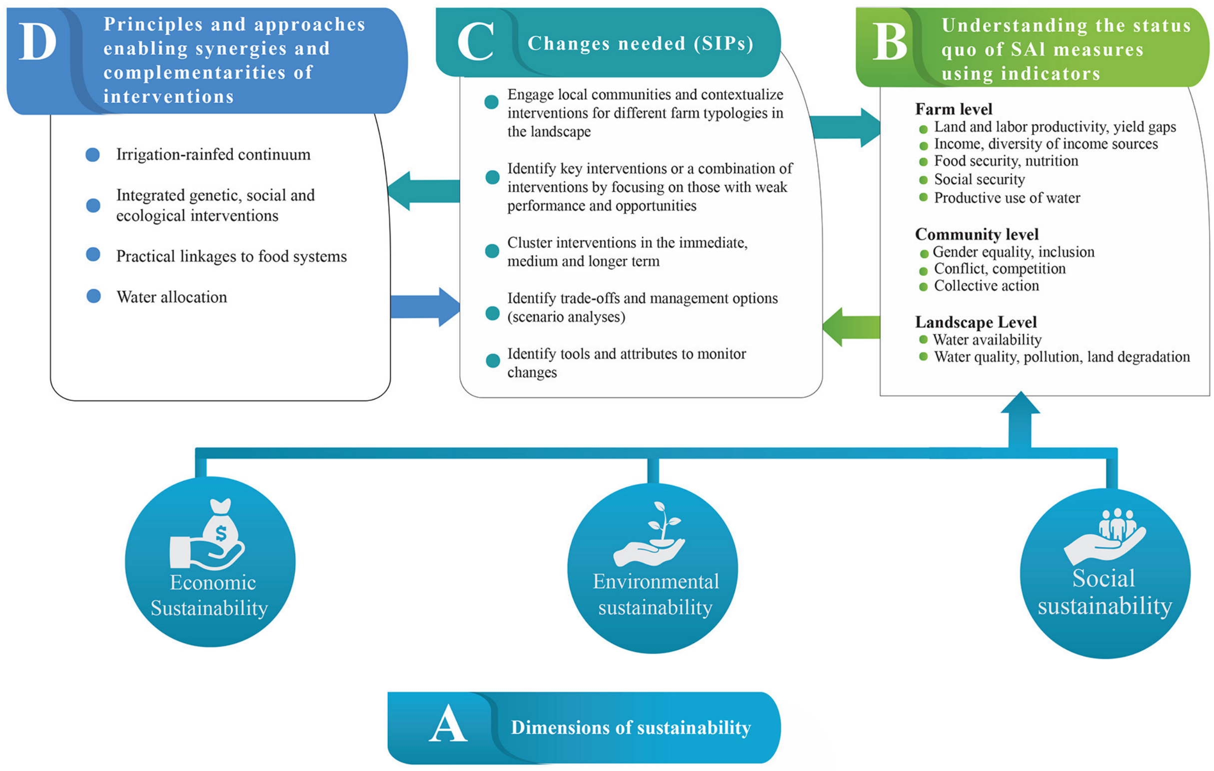

FIGURE 4
A methodological framework to assess the status quo of SAI measures and to develop sustainable agricultural intensification pathways (SAI: Sustainable agricultural intensification; SIPs: Sustainable intensification pathways. Each alphabet **(A–D)** represents sequential steps and explained by texts next to it)

the ecological intensification into the forefront could provide the principle and strategic direction where the water-centric SIPs could be rooted. Investigating the relevant indicator at this stage is beneficial in realizing water-centric SIP.

Time, space and a social dimension are critical in the identification of indicators. Common landscape-level indicators may not be relevant for farms, and vice versa, although some may be cross-cutting. Furthermore, today's indicators for food security might be less relevant in the long run. This implies that the indicators could be scale specific but also interactive across scales (Figure 4B). Farms and landscapes are heterogenous, hence reaching mutual consent on the choice of representative indicators is a challenge, and the question is how to address these system hierarchy and scale dimensions at a time.

Different techniques are available to deal with heterogeneity, of which the common practice is to cluster farms and landscapes into a homogeneous group (Haileslassie et al., 2016) (Figure 4). Landscape typology can be constructed using traditional altitude belts or the farming systems (Figure 4) in the landscape under consideration. A quantitative statistical tool such as multivariate analysis, based on a survey dataset, can be applied to construct farm typology (Haileslassie et al., 2016; Mutyasira et al., 2018). Alternatively, participatory learning and action may be undertaken, employ informal group discussion and key informant interviews to create farm typology (Figure 4). This method is advantageous due to the inclusion of additional groups of females and "landless" farmer—these groups are significant in the communities but were omitted in the survey for the statistical typology. Such an approach would help in managing system hierarchy, by nesting the individual farms into farm clusters and subsequently the farm clusters into landscape position (Figure 4).

To understand the changes needed, the next step involves the status of sustainability indicators by comprehensively exploring the performances of each of the selected indicators (Figure 4B). Depending on the number of indicators identified, sustainability assessment could be data-intensive and therefore expensive. In keeping the exercise cost-effective, relevant and locally available datasets addressing scales of interest should be located.

Data sourcing mechanisms ought to consider multiple scales and methods. While Household Survey (HHS) is a useful tool to capture farm-level data for the target indicators, Focus

TABLE 1 Generic indicators and indexes proposed for understanding the performance of sustainability.

Target dimensions	Generic indicators**	Units	Importance*	Scale	Source of information
Economic sustainability	Agricultural income	USD/Head	H	Farm	Survey
	Crop value	USD/kg	M	Farm	Survey
	Income sources diversity	# income sources/HH	M	Farm	Survey
	Income stability	% changes between years	H	Farm	Survey
	Yield	kg/ha	H	Farm	Survey/literature
	Water use efficiency	Kg/m^3	H	Farm/LS	Survey/literature
	Input efficiency	Kg input/kg return	L	Farm	Survey/literature
	Cropping intensity	# crop/yr.	H	Farm	Survey/literature
	Yield gaps	% deviation from potential	L	Farm/LS	Survey/literature
Environmental sustainability	Biodiversity	# crops on the farm	L	Farm/LS	Survey/literature
	Agrochemical inputs	kg/ha	L	farm	Survey/literature
	Erosion	tons/ha	H	Farm/LS	Survey/literature
	Level of water pollution	Level of pollution risks	H	LS	Survey/literature
	Nutrient dynamics	% manure recycled	H	Farm	Survey/literature
	Land-use change	% change to agriculture	M	Farm/LS	Survey/literature
	Change in water storage	% change from the baseline	H	LS	Survey
	Environmental flow	% of total water flow and flow variability indicators	H	LS	Survey
	Trade-off of water values	Qualitative as perceived by the community	H	LS	Survey
	Water quality	% change of different water parameters	H	LS	Survey
Social sustainability	Information access	Radio/TV/Mobile/Internet	M	Farm	Survey/literature
	Gender equity/ social security	Access to water and land resources, decision making	H	Farm	Survey/literature
	Access to credit	% with access to credit	H	Farm	Survey/literature
	Level of poverty	Above or below the poverty line	H	Farm	Survey/literature
	Conflict over resources	Frequency and nature of conflict	H	LS/CM	Survey/literature
	Food and nutrition security	# of food insecure months	H	Farm	Survey/literature
	HH- Water security index		H	Farm/LS	Survey
	Water-related risk	The scale of water-related risks (drought, flood, pollution)	H	Farm/CM/LS	Survey/literature

*Relevance is indicated based on an expert's knowledge. **A complete list of indicators to understand the performance of sustainability for SSA is complicated. The given generic indicator needs to be enriched and prioritized through a participatory approach at local level. L stands for low, M for medium, and H for high. LS stands for landscape, CM for the community and HH stands for a household.

Group Discussions (FGDs) and Key Informant Interviews (KIIs) can help collect qualitative data at community/farm typology and landscape levels. Geospatial datasets can be used to triangulate the HHS datasets and capture bio-physical data at a landscape scale (e.g., weather attributes, groundwater distribution). Furthermore, due to the ongoing advances in high-resolution satellite imagery and computing engines like the Google Earth Engine, the use of products derived from Sentinel 2 or Landsat, such as FAO Water Productivity Open-access Portal (WaPOR), can complement the household surveys and assess key changes in land and water resources across watersheds in a landscape.

Analysis of the relevant datasets could involve, for example, simple descriptive statistics such as coefficient of variation (CVs) or the development of indexes such as food security, water productivity, biodiversity and poverty (Table 1). Depending on the target indicators, point and spatial modeling exercises can be considered to quantify risks (climate change-related, erosion), opportunities (availability of groundwater, achievable yield), and trends. These can assist in the evaluation of the farmers' vision of short-, medium- and long-term livelihood ambition.

The performance of sustainability indicators can be evaluated for each sustainability dimension and at the individual indicator level. Individual indicator level evaluation is important in essential in determining where future intervention (SIPs) is needed, with comparisons that can be made among the values of indicators in relative or in absolute terms. The absolute and relative values of the performance of the indicators reveal what is achievable under the current level of knowledge and practices, can track the progresses made over time. Tools such as radar charts can be engaged to visualize and compare the performance of indicators and identify the specific benefits and trade-offs.

Systematic identification of changes needed (SIPs): One of the bases for SIPs design is the *status quo* of SAI measures. In addition to the poor performing indicators, SIPs design is determined by farmers' livelihood expectations, government policy goals, emerging risk, and available options. Mixed methods involving science backing and community engagement help reveal the causes behind weak performing indicators and in prioritizing the interventions and clusters emanating from the SIPs design determinants. SIP is about co-designing context- specific interventions through an iterative participatory process (Kumar et al., 2019). The prioritization of the different interventions could follow simple tools such as pair-wise ranking. This type of discussion can be organized along with *status quo* feedback and SIP-co-design sessions at the farm typology and landscape levels.

In identifying the intervention or cluster of interventions, for farm typologies and landscape for a specific time scale (Figure 4C), critical thinking is vital, and must include: (a) the type of innovations required to address priority constraints concerning results of the SAI assessment; (b) potential risks such as climate change (Mutambara et al., 2016) and opportunities like the level of water resources endowment; (c) scenarios to manage trade-offs and principles to integrate innovation and harness their complementarities—irrigation rain-fed continuum, integrating genetic, social and ecological interventions; practical linkage of SAI to FS, equity, water allocation etc. (Figure 4D), and (d) a model to maintain and improve connectivity among farm clusters and landscape positions through governance (policies, institutions) to understand resources allocation, common property resources management and experience sharing (innovation platform). In SIP design and its implementation, the application of adaptive management can help navigate the critical thinking and post-implementation monitoring and learning.

Improving connectivity among landscape positions and farm clusters: The proposed framework assumes landscapes bounded by large-size watersheds and livelihood activities and natural processes connected through the hydrological process. This entails the presence of improved governance mechanisms which can coordinate among upstream-downstream and incentivize or disincentivize SAI measures (Clement et al., 2011) (Figure 4). From the perspective of SAI, governance refers to the norms, institutions and processes that determine how power and responsibilities over natural resources are exercised. It comprises how men, women, indigenous people, local communities and marginalized members of the society (minorities) participate in the decision-making process and benefit from natural resources management (NRM). Rules and norms for the same can be both formal and informal. A wide range of social movements, networks and federations have emerged to support the transitions toward sustainability and equity in SSA (Pretty et al., 2020). Social capital has been established in SSA, with the presence of intentionally formed collaborative groups within specific geographic territories—water user association, innovation platform and watershed management group. Local governance can facilitate experience sharing with these collaborative groups, like local institutions (Mutambara et al., 2016), in turn enhancing the spill-over effects of the SAI measures.

SAI practices may veer in unpredictable trajectories, e.g., environmental pollution, land use conflict, as experienced in many instances in the SSA region (Assegide et al., 2022; Teklu et al., 2022). SIPs design cannot be a one-time undertaking; it must evolve to address emerging changes and capitalize on new opportunities (Kumar et al., 2019). Thus, mechanisms to operationalize adaptive management approaches may prove useful (Haileslassie et al., 2020b). Adaptive management is an approach that helps to act under prevailing uncertainty about what is being managed and the impacts of actions (Kumar et al., 2019). It is an effective tool to manage SAI in landscapes and has the benefit of addressing the knowledge management gaps. Sustainability assessment (Table 1) could also be linked to the adaptive management matrix used across scales and thus help to keep improve connectivity and manage trade-offs. Notably, at present this practice is lacking in many SSA countries (Haileslassie et al., 2020b).

Conclusions

There are several critiques and issues pertaining to the science and practices of sustainable agricultural intensification. The current practices fail to link sustainability assessment with context-specific SIPs design. Methodological options that consider multiple scales—addressing emerging issues and opportunities, related to scarce water resources—are limited. A consideration of AWM at the core of SIP development is critically absent, as is the linkage of SAI with the larger FS. In many cases, there is a paucity of rigorous efforts of trade-off management through targeting strategic entry points, such as water allocation and monitoring and recognition of multiple values of water, that leverage complementarity and synergies of interventions.

Within this context, this study offers three contributions: first, it synthesized and provided insights into the gaps in the science and practice of SAI in SSA and in the framework of water resources management. Secondly, a methodological framework is proposed that connects sustainability assessment methods to participatory SIPs design and adaptive management approach at multiple scales; furthermore, it illustrates how the co-design of sustainability domains and indicators can help in AWM centered SIP development. Third, the study proposes approaches to maneuver the heterogeneity of biophysical and social settings (in tailoring the technology options to context) along with the SIP design principles to enable synergies and complementarities of the SAI measures. The knowledge generated, and the methods proposed by this review can help researchers in integrating sustainability assessment and design of SIPs. The study can also guide policymakers and practitioners on how best to plan, implement, and monitor sustainable intensification initiatives such as Framework for Irrigation Development and Agricultural Water Management in Africa across multiple scales.

Author contributions

AH: conceptualization. WM: review of literature. AH and WM: methodology and writing original draft. SU, EL, and PS: review and editing. All authors have read and agreed to the final version of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Review: Groundwater research in the Ethiopian Rift Valley Lakes region

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Despite its proximity to many research institutions in the country and prevailing environmental and water security challenges, water resources research in the Central Rift Valley of Ethiopia has few decades of history. Research undertaken so far, mainly focus on the lakes' environment and anthropogenic activities in their proximities. Worsening deterioration of the water resources and environmental conditions; and the need to address overlooked but determinant natural and anthropogenic processes spurred a critical review of what has been done so far. This work provides an overview of the history of water research in the central rift valley and tries to reveal research gaps related to surface water-groundwater interaction, water quality, and changing trends in the hydro ecosystem and possible causes. Apart from this, articles dealing with the geological and structural setup of the central rift valley were systematically reviewed to show their control over the hydrologic system. The review work has revealed that although the current state of the central rift valley is a product of anthropogenic and geogenic processes; which are happening within the sub-basin and its adjacent basins that need to be addressed at a higher thematic, spatial, and temporal scopes, there is gap in reviewed research, to address the issue at this level. The forefront environmental challenges and the need for quick fixes, lack of data, and funding are found to be some of the reasons to limit the scope of research activities, mainly to shallow groundwater zones and surface hydrological processes around the lakes. This approach has hindered seeing the bigger picture and resulted in ineffective environmental and natural resources restoration measures and policy decisions.

KEYWORDS

Rift Valley Lakes, Ethiopia, groundwater-surface water interaction, groundwater flow controls, Ethiopian wetlands

Introduction

Research in earth sciences is relatively getting more attention in recent decades. There were few research works undertaken by foreign researchers in the Ethiopian Rift Valley Lakes area, during the 1920s; as part of the main colonial time objective of looking for natural resources. The opening of Addis Ababa University (AAU) in 1950 and the subsequent opening of the geology department, as one of the first four fields of studies, created a leap in research in earth sciences (AAU, 2013). The establishment of the Geological Survey of Ethiopia (GSE) in 1968 and Arba Minch Water Technology Institute in 1986 were decisive steps that helped to investigate and map the geology and structural set-up of Ethiopia and its water resources (GSE, 2021). Since its establishment, the GSE has conducted regional geologic, geophysical (land gravity and airborne), and geochemical mapping works that were used as a basis for various groundwater related research (Gasse and Street, 1978; Chernet, 1982; Chernet et al., 1988; Darling et al., 1996; Benvenuti et al., 2002). Earlier research works in water resources were limited to expeditions in search of the Nile Source. Research in groundwater was not area of attention till the increased water demand, deteriorating water quality and quantity conditions and degradation of the hydro-ecosystem forced the intensification of water research in recent decades. At present, water education and research activities are carried out by more than eight universities found across the country. Research topics like groundwater hydraulics, interactions between groundwater and rivers, lakes, and wetlands; land use and climate changes; pollution, trans basin flows (Alemayehu et al., 2018) and evaluation and modeling are on the rise (Ayenew, 2001, 2002; Tekle-Haimanot et al., 2006; Kebede et al., 2007, 2008; Belete et al., 2016; Bonetto et al., 2021).

Despite all the efforts, a clear understanding of the hydro-ecosystems of the CRV is lacking. The causes for the alarmingly degrading lakes' environment, the diminishing river flows, the drying up of springs and the lowering of the groundwater tables on one hand; and the emergence of new lakes and swamps on, the other hand, are not well-explained. The ever-increasing water demand for irrigation, industrial use and domestic purposes led to the emerging water management and governance problems that need policy adjustments, which are based on good understanding of the hydrological dynamics in the basin. This work aims to identify major gaps required to understand the CRV in a better way; without which managing the water resources of the CRV and ensuring water security for generations to come is difficult. Although the focus of this paper is on groundwater-related research, it also touches on aspects affected by the missing gaps in the core task of a clear understanding of the hydro-geo-environment.

Objectives

The main objective of this work is to identify gaps in groundwater and related studies undertaken in the CRV to help understand the CRV's hydrodynamics and the hydro-ecosystem in a better and wholistic manner; for better management of the water resources and ensuring water security.

Methodology

The study area

The Central Rift Valley (CRV) lake basin system is part of the Main Ethiopian Rift (MER) that includes four present-day residual lakes, Zeway, Langano, Abijata, and Shalla; and a tectonically controlled endorheic basin (Street, 1979; Chernet, 1982). It covers a total area of 14,480 km^2 bounded by 7°00$'$56$''$ to 8°28$'$8$''$N latitude and 38°03$'$38$''$ to 39°24$'$48$''$ E longitude (Figure 1). The rainfall distribution over the study area has wide spatial variability ranging from mean annual rainfall of 700 mm in the lowlands to 1,200 mm in its eastern and western highland parts. The CRV has been designated as a potential core site by the ERICA Project ("Environmental Research for Intertropical Climate in Africa") for being under the influence of the Intertropical Convergence Zone seasonal migration.

Various studies show that the basin has been subjected to changes in water level and water salinity, at least during the Late Pleistocene (Le Turdu et al., 1999). The Zeway–Shala closed basin is the central part of the Main Ethiopian Rift (MER), which is used as a reference site for regional to global paleoclimatic reconstructions.

The valley supports wide-ranging socio-economic and ecosystem services. In terms of landuse, 76.8% of its area is dominantly under rainfed agriculture. Irrigated agriculture covers <3% of the basin. About 44% of the existing irrigated areas rely on surface water from streams. Thirty-one percentage pump directly from Lake Zeway, and about 25% from groundwater.

Data sources, materials, and review steps

Most of the published articles used for this paper were collected from online sources such as a simple google search, Semantic Scholar, Google Scholar, ResearchGate, Science Citation Index Expanded (SCIE) bibliographic database, which is maintained by Thomson Reuters, and SCI-Expanded, which indexes the world's leading journals of science and technology. The privilege from home University was used to acquire e-journals from a few publishers. Published maps and books in Ethiopian Geological Surveys and Addis Abeba University Libraries were also used. The 5Ws framework (Who—What—When—Where—Why) was used to frame the search. Articles that are not available online were supplied by authors on request. Search terms including "geology," "rifting," "groundwater," "Central Rift Valley Lakes," "Main Ethiopian Rift," "water quality," "climate," and "Ethiopia" were used to locate publications related to the topics under consideration.

A total of 496 journal articles, book chapters, reports and PhD theses were collected, among which 94 are analyzed. Available publications were checked for their originality and published in reputable peer-reviewed journals to minimize bias. Collected books, reports and articles were grouped into five major groups under "geology and structure," "groundwater and surface hydrology," "Climate," and "Landuse—landcover," and "others" categories and organized in EndNote Library (Table 1).

The selection of articles to be reviewed for groundwater and related research were done based on their research objectives, time of research undertakings, scope, and level of study and scores of researchers on known online rating sites. Rather than focusing on the nitty-gritty of individual papers, research papers are grouped into thematic areas and qualitatively reviewed for common and important missing gaps needed to better understand and characterize the basin. Articles were carefully read, compared, interpreted, and checked for their complementarity. Finally, results were discussed and narrated. A simplified flow diagram of steps followed during the review process is shown in Figure 2.

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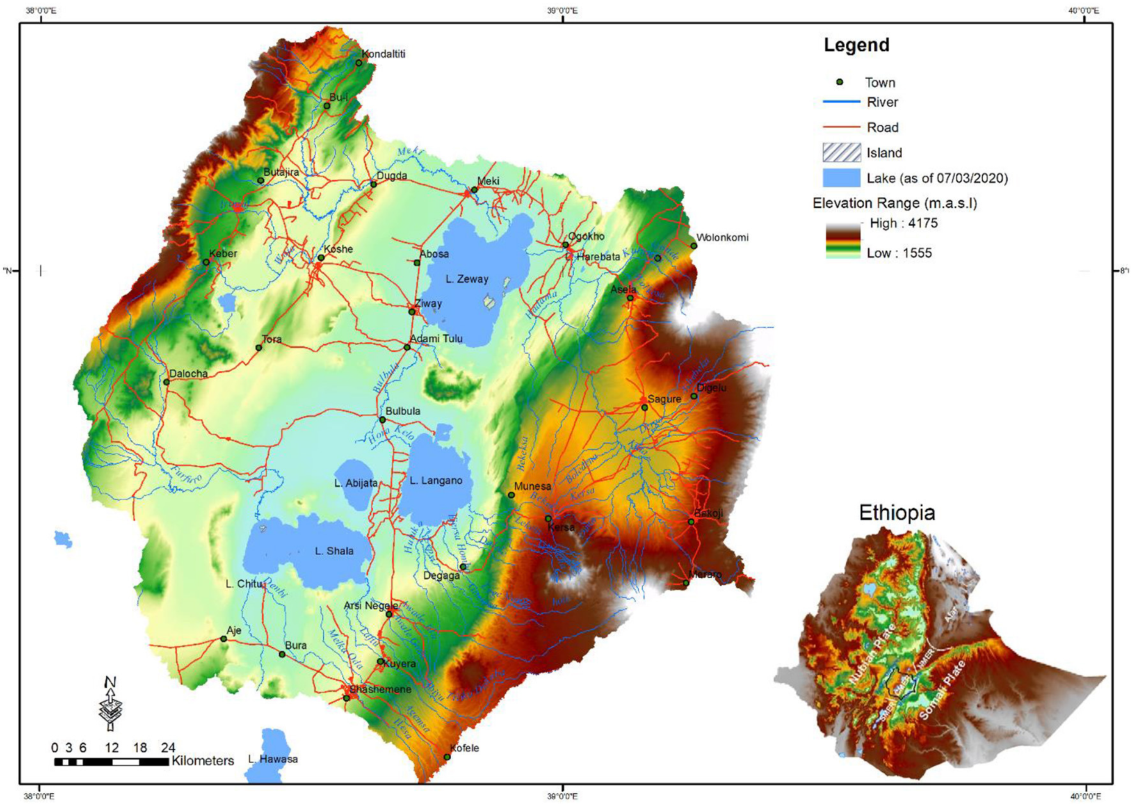

FIGURE 1
Location map of the Central Rift Valley.

TABLE 1 Overview of collected data.

Category	Source	Year of publication	Retained in EndNote Library	Analyzed
Geology and structure	Online e-journals, reports, and books	1920–2021	194	27
Groundwater and surface hydrology	Online e-journals, reports, and books	1932–2021	198	42
Climate	Online e-journals, and reports	1978–2021	43	13
Landuse-landcover	Online e-journals	1999–2020	32	10
Others	Online e-journals, and reports	1995–2018	29	2

Results and discussion

Triggers for groundwater and related research

Research activities in groundwater and water-related topics in the CRV are preceded by researches done in areas of geological and structural settings of the CRV. As part of the Greater East African Rift System (EARS), the CRV was studied by several international and local geoscientists, with main objectives of investigating the rifting process, paleoclimate and sedimentation, and exploring mineral resources associated with rifting processes and lake environments. The earlier works include that of Mohr (1970), Paola (1971), Street (1979), Browne and Fairhead (1983), Wolde (1989), Lars et al. (1991), and Ebinger et al. (1993). These research works were followed by more organized and systematic research works, such as the EAGLE Project (Bastow et al., 2011). The discovery of geothermal energy (Paola, 1971; Kandie, 2014; Sisay, 2016; Boone et al., 2019) and industrial minerals like diatomite (Million, 1989; Abera, 1994) and soda ash (EIGS, 1989) also initiated the need for detailed geological mapping in the basin (Tadesse et al., 2003).

Groundwater and related research were, predominantly, the focus of academic institutions abroad and within Ethiopia. In this regard, opening the field of specialization in hydrogeology at AAU and Arba Minch Water Technology Institute in 1986 created a significant leap. Understanding the paleoclimate, lake-level fluctuation, the geochemistry of sediments, isotope pattern of precipitation, fluid-rock interaction, lake-groundwater relationships, and understanding the hydrogeological system of the CRV were among the topics that attracted researchers (Baumann et al., 1975; Gasse and Street, 1978; Darling et al., 1996; Rozanski

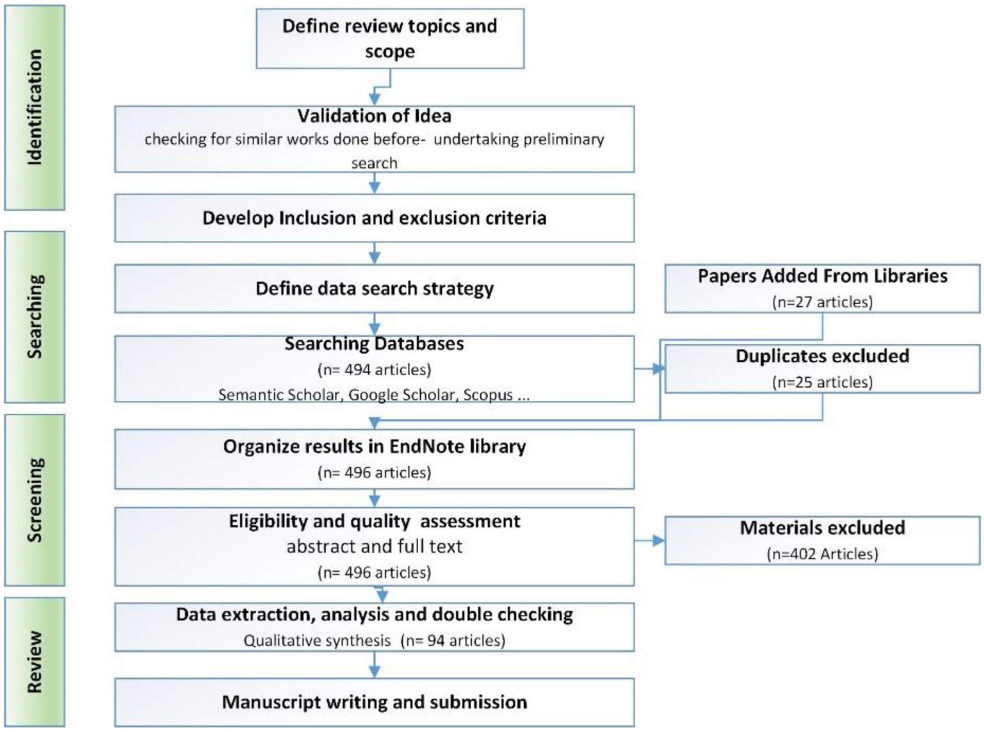

FIGURE 2
Simplified review flow diagram.

et al., 1996; Ayenew, 1998). Water quality deterioration and degradation; and modeling and evaluation of the water resources are emerging research issues (Haji et al., 2018; Thomas et al., 2019; Abraham et al., 2021; Bonetto et al., 2021; Kebede et al., 2021; Ligate et al., 2021). The increasing need for the development of water resources initiated mapping projects at different scales, and the development of master plan studies (Chernet, 1982; Chernet et al., 1988; HALCROW, 1989; MoWR, 2009). These works have laid the basis for groundwater and related research activities.

Geological and structural setup of the CRV

The geology and structural setup of CRV are, relatively speaking, the most researched thematic area. Many research works were done in the past half a century in these areas. Among many earlier works, the research by WoldeGabriel et al. (1990) is a comprehensive work on geology, geochronology, and rift basin development. Benvenuti et al. (2002) undertook and interpreted a stratigraphical, pedological, and geomorphological study, including a new geological map scale 1:250,000, to provide a Late Quaternary-centered revised geological history of the basin.

The tectonic analysis of the Asella-Langano Margin by Corti et al. (2020), the study on the Wonji fault belt by Pizzi et al. (2006) and on the volcanism, tectonics and fault architecture of the Main Ethiopian Rift by Le Turdu et al. (1999) and Agostini et al. (2011a,b), showed the configuration of regional and local geological structures that are one of the major groundwater flow controlling factors in the basin. The depth estimates of anomalous subsurface by Kebede et al. (2021), examine the depth to the crystalline basement, which is important to determine the groundwater flow dynamics in the basin. The CRV was part of the giant research project: "The Ethiopia Afar Geoscientific Lithospheric Experiment (EAGLE)" that probed the transition from continental rifting to incipient seafloor spreading (Bastow et al., 2011). The structural connectivities of CRV with adjacent basin was indicated in the works of Gasse and Street (1978), WoldeGabriel et al. (1990), and Tiercelin and Lezzar (2002). Explorations for geothermal energy also provided highly valuable data that is necessary for a thorough understanding of the basin. Drilling at Aluto geothermal site provided lithological and structural information as deep as 2,500 meters (Meseret and Bayne, 2005). At Tulu Moye, recently completed drilling stopped at 2,900 meters. Ongoing drilling activities in all the three exploration sites for geothermal energy: Aluto, Tulu Moye, and Corbetti are expected to highlight the nature of aquifers at more depth. These works are key to establishing the hydrological connectivity of CRV with adjacent basins and determining regional flows.

The research by Sagri et al. (2008), on the reconstruction of the paleo river network; by Jones and Mgbatogu (1977) on Late Quaternary lake levels in southern Afar and the adjacent Ethiopian Rift; and the work on the influence of volcanism, tectonics, and climatic forcing on basin formation and sedimentation in the Zeway–Shalla Lakes Basin system by Le Turdu et al. (1999), provided evidence-based knowledge on the formation process and evolution of the lakes. Similar studies on Late Quaternary lake-level fluctuations and environment of the Northern Rift Valley and Afar Regions by Gasse and Street (1978), and on the evolution of Zeway–Shala lake basin by Benvenuti et al. (2002), reached to similar conclusions on lakes formation processes.

In addition to these works, the broad review of 300 million years of Rift Valley Lakes in central and east Africa (Benvenuti et al., 2002), the Paleoenvironment of Lake Abijata, Ethiopia, during the past 2000 years by Bonnefille et al. (1986), the study on the Late Quaternary lacustrine sediments of the Zeway–Shala Basin by Balemwald (1998), the research on Late Quaternary Lake Levels in the Rift Valley of Southern Ethiopia and elsewhere in Tropical Africa by Grove and Goudie (1971) and Grove et al. (1975), examined the paleolake environment which is a key to understand the present hydrological dynamics in the CRV. The study on the evolution of the northern part of the Ethiopian Rift by Kazmin et al. (1980) and the work of that of Giday et al. (2016) and related the structural and geomorphic features of the EARS with the genesis of the rift valley lakes.

These systematic evidence-based researches, which were based on field investigation, radiometric dating, and data from deep drilling for geothermal energy provide in-depth analysis of the CRV. Research in the CRV has gradually evolved to a higher level, addressing topics which are complementary to each other. These works provide some of the required information to establish the relationship between CRV and adjacent hydrogeological regimes. They revealed the complex lithological and structural setups of the basin to help characterize the groundwater dynamics in it.

Geological map of Ethiopia by Kazmin et al. (1980), Geological Map of the Lake Zeway-Asella region by Abebe et al. (1998), Geological map of the Zeway-Shala lakes basin by Dainelli et al. (2001) and the Geological map of the Asella-Langano margin by Corti et al. (2020) are important sources of the geological information on the CRV. Apart from their limitations in scale, lack of detailed information on deep structures and lithological configuration, and presence of little inconsistencies in terminologies and dating of ages of events and rocks, these works are sufficient for hydrogeological characterization of the aquifers and other water-related research.

Groundwater and related research in the CRV and their connections with geological research

Research on water resources of Ethiopia has an older beginning but a retarded development. In his work on the history of the scientific study of Tropical African inland water, Talling (2006) mentioned the period 1925 to 1945 as a period of advancing colonial administration in many African territories, during when research was stimulated by economic and social issues. According to this work, the two main areas of interest were hydrology and fisheries. The work on hydrology evolved into the estimation of water budget and flow gauging of many rivers. In Ethiopia, however, only a few expeditions including the Cambridge Expedition in 1930, to the East African Lakes (Beadle, 1932), were recorded before 1935. Water samples were collected and analyzed during this expedition. Later, during the brief period of Italian occupation, several surveys of major rift valley lakes and the elevated Lake Tana were made (Talling, 2006). However, this move remained discontinued till the 1970s.

In the 1970s, groundwater research and related topics made a slow restart in the CRV. Few researchers that were seen doing related works across many years, were actively engaged. The work on water chemistry, mineralogy, and geochemistry of sediments in the Ethiopian Rift by Baumann et al. (1975), is probably the oldest available research followed by Chernet (1982) work on the hydrogeology of the Lakes Region. The study by HALCROW (1989) and MoWR (2009), which was done as part of the rift valley lakes integrated natural resources development master plan, is a basin-wide work that addressed various aspects of the CRV. One of the few studies on lake-groundwater relationships and fluid-rock interaction in the East African Rift Valley was that of Darling et al. (1996), which was based on isotopic evidence. A PhD research by Ayenew (1998), examined the hydrogeological system of the CRV using mainly remotely sensed data. He probably is the one who first attempted to perform numerical flow modeling of the groundwater of the CRV (Ayenew, 2001) and to use environmental isotope-based integrated hydrogeological study of some of the Ethiopian Rift Valley Lakes (Ayenew, 2003). Environmental isotopes and geochemistry were used by Kebede (2004) in investigating groundwater and lake hydrology of the Ethiopian Rift. The hierarchical cluster analysis of hydrochemical data as a tool was used by Ayenew et al. (2009) to assess the evolution and dynamics of groundwater across the Ethiopian Rift.

Few research works were made regarding groundwater-surface interaction and trans-basin flows. Among these, the study on Meki River's streamflow sensitivity to climate and land cover changes by Legesse et al. (2010); Modeling for Inter-Basin Groundwater Transfer Identification: The Case of Upper Rift Valley Lakes and Awash River Basins of Ethiopia by Mohammed and Ayalew (2016); the SWAT based hydrological assessment and characterization of Lake Zeway sub-watersheds, Ethiopia, by Desta and Lemma (2017) are to be mentioned. One of the few works on lake–groundwater interactions is that of Tenalem and Tilahun (2008). It assessed the lake–groundwater interactions and anthropogenic stresses, using a numerical groundwater flow model (Tenalem and Tilahun, 2008). Kebede (2013) briefly discussed the typical feature of the Butajera-Asella transect.

There are studies done to assess and evaluate the water resources in the CRV and the Rift Valley. Among these studies are: Comparative assessment of the water balance and hydrology of selected Ethiopian and Kenyan Rift Lakes (Ayenew and Becht, 2008); Rift Valley Lakes Basin Integrated Resources Development Master Plan Study (MoWR, 2009); the Study on Groundwater Resources Assessment in the Rift valley Lakes Basin in Ethiopia (JICA, 2012); estimation of groundwater recharge and water balance of the Rift Valley Lakes by Kebede (2013); Quantifying Increased Ground Water Demand from Prolonged Drought in the East African Rift Valley (Thomas et al., 2019); Analytical Hierarchal Process (AHP) based analysis of groundwater potential in the western escarpment of the Ethiopian rift valley (Abrar et al., 2021); Groundwater Resources in the Main Ethiopian Rift Valley: An Overview for a Sustainable Development (Bonetto et al., 2021); and Quantifying the Regional Water Balance of the Ethiopian Rift Valley Lake Basin Using an Uncertainty Estimation Framework (Abraham et al., 2021). However, there are significant differences in the figures they are providing, and in the approaches, they are following.

Water quality

Results of the Cambridge Scientific Expedition in 1930 to the East African Lakes (Beadle, 1932) is probably the oldest work on sampling and analysis of the waters of the CRV lakes. The research on water quality of the CRV, was mainly focused on the existing fluoride problem in the basin. Some of these research works include, the work Tekle-Haimanot et al. (2006) on the geographic distribution of fluoride in surface and groundwater, Ayenew (2008) work on the distribution and hydrogeological controls of fluoride in the groundwater of central Ethiopian rift and adjacent highlands; and Demelash et al. (2019) systematic review and meta-analysis on fluoride concentration in groundwater and prevalence of dental fluorosis in Ethiopian Rift Valley. Kebede (2013) summarized the geochemistry and water quality of the groundwater of Ethiopia. In this work, the geochemistry of fluoride was found expressive of groundwater situation in the CRV.

Although works on fluoride are dominating, some researchers were dealing with the general water quality aspects. The work on water chemistry, mineralogy and geochemistry of sediments in an Ethiopian Rift by Baumann et al. (1975) is one of the oldest research. The mechanism of water quality degradation in the lake regions of Ethiopia was analyzed by Chernet et al. (2001). Zinabu et al. (2002) investigated the long-term changes in chemical features of waters of the seven Ethiopian Rift Valley lakes, including those of the CRV. Ayenew (2005) research on major ions composition of the groundwater and surface water systems and their geological and geochemical controls in the Ethiopian volcanic terrain is the most cited and comprehensive analysis. The research by Kebede et al. (2008) dealt with groundwater origin and flow along selected mountain-valley transects in Ethiopian rift volcanic aquifers. Hydrochemical characterization and quality assessment of groundwater of Meki River basin were done very recently (Mesele and Mechal, 2020). Zeway Lake was included in Masresha et al. (2011) research on the speciation of selected trace elements in three Ethiopian Rift Valley Lakes, including Koka, Zeway, and Awassa; and their major inflows. Lake Shala was one of the East African Soda Lakes studied by John and MacIntyre (2016), for its morphometry and physical processes, chemical stratification and mixing, temperature trends, and climate changes.

Water development in Ethiopia, particularly groundwater development, is at its initial development stage. Potable water supply coverage in Ethiopia, during the late 1980s, was below 20%. Groundwater use for irrigation is only a decade old. Compared with this slow pace of groundwater development, the growth in groundwater research is encouraging. These researches have set the basis for groundwater research in the CRV. Although the knowledge on the deeper groundwater aquifers is limited, the shallow groundwater aquifers are better understood. This research helped developers to make informed development plans.

Climate and the hydro-ecosystem

Similar to the hydro-ecosystem, geological processes, such as rifting and uplift and the hydrogeomorphology setting have modified the present climate condition of the CRV and the hydrology of the lakes. Aside from analyzing the paleoclimate, paleo river network and lake environments discussed above, many researchers have attempted to research the contemporary climate situation and the state of water resources in the CRV. Nicholson analyzed the historical fluctuation of the rift valley lakes as part of the comprehensive study that covered Lake Victoria and lakes in the Northern Rift Valley of East Africa (Nicholson, 1998). Ayenew (2002) studied the recent changes in the Lake level of Abijata, followed by his work under the title "The changing face of the Ethiopian rift lakes and their environs: call of the time" (Ayenew and Legesse, 2007). Legesse et al. (2004) analyzed the hydrological response of Lake Abijata to changes in climate and human activities. Similarly, Abraham et al. (2018) studied the hydrological responses of climate change on Lake Zeway Catchment. Seyoum et al. (2015) investigated the relative impacts of natural processes and human activities on the hydrology of the CRV lakes. Characterization of water level variability of the Main Ethiopian Rift Valley Lakes was done by Belete et al. (2016) and environmental assessment of the East African Rift Valley lakes was done by Eric et al. (2003). Research by Gadissa et al. (2018) analyzed sedimentation and loss of lake volume in the CRV that happened due to changes in climate.

Apart from the degradation of the lake environment, there are huge landuse/landcover changes taking place affecting the hydro-ecosystem. There are few studies addressing causes and effects of this alarming trend at the CRV level. The followings are among the few works to be mentioned. Impact of land use/land cover changes on the lake ecosystem of Ethiopia's central rift valley by Elias et al. (2019) addressed changes taking place in the lake environment. The work by Mengesha et al. (2014) uncovered the impacts of land use, land cover and climate change on the bird community in and around Lake Zeway. Another research by Muluneh et al. (2017), investigated the effects of long-term deforestation and remnant forests on rainfall and temperature in the CRV.

Most wetlands in the CRV, on which the existence of the lake systems is dependent, are largely controlled by geological structures. However, their existence is threatened, research on wetlands of the CRV is almost non-existent. Some of the wetlands in the CRV are included in the country-wide overview undertaken by Leykun (2003). Studies on local ecological knowledge and wetland management in the Ethiopian Rift Valley (Gebrehiwot, 2020) and Gap and Opportunity Analysis of Hydrological Monitoring in the Zeway-Shala Sub-basin, Ethiopia (Donauer et al., 2020) are also among the few research done on the wetland systems. Although not exhaustive in exploring the wetland of the CRV, these works highlight the state of the endangered wetlands and create awareness on their vulnerability to anthropogenic and climate variabilities.

Limitations and gaps in groundwater and related research

Despite the availability of the above-mentioned geological research, efforts to make use of them for groundwater and related hydrological studies were not going in parallel. Most hydrogeological research and related mapping activities have been affected by the lack of lithological log data, pumping test results, water quality data, and poor data quality (Chernet et al., 2001). As a result, there are important groundwater characterization factors of the CRV, which were not well-addressed or missing. The followings are the main gaps in the groundwater and related water research mentioned above.

- Unable to establish relationship between fault swarm vis-à-vis groundwater divide, which is required to establish regional and local flow paths and consider its impact on water budget calculation and allocation efforts.
- The hydrogeological and hydrological significance of the dominant structural features in the basin- Wonji Fault Belt (WFB) and Silti Debrezeit Fault System (SDFS) convergence zone, is not well-established.
- There is limitation in understanding the paleogeomorphology of the CRV and the grabens formed by each fault zone, the obscured valleys that may have been buried along the rift aquifers. Understanding these helps to identify where filled grabens with good aquifer characteristics and the good aquifer and horsts are located, and the possibility of finding buried river networks that may have been filled with pyroclastics, as that of the nearby Kessem-Kebena River system (WoldeGabriel et al., 1992).
- Possible modification of the hydraulic property of aquifers by the progressing rifting is not analyzed.
- Response of the hydrogeological system to seismicity, which are happenings in the CRV, is unknown (e.g., the 2017 Langano earth quack, with a magnitude of 5.3).
- The undetermined hydrological connection between the CRV and following flow controlling features: Awash River basin in the northeast that is connected through fault swarms along the Gurage escarpment; similar possible connections with Hawassa and Agere Selam escarpment; and Wabe Shebelle River Rift zone; Bilate River basin (through Awassa caldera); the Omo River canyon; and Abaya-Chamo lakes.
- Unknown regional connectivity role of the regional Ambo lineament, which cuts across different basins, including the CRV.
- The regional hydraulic connectivity with Karoo Rift in the south, the Blue Nile Rifted basin, which is truncated by MER from Ogaden rifted basin, and Anza Rift in the south are also not determined.
- The hydrogeological implications of the general basement gradient, which is toward Awash River Basin, and the narrow-uplifted block (Mt. Damot) between MER and Omo Rift are not yet investigated.
- The tendency to use various models to determine the water balance and characterize the basin with little or no reference to other model outputs—unfit models to the hydrological and hydrogeomorphological setup of the CRV.
- The main limitations of research in water quality are:

TABLE 2 Major gaps and challenges in groundwater water and related research in the CRV.

Category	No. of articles	Study objective	Similarities and differences	Strength	Gaps/limitation	Challenges
Geology and structure	27	Dominated by the rifting process	Studies complement each other and show continuity	Systematic evidence-based research, supported by field surveys available techniques and instrumentations	Very much focused on the rifting processes and poorly linked with other disciplines	Difficult to replicate methods and approaches used by international scientists due to the capacity limitations and awareness at the policymakers' level, locally
Groundwater, surface hydrology, water quality, wetland	42	Development and academic research	Based on limited primary data, not at a basin scale	Provide good information on the shallow groundwater	• Limited to shallow groundwater • Poorly address groundwater-surface water interaction • Pollution fragmented studies that failed to see the broader/regional aspects	• Limited funding, local capacities to handle high-level research limited • Insufficient groundwater and lake level, and flow data • Weak policy and funding support
Climate	13	Academic and grant driven	Strong paleo-climate analysis	Established a link between climate variability and changing lakes environment	Studies of the present scenario are fragmented	No sufficient measured climate data
Landuse-landcover	10	Investigate current problems and suggest solutions	Focus on the lakes' environment and land degradation	Able to show trends and send alarm	• Not at a basin scale and poorly established cause-and-effect relationships • However, many papers put anthropogenic factors as the major driver of land degradation	Poor coordination among researchers to do multidisciplinary integrated research

- The scale in determining the spatial distribution of fluoride, as concentration may vary depending on lithology, climate, and hydrological factors.
- Unable to fully capture the vertical variation in concentration, and variations across the different hydrogeological regimes.
- Impact of the calc-alkaline nature of Butajera ignimbrite on the water chemistry of the CRV was not investigated.
- Capacity gaps to analyze hazardous toxic substances and heavy metals discharges as industrial effluents and impacts of the increasing long-term application of agricultural inputs.

The biggest problem observed in research that attempted to analyze impacts of the changing land use-landcover and climate change on the CRV lakes, the wetlands and the water resources is the failure to address problem at a basin scale and failure to see connectivity with adjacent basins. Ignoring the influence of topography, hydrogeomorphic structures, and the earth's thermal influence, particularly in such a rifting area like the CRV, and the spatial variability controlled by the two adjacent plateaus. Unlike many other parts of the country, there is visible variation in moisture vegetation response observed on the leeward vs-a-vis the windward sides, which is not well-captured. Most of the works overlooked the impacts of the increasing temperature trend in the basin on the lake water level. Studies on sedimentation, little uncover the contribution from anthropogenic processes (Le Turdu et al., 1999) and changes in the hydrological processes and in the rivers' flow pattern and their sediment loads as a result of changes in land use/landcover. There is increasing blame on water abstraction for development from lakes and rivers. This conclusion failed to analyze the emergence of new lakes and wetlands in upstream areas; the expansion of mangroves because of the increasing silt accumulation and geological structural controls; expansion of irrigation in the highlands that didn't allow return flows to river systems; impacts of changed land tenure system; and the ever-increasing abstraction of groundwater for domestic and industrial water demands. The strength and gaps of research undertakings in the past decades are summarized in Table 2.

Conclusions

Research on the geology and structures of the CRV and the rifting process is continuously progressing and provides the necessary knowledge required for proper hydrogeological characterization of the basin and to show its hydrological connectivity with adjacent basins and regional structures. The lack of an integrated-multidisciplinary basin-wide approach and focusing only on lakes-side activities are major drawbacks of the water-related research activities in the CRV. Although the socio-economic processes, such as population growth, urbanization, competing water demands between irrigation, domestic, and industrial demands and climate change are major water security problems, the geological and structural setup of the CRV has a lot to contribute. The hydrogeological dynamics in the highly porous aquifers; the influence of the perpendicularly striking structures to the surface water flow direction and the nearly vertically dipping parallel, and transecting structures; the hydrogeological relationships with adjacent basins; and the connection of the lakes with these phenomena are not well-investigated. The impacts of the anthropogenic and geogenic processes need to be analyzed in an integrated manner and at a basin level. Unless such knowledge gaps of the CRV are addressed, proper evaluation and optimum and sustainable use of the water resources will be difficult. The current approach of providing piecemeal solution, to tackle basin level problems of degradation of the hydro-ecosystem, may not provide lasting solution to avert potentially irreversible damage happening to the lakes' environment.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Disrupted water governance in the shadows: Revealing the role of hidden actors in the Upper Cauca River Basin in Colombia

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Colombia's policy in the Upper Cauca River Basin is diminished by a lack of legitimacy in local areas respecting the control of territory and water. Such illegitimate interference provides a hiding place and fertile ground for the illegal activities of "hidden" actors. This paper aims to scrutinize the potential power of such hidden actors to influence water governance. We engage with critical discussions of water governance to reveal the role of these actors in controlling territory and water in the Upper Cauca River Basin. Extensive fieldwork was carried out, including workshops, interviews, and informal talks. Despite the Colombian government not recognizing hidden actors and their part in influencing water-related policies, the information gathered revealed their active agency in the basin. The paper shows how these actors play a determining role in territorial development and water resource management, disrupting the functioning of the State's water governance. Hidden actors, to promote their own, mostly illegal and illegitimate businesses, seize upon the current lack of clarity in the national normative standards, the deficiencies created by an inconsiderate implementation of national water policy, and the State's lack of legitimacy at the local level. This paper concludes that the awareness of hidden actors and their invisible power over water governance provide a better sense of the reality on the ground for policymakers in Colombia.

KEYWORDS

hidden actors, disrupted water governance, water-land use, Colombia, Upper Cauca River Basin

1. Introduction

Contrary to past and present *apolitical* views on water issues, this paper seeks to contribute to the critical water governance literature by illuminating the role "hidden" actors have in shaping the complex interplay between water and territory management. We intend to demonstrate how water-related processes are politically driven and cannot be separated from the underlying socio-political and economic realities on the ground (e.g., Rusca and Cleaver, 2022). Water governance is defined here as "the practices of coordination and decision making between different actors around contested water distributions" (Zwarteveen, 2015). Water governance is shaped by political discourses and the practices of many different *actors* with socio-economic and other interests in the institutional arrangements for land management and the related competition over territory.

The competitive relations among actors who seek to control both of these resources make up a complex of dynamic and often ambiguous interactions. In such a contested environment, actors wield sufficient power to influence the balance of resource distribution.

Consequently, a fundamental aspect of the analysis of water governance—either the structure, the process, or the result—is the concept of *actor mapping*. This involves distinguishing and identifying different actors, particularly informal actors, who are explicitly or implicitly involved in shaping water governance, which is crucial to a better understanding of the overall situation. Such identification may help informal actors to perform roles as acknowledged stakeholders and as important forces for processes of reform and development (Wegerich et al., 2015; Reed et al., 2018). However, most studies have focused only on formal actors, particularly those who have a physical presence in water-related decision-making processes. In contrast, critical water governance emphasizes the complexity of interactions taking place between formal and *informal* actors in everyday social life as a window into the "hidden" workings of power relations. This school of thought focuses on discovering hidden actors and invisible interactions within a community, often involving women, children, and those who are discriminated against by another community group and excluded from decision-making. However, limited research has been carried out on those various informal actors who of their own accord choose not to participate in decision-making. These informal actors have the potential to significantly influence decision-making, but tend to work in the shadows and remain invisible to the public; they are indeed almost ghost-like (Nagheeby, 2020). This makes it difficult for researchers and policymakers to find them. They compete over "legitimate" access to land and water and make use of their power to influence decision-making for water governance to their benefit. We call them hidden actors because it is either difficult to detect their footprint in water governance, or most people including the government have no clear picture of their influence. The politics performed by hidden actors in water-related processes lacks theoretical and empirical understanding: although they are not an unknown subject in the study of water governance (Wegerich et al., 2015), very little attention has been paid to examining the role of these informal, hidden, invisible, and "illegitimate" actors fighting for water and territory.

The Upper Cauca River Basin (UCRB) in Colombia offers a perfect example of the intervention of hidden actors. The complex struggle between the central government and illegal, hidden actors to control water and territory is readily apparent here. The UCRB is recovering from long-term conflict. While rural populations struggle with social inequalities, including lack of access to basic sanitation, violence, dispossession, and oppression (Arbeláez-Ruiz, 2021), the catchment has been degraded by various competing human activities, including widespread extractive processes such as legal/illegal mining (Alvarez-Pugliese et al., 2021; Gallo Corredor et al., 2021; Rochlin, 2021), logging (González-González et al., 2021), monocultures (Correa-García et al., 2018), and those associated with illegal activities such as coca leaf production (Thomson et al., 2022). Vélez Torres and Vélez Galeano (2019) reviewed historical environmental conflicts in the UCRB. They found 18 cases between 1980 and 2016 that arguably concern in some way the role of hidden actors. These cases invariably involved the distribution of economic and political power to control water. The cases were assigned to three main categories: first, those related to agribusiness; second, those concerning mining-related activities; and finally, those regarding the construction of hydraulic infrastructures. At the same time, remote sensing studies have shown that, although land covers have statistically been relatively stable in the UCRB, transitional crops have decreased at altitudes of more than 3,500 m above mean sea level (mamsl), making way for other anthropic land covers, which, it might be argued, are related to the activities of hidden actors displacing cover attributed to the Paramos ecosystem (Valencia-Payan et al., 2018). Besides these interruptions, Colombian water policy has been affected by a lack of legitimacy in rural areas, non-recognition from community stakeholders, and severe disruptions to its capacity to monitor and enforce environmental law with a legitimate and efficient judicial system (Le Billon, 2011). Although large investments have been made in water management, they have been put in place with weak interinstitutional coordination, limited leadership and teamwork, and in some cases with insufficient information, which have contributed to the progressive deterioration of the basin (Sánchez Torres et al., 2022). These hindrances are exploited by actors operating in the shadows, who take advantage of such problems to fulfill their own illegal agenda.

This paper seeks to examine the influence of hidden actors in the UCRB on the competition over water and territory. We intend to uncover recognition and representation processes, the role of hidden, local actors, and the complexity of socio-political settings surrounding water and land management processes. From a practical point of view, understanding these hidden dynamics may help to alleviate the problem of disrupted governance above-mentioned. To achieve this understanding, we adopt a qualitative approach. Data was collected from social-mapping workshops, semi-structured interviews, and informal talks with experts and community leaders. The fieldwork was performed in Cauca Department, south-west Colombia (Colombia contains 32 departments and a Capital District), in the municipalities of Santander de Quilichao, Silvia, Piendamó, and Popayán (Figure 1), and took place principally from mid-2019 and intermittently during 2020 and 2021. The study shows that the national water governance in the UCRB suffers from a lack of clarity in national normative standards, the deficiencies caused by an inconsiderate implementation of national water policy, and the State's lack of legitimacy at a local level. Within such imperfect conditions, hidden actors—e.g., large-scale mining operators and armed groups and their related interests in illicit crops—manipulate national water governance procedures to assist their illegal activities. As a result, hidden actors in the UCRB transform land-planning processes and water-land use dynamics in their own interests, thus affecting the communities' decision-making and autonomy in the river basin.

To arrive at this conclusion, we first review the available knowledge of Colombia's struggle to promote water and territory governance, and its association with hidden actors. Then, Section 3 outlines the theories of water governance that we rely on in this study and describes the research methodology. Next, Section 4 presents the results and explains how our findings support the

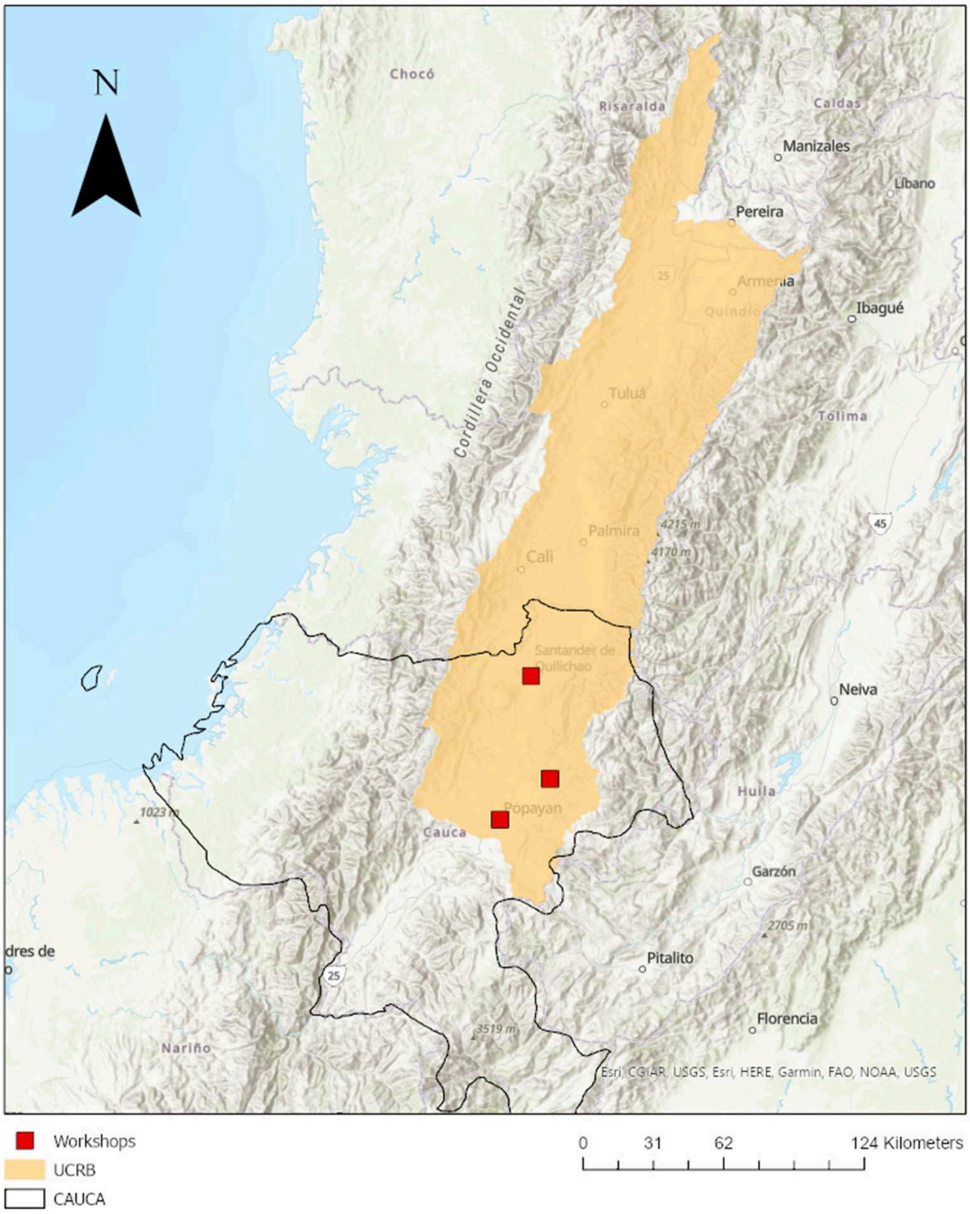

FIGURE 1
UCRB and Cauca department location map.

thinking that hidden actors disrupt national water governance. Finally, in Section 5, we give our conclusions.

2. General background: Colombia's struggle to promote water and territorial development policies

Given the multi-layered complexity of the activities of hidden actors in the UCRB, they must be situated beyond water governance and in Colombia's broader socio-economic and political context. The Colombian government has been steadily constructing a modern natural resource management model, taking a wider perspective extending beyond water issues. This started as early as 1974, with the National Code of Natural Resources and Environmental Protection (Presidente de la Republica de Colombia, 1974), which was followed by the 1991 Constitution and the 2010 National Integrated Water Resource Management Policy (IWRNP). However, the present condition of the water environment in Colombia does not match the goals and indicators projected in these policies. According to reports by the National Environmental System (SINA) and the National Water Study, this is evidenced by the daily reality for many regions and production sectors in the country (Instituto de Hidrologia Meteorologia y Estudios Ambientales, 2019).

The Colombian government tries to legitimize water policy, enable further intervention of the State in the country's rural and remote areas, and contribute to improved security and community wellbeing (Schultze-Kraft, 2014). Nonetheless, poor management and a lack of State reach have resulted in policies being implemented without concern for local requirements and desires. Water governance, a central element in the official discourse of IWRM underpinned by the requirements of the UN's Sustainable Development Goal 6.5, has also been affected by such unfitting conditions.

Colombia has aimed to promote territorial development, the provision of public services, and community participation through its system of municipalities. In this system, planning and participation are embedded within the State's institutional structure through its political, administrative, and territorial activity in municipalities. With this rationale, citizen participation aims to design, discuss, and carry out various territorial management and planning models (Andrade and Rodríguez Becerra, 2008). However, in different parts of Colombia, especially rural areas, citizen participation and the practical management of territory are affected by the presence of hidden actors who, to satisfy their own wishes, influence participatory and management processes. These illegitimate actors work as external forces locally and disrupt the territorial realities in their own interests, which are often in opposition to national interests.

The conflicts around water and territory management in the UCRB offer an excellent example of the intervention of these hidden actors. Hidden actors can shape the conditions on the ground, thereby determining hydrosocial realities (Duarte-Abadía and Boelens, 2016) that are often concealed from the State. This suggests the limitations of national and international environmental policy in achieving sustainable development objectives, and highlights a contradiction with the hegemonic discourse of the State. Such is often the case with idealized institutions and policies created within an IWRM framework (Molle et al., 2009; Giordano and Shah, 2014). Also affected are the measures that communities try to take to coexist and survive in their local areas when faced by these often violent actors, who interfere and disrupt communities' capacities to oversee the use and management of the land. Lastly, the influence of these actors makes evident that little or no control is exerted by official territorial environmental planning. The government has an urgent need to reach these peripheries and support there the processes of recognition, representation, and redistribution of natural resources, especially water (Fraser, 2009; Zwarteveen and Boelens, 2014). We will elaborate on these points during our analysis of hidden actors in the UCRB, thereby highlighting a key problem for IWRM in developing countries such as Colombia.

3. Theoretical perspective and methodology

While the examination of water governance rides on varied theoretical waves, it centers mainly on uncovering the role and linkage among power, structure and agency in shaping water governance. However, in practice, different actors have diverse, often contradictory, understandings of governance which reflects the contested nature surrounding the control of water and results in very different policy strategies and decisions. Governance concerns the activities to influence "the social construction of shared beliefs about reality" (Castro, 2007) in which different actors are competing for (1) distributions of water, (2) distributions of voice and authority and (3) distributions of knowledge and expertise (see Zwarteveen et al., 2017). In such competition, various individual and collective, formal and informal actors within different territorial bounds use their capability to shape, sustain or resist the arrangements of authority and power to control water in their own favor. Therefore, water governance is a political process in which political actors exercise their political power to define the ends and values concerning the socio (and economic) water development. However, defining these powerholder actors, which is not an easy task in practice, is crucial for better understanding of the reality concerning water governance. As already mentioned, the water governance literature tends to capture rather formal and informal actors who are often visible to us and make a legitimate part of "civil society." In this paper, we intend to highlight those actors who are often invisible and seen as illegitimate in water governance but play a crucial role in shaping the surrounding reality.

Against this backdrop, the general concept of Integrated Water Resource Management (IWRM) and the principles of good water governance assume that there is a necessity to create a wider spectrum of stakeholders who should be able to engage in a constructive governance process (Harrison, 2019). Contrary to the functionalist approaches and normative notions of good water governance, which tend to overpass the operations of those in power, the critical water governance perspective (e.g., Warner et al., 2008; Perreault, 2014) attempts to carefully elucidate the political nature essential to the institutional arrangements and historical socio-environmental relationships in question. This paper takes a critical water governance perspective (Castro, 2006; Molle and Mollinga, 2009; Swyngedouw, 2009; Zwarteveen et al., 2017; Kumar et al., 2021; Rudolph and Kurian, 2022), in which governing procedures take place in pre-existing societal and physical landscapes and in diverse complexities.

Water management requires adequate territorial management that recognizes the systemic nature of this resource (Pérez Correa, 2014). It is not enough to regulate or manage only water; it is also necessary to deal with the territorial dynamics in which water and its management are integrated. However, while river basins may be considered natural units, they are in practice represented more as political units connected to parts of a territory (Warner et al., 2008). Power imbalances and disconnections between agents and structures at three levels—local, regional, and national—which comprise the nation's governance structure may impair water governance processes (Clement and Amezaga, 2013).

In addition, competition for the control of land and water emerges from political processes that are influenced by different stakeholders, who often have conflicting interests. Since by its nature water governance is complex, the relations between the participants are multidimensional. In places like Colombia, such complexity can be socially constructed by way of a vast diversity of

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TABLE 1 Activities, scope and methods used.

Activity	Scope	Method
Stakeholder mapping	Identify stakeholders that partake in water governance associated processes	Developed throughout 2019–2020 and 2021 following the Public-Private Dialogue (PPD) Stakeholder Mapping Toolkit by The world bank group (Kuriakose and Eknath, 2020) Literature reviews complimented the information collected on stakeholders present in the UCRB and policy reviews that already identified critical stakeholders for policy design and implementation
Participatory workshops	Interact with communities in the basin to create rapport and establish connections with the broader community from the basin. These workshops were held from January through March 2021	Social cartography was used to understand the reality culturally constructed by the people from their territorial, interpersonal and political experiences (Mancila and Habegger, 2018). This information allowed the research group to identify community concerns and priorities regarding processes related to water governance in their territories
Key stakeholder interviews	Identify discourse trends found during the participatory workshops that had also been encountered during the stakeholder mapping process	Semi-structured interviews are used to perform this task to compare the findings amongst all interviewed leaders

ontologies, epistemes, and images of what constitutes a particular reality, creating an amalgam of diversity and conflict (De la Cadena and Blaser, 2018). Within this competition for water and land, some actors may find advantages in running their business from the shadows and they accordingly tend to remain hidden. We follow this way of thinking to critically examine water governance in Colombia's UCRB to discover the frequently missing pieces of the puzzle—*hidden actors*. However, investigating these hidden actors is no easy task and needs to be done very carefully due to many concerns, including security.

To investigate the role of hidden actors in the UCRB, this study adopts qualitative research methods. The most important source of information on this analysis of water governance in the UCRB was field research that lasted nearly 3 years from 2019 to 2022. The COVID-19 pandemic seriously affected our fieldwork and we had to further extend it due to several other disruptions. Apart from the extensive analysis and desk reviews of the available policy documents, the following main methods were employed to better capture the real-world complexity of the UCRB: (a) stakeholder mapping; (b) participatory community workshops; (c) key stakeholder interviews including consultations with experts; and (d) participant observation—these are explained in greater detail in Table 1.

For 18 months (non-continuously), starting in the second part of 2019 and proceeding intermittently throughout 2020 and 2022, a stakeholder mapping exercise was carried out with input from the Water Security and Sustainable Development Hub.[1] The goal of this exercise was to gain an overall image of the status of water governance at the UCRB. The findings of this stakeholder-mapping process were presented and discussed at several Hub-run workshops, where experts from five different countries and of differing backgrounds commented and gave feedback upon the findings. The stakeholder mapping gave a foundation from which to explore how the campesino movement,[2] afro-Colombian groups,[3] and indigenous communities[4] settled in the UCRB, particularly in the areas of the Cauca Department. It is hoped that this mapping will help to enlarge our understanding of the occupation, ownership, use, and exploitation of natural resources in their territory, including production activities, territorial risks, and water hazards. This knowledge provided a solid basis for the social-mapping workshops (Powell, 2010; Wilson, 2014; Hamilton and Salerno, 2020), which aimed to represent the communities spatially and seek their knowledge and perspectives on decision-making processes. The knowledge acquired was subsequently systematized by delineating the narratives and symbolism discerned in the social-mapping workshops and cross-checking them with the results of the stakeholder-mapping process. Finally, the knowledge gathered allowed us to analyze interests and positions in favor of or contrary to specific public policy actions, and to measure the potential benefits and drawbacks of these actions.

Additionally, we organized a series of community workshops, as detailed in Table 2, with the participation of 60–80 people from 15 different communities, NGOs and private stakeholders. The workshops served as meeting-places with the communities to gain an understanding of the socio-cultural, environmental, and economic dynamics that assist a territorial diagnosis. These workshops were held from January to March 2021 and from July to November 2022 taking place at the Cauca Department's

1 For more information, please see Water Security and Sustainable Development Hub, Available at: https://www.watersecurityhub.org/.

2 The Campesino is a producer who lives from production for self-consumption and who, in the case of excess harvest, can market it, without this being his or her purpose. It a group of people with a joint historical basis and its productive inheritance.

3 Afro communities, unlike indigenous communities, have a much harder time at receiving differential recognition, even if the term refers to the fact of having as ancestors Africans who were captured, enslaved and transplanted to different territories outside Africa and therefore being heirs to their physical characteristics and possibly those of their culture. It is an umbrella term that encompasses other categories that are separate in their legal treatment, such as black communities, Raizal and Palenquero communities, but serves to affirmatively nominate all of them. This means they lack an established institutionality that empowers the communities as a whole.

4 Within the UCRB there is a great number of indigenous communities constituted by several indigenous ethnicities, located within different indigenous reservation areas. Amongst these many communities are the Kisgo, Ampiule, Misak, Paez, and Nasa. The Resguardo (Reservation) is a socio-political legal institution of Spanish colonial origin in America, consisting of a recognized territory of a community of Amerindian descent, with inalienable, collective or communal property title, governed by a special autonomous statute, with its own cultural guidelines and traditions.

TABLE 2 Workshops detail.

Workshop	Description
1st workshop (North of Cauca)	The northern part of the Cauca department is a highly productive area agriculturally wise. However, most of its economic activities rely on large scale sugarcane production. This workshop sought to bring together some of the most relevant stakeholders identified within the UCRB and aid in identifying undisclosed or hidden dynamics within the basin. In this workshop, 20 people participated, representing 15 different communities, NGOs, and private stakeholders
2nd workshop (Palace Basin)	The Palace River Basin is one of the Water Security Hub Colombia Collaboratory research interest areas. It is located in a mountainous area characterized by its highly diverse geography and rich ecology. Given its biophysical characteristics, it is an area of high importance for water resource production and preservation. Several small towns are located thorough the basin as well as indigenous reservations. This workshop was carried out in an indigenous reservation with around 25 participants from ages 17–85, both men and women selected previously to the research team's arrival by the reservation authorities. Although COVID restrictions were in place during this workshop, the reservation, using its autonomy, determined the event's conditions and attendance
3rd and 4th workshops	These workshops were carried out in the City of Popayan, the capital city of the Cauca department. It was carried out between municipal authorities and some community leaders from tributaries of relevance to the city's water supply. Unfortunately, COVID restrictions were in place when this occurred, so attendance was highly restricted, and only ten people attended each time
5th to 13th	During the second half of 2022, eight workshops were carried out within the frame of a Water and food Security Diploma Course in Silvia, Totoro, Cajibio and Popayán. The diploma course aimed to develop a co-constructed understanding of governance. The Universidad del Cauca team presented relevant information about the construction of meaningful governance processes, and the communities provided feedback and insight into the research. Unveiling hidden actors were not the aim of this workshop; nonetheless, several points were made by the communities highlighting the necessity to unveil the hidden dynamics in water governance. To further elaborate on this point, communities were asked to answer the question, "Who manages the territory?"; this question prompted the communities to question the central government's authority and to deepen the subject of hidden actors

indigenous reservation areas, campesino territories, and municipal capitals. As explained below, the analysis of these interactions showed anomalies in what the research anticipated would be local public policy preferences in certain regions, which point toward disruption of governance.

With the knowledge acquired, an in-depth study of the UCRB case was performed with additional observations from actors at the local and regional levels, who were identified using a "snowball technique" (Mirzaei et al., 2017). The initial identification of the actors, groups, and institutions with direct influence in the area of interest provided an essential basis for understanding the innate dynamics of the basin. All the stakeholders and actors who took part in the community workshops were contacted, and following dialogue with the community leaders, they decided to send designated speakers to be interviewed. A total of seven representatives agreed to be interviewed. These community leaders anonymously expressed their opinions and confirmed the research team's findings of disrupted governance processes.

One may reasonably ask whether or not an interview sample of this size is sufficient for attempting such an analysis. An adequate sample size in qualitative research is one important way to support the quality and credibility of the data, analysis, and results (Spencer et al., 2003). Contrary to quantitative research, samples in qualitative research may in some cases be relatively small when the objective is to substantiate a case-oriented analysis, depending on the scope, aims, and nature of the research, the quality of the data, and the study design. In addition, qualitative samples are often purposive, in that the knowledge sought is for a particular purpose and so not necessarily to be generally applied. The purposive sampling technique is a deliberate and non-random informant selection tool. In this approach, the researcher decides to interview *key informants* who are able to provide knowledge of a depth fitting to the purpose of the study. Key informants are representative of the community and can provide this comprehensive understanding of a certain situation (Tongco, 2007). In our case study, our key informants are community leaders, and we chose to interview them because of their extensive knowledge and experience and their leadership role in their community, as well as the unwillingness of other community members to be interviewed due to security issues.

Some rural communities in the UCRB are highly organized. They have a robust institutional infrastructure with communication channels in place to protect highly vulnerable people from exposing themselves to or creating security risks for communities in an area with a history and present of violent conflict. For this reason, most engagements with communities are arranged through community leaders who have appropriate socio-political insight and knowledge of their territory, as well as the consent of all the communities they represent to speak for them. The processes of collective deliberation in these communities are well-documented. They are based on deep ethical roots (Varese, 2018) by which leaders represent what the community has decided through their discussions.

In the circumstances, it was necessary to request the participation of community leaders to corroborate the findings and find explanations for the dilemmas encountered. These key stakeholders functioned as verifiers or revisors to confirm or correct the hypothesis created during the other two parts of the research process. The researchers fostered a space of trust and credibility with the communities to enable the actions of the research group in the study area. However, the open nature of this space made public verification of potentially dangerous information difficult. It required an alternative form of communication in which the actors were not exposed to the other participants, since they considered it a priority to maintain their anonymity as a necessary condition for their safety. The interviewees were unwilling to have their voices recorded or to be filmed: the interviews were therefore conducted in person and individually, with the information provided by the interviewee recorded in written form by the first author. This unwillingness to leave concrete evidence of their participation is a fundamental condition for the security and cooperation of the actors interviewed.

4. Results and discussion

4.1. Contested agenda over land and water: State vs. communities vs. the hidden actors

Our analysis of the dynamic relationship between the State and local communities shows that water governance in the UCRB can be understood as both a result (for communities) and as a process (by State). Water governance, in its form as a result, understands governance as a system which determines who gets what water, when and how, and who is entitled to water and related services and their benefits (Allan, 2001); water governance as a process considers governance as the processes and institutions involved in decision-making, rather than the outcomes of this decision-making (Lautze et al., 2011; De Stefano et al., 2014). How are such results and processes manifested in Colombia and the UCRB?

In Colombia, the IWRNP comprehends sustainability within the systemic compass of the hydrological cycle, the natural system's (ecosystem's) central ecological structure, and the interactions associated with physical, biotic, social, economic, and political-institutional elements. Its managerial attempts to operate a national strategy in the entire territory are based on a participatory principle involving government and community actors. The government accordingly seeks to ensure the effective implementation of a programmatic agenda, to handle not only the use and misuse of water resources, but also the economic development and social welfare of the country through proper management and governance of water.

In this agenda-setting process, institutions intervene as representative bodies but are confronted by individuals who are not necessarily recognized as an active part of the system. On the contrary, they are perceived as outside influences that affect the capacity of institutions to grasp a true understanding of society. This misrecognition counteracts the conception of autonomy that communities and individuals have in the basin.

The term agenda itself indicates a set of perceived problems that require public debate or even direct and active intervention by legitimate authorities. For this reason, not all issues end up on the political agenda; there are entry conditions and, therefore, exclusion mechanisms (McGinnis, 2011). However, the social and political processes concerning the IWRNP are inextricably embedded in the governmental agenda itself. The effort to transform the discourse into solid, palpable facts is much more than just an administrative problem; it is the continuation of the political struggle with other means and in different scenarios.

In the south-west of Colombia, in the UCRB, the communities' attempts to exercise autonomy when managing their territory have taken place in an environment of conflict and not of consultation. The Colombian State has severe difficulties recognizing and representing in its territories the ancestral communities and their wishes. This situation is provoking disputes over the use of water resources and land (sugar cane, coffee, avocado) or mining activities (gold, coal, silver), which are evident at the eastern slopes of the western mountain range (Cordillera Occidental) and the western slopes of the central mountain range (Cordillera Central), putting water at risk. These circumstances are not recognized as a fundamental principle of negotiation between the communities and the State, which creates violence, forced displacement, poverty, soil and water contamination, and toxicological harm against the communities (Gallo Corredor et al., 2021).

In terms of the implementation of the IWRNP, i.e., the phase during which actions and effects are produced within a normative framework of intentions, the link between the decision-making process and execution can be seen as a "top-down" implementation model based on the hierarchical distribution of authority (Roth Deubel, 2002). But the implementation process is also experimental; it is constantly redefining its objectives and reinterpreting the results (with an emphasis on the production of indicators). This process is evolutionary. Since the first efforts by the central government to instate resource management policies in the 1970s, those have been in constant change and adaptation. This means it is impossible to separate the distinct stages of this policy and its transformation process, which tends to be reformulated as needed according to the context.

In accordance with these principles, those in charge of implementing the IWRNP have sought to improve its capacity to achieve its objectives. It is possible to observe strategies and implementation mechanisms in constant evolution, which implies persisting revision of policy to adjust it to the political agenda; they could in other words be said to be part of a learning process (Guhl Nannetti, 2014). The solution is not only technical; it also involves giving priority to a political approach of recognition, redistribution, and representation (Yaka, 2019). The IWRNP has accordingly required constant refinement to harmonize it with the varying environmental policies already in place. It has sought to use environmental planning as an articulating, integrating, and systemic instrument of local, regional, and even national initiatives which promote the harmonization of state planning between the government, the community, and the individual.

While citizen participation offers a valuable path toward achieving equitable and sustainable water resource management, the study of hydrosocial relations reveals the existence of multiple normative orders (Wilson, 2014). Viewing water resource management in Colombia from this perspective, policy actors increasingly recognize the constraints that follow from growing institutional involvement as the intricacy of territorial water resource management rises. However, they also recognize how opportunities arise to develop effective policies that provide solutions to problems originating in the territory.

With the above in mind, although IWRM is a significant initial effort by the Colombian government to build water security nationwide, it does not recognize that, in some cases, the colonial conception of IWRM infringes upon sovereign models of indigenous territorial and resource management historically practiced by local communities (Wilson, 2014). It also assumes that the national government has a high capacity for territorial management. However, government management of land shows how these processes are marred by power imbalances and disconnections between actors and structures at the three levels constituting the governance structure of Colombia: local, regional, and national. As a result of the desk review of existing policy documents and the social-mapping workshops, the following national, regional, and local actors were identified (Table 3).

During the stakeholder recognition and analysis procedure in the UCRB, it was noted that there is no direct participation from the water resource users in the decision-making processes of water resource management; in the IWRNP, users are theoretically included by way of the democratic mechanisms through which Colombian citizens are represented, i.e., through local, regional, and national governments. However, this situation presents great difficulties because the real needs of the water users are interpreted by the elected representatives of the government institutions. From this standpoint, the planning and management of water resources assumes that official participatory processes are sufficient to regulate a territory.

It is necessary therefore to ask whether adequate consideration is given to the views and realities of the disputants, and if not whether this leads to an inappropriate diagnosis and definition of the problems, i.e., potential solutions to undefined problems are proposed, giving rise to their impracticality. Transversal conflicts or conflicts arising from intercultural interactions related to management processes are not necessarily resistant to a solution; however, they need to be fundamentally reinterpreted to reach agreements. Therefore, it is required to use an approach that allows the disputants to create new alternatives to understand the problem as a way of transforming conflicts to avoid falling into identity politics.

The need to recognize the specific identities of the various groups present in the territory aligns with the requirement to appreciate the position of the multiple individuals who make up these groups, and who wish to participate in their management mechanisms. Currently the implementation IWRNP assumes that justice is achieved by giving equality of status to all the participants, without paying attention to the different specific identities of these participants. This validation is a reasonable expectation for any group participating in the process. Unfortunately, this recognition has not been achieved and is one difficulty facing water resource management and land-use planning in the UCRB.

It is therefore necessary to identify the injustices to cultural values resting in institutionalized hierarchies, injustices which prevent some members of society from participating as equals in a variety of social processes. It is not a case of redesigning users' identities but de-institutionalizing the norms that prevent parity and replacing them with others that promote it. It is from here that an initial model of hierarchical levels can be formed, where interactions are promoted from within the territory (the communities and those who inhabit a determined space) to foster the processes of sharing information, interests and knowledge between each level of the system. This affords a way to deal with the asymmetries present in the current strategies of interaction, which represent rifts and manifest in conflicts.

When drawing the interaction model emerging from the fieldwork, it became evident that external agents have designed policies, because they aim at objectives and goals that are alien to the local communities. From this reality, inconsistencies are projected which alter the UCRB's theoretical approach to water resource management. They have resulted in an environmental management policy with strategic shortfalls in key territories for vulnerable local communities. According to the communities, this problem is manifested by mining concessions, hydropower permits, and access to land for large-scale monocultures, which have been granted to multinational corporations without considering the desires of rural inhabitants or possible effects upon their livelihoods through the degradation of water resources in the area. According to Duarte-Abadía et al. (2015), large-scale projects of this kind "tend to produce severe social and environmental impacts, with burdens and benefits unevenly distributed among different social groups, regions, and scales."

This state of affairs has given rise to conflicts resulting from differing conceptions of desirable land usage that cause a three-way collision between the State, the communities, and the hidden actors. The implementation of policies for land use and the conservation of natural areas are necessarily affected by how far the central State are able to enforce these regulations. The oversights in public policy decision-making due to a hegemonic vision of environmental policy aggravate the communities' vulnerabilities and enable the hidden actors to promote their political and economic agenda.

After identifying the actors, a collation process was carried out to discover what has been done to further the development of the territories of cabildos and municipalities[5] in the UCRB. These developments concerned access to roads and drinking water, crop improvement, the upgrading of educational facilities, and citizen participation in the decision-making processes behind budget implementation. However, it was not easily understandable why these activities, which would improve living conditions in some department sectors otherwise overlooked for assistance, were not given priority by the communities as actions necessary to assist their progress and that of their land. This finding was made following an in-depth consultation with entities and communities during the initial stage of the study, which confirmed the varying levels of demand for these activities, leading to concerns within the research team as to why such a condition was being encountered. However, it is not an easy task to recognize hidden actors, since they thrive amid regulatory confusion, which hinders transparency and accountability, reinforcing knowledge and power asymmetries between users, providers, and decision-makers. These circumstances help hidden actors to keep their illegal activities

5 The Cabildo is a post-colonial administrative organ that ruled over a particular municipality or, particularly, an area within a municipality. It serves now as a representation tool toward the larger State bureaucracy, where the will of a group of people, in this case, Indigenous, is manifested and vested with autonomy and its legislative structure within the Colombian central government. The aforementioned is different to the Municipality as conceived by the national constitution of Colombia, which is recognized as a local level jurisdictional unit of the central government. Currently in the UCRB there are more than 100 indigenous reservation areas articulated with as many cabildos.

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TABLE 3 Identified national, regional, and local actors in relation to water governance of the UCRB.

Stakeholder	Resources allocation and pollution control			Watershed management		Sectoral water demand management and drinking supply	
	Technical and scientific support	Management	Education	Policy and regulatory implementation	Intersectoral coordination	Public Sphere	Operators
Potable Water Commission		X					
Environment Ministry	X	X	X	X	X		
National Teaching Service			X			X	
National Utilities Superintendence		X		X			
NGO's						X	
National Natural Parks Authority	X		X	X			
Colombian Geological Service	X			X			
Water Viceministry	X	X	X	X	X		X
Departmental Coffee Growers Committee						X	
Compañía Energética de Occidente (Electric Utility Company)							X
Consejo Regional Indígena del Cauca (Council of Indigenous Communities of Cauca)						X	
Corporación Autónoma Regional del Cauca (Regional Env. Auth.)	X	X		X	X	X	
Totoró Municipality		X		X			
L. Piedras Basin Planning Committee						X	
Fundación Procuenca Río Las Piedras	X		X		X		
Acueducto y Alcantarillado de Popayán – D. Ambiental (Water Utility Company)	X	X	X		X		X
Asociación campesinos Quintana						X	
Asociación campesinos red de reservas- sociedad civil cuenca Piedras						X	
Indigenous reservations and cabildos (Quizgó, Guambia, Ambalo, Totoró, Puracé)						X	
Municipal Planning Office (Silvia, Totoró, Puracé, Popayán)		X		X			
Municipal Agriculture Office (Silvia, Totoró, Puracé, Popayán)		X		X			
Municipal Government Office (Silvia, Totoró, Puracé, Popayán)		X		X			
Municipal Health Office (Silvia, Totoró, Puracé, Popayán)		X		X			

National, Regional, Local.

undetected. The centralized nature of the Colombian State is partially responsible; it isolates the government and makes certain activities hidden, or easily overlooked by policymakers. Moreover, on many occasions, due to a lack of logistic, financial, or political capacity (or willingness), the State does not have a legitimate presence in the development of local municipal policies, especially those located at the periphery (far from the centers of power and social, political, and administrative control), allowing them to be adapted by hidden actors to push their agenda (Ballvé, 2012).

4.2. Hidden actors

> "*We do not exist for the government; we are just a stepping-stone for someone else.*"—a member of an afro-descendant community in the UCRB

At this point, we began to question, who are these hidden actors? What are they doing? What is their business? Only through the interviews and discussions with community leaders and experts could we seek answers to these questions.

In the interviews, we observed an underlying distrust of most people external to their communities. Though as researchers we have a long-standing research and empowerment relation with communities, there was a lack of willingness among the interviewees to speak openly on the observed anomalies; this meant that the process was slow and had to be done carefully to avoid complicated or even dangerous situations.

To achieve this, we agreed with the interviewees to conduct interviews outside of community boundaries. According to the interviewees, it is never entirely clear who might be listening in and how they might react. All participants had a firm comprehension of the geographic boundaries of their land; they also had a thorough understanding of how their communities came to be. It was evident that the communities had a distinct identity that greatly varied from one community to another. Grouping them as a single stakeholder when planning strategies would be a mistake, given that the aspirations, objectives, goals, and identities of these communities are entirely different.

However, as questions concerning the hidden actors emerged during the interviews, similarities in the conception of the problem began to appear. Interviewees drew associations between hidden actors and acts of violence, dispossession, exploitation, and environmental degradation. For example, a member of an Afro-descendant community explained that the river was "everything" to them. It has sustained them and helped form their identities. The economic phenomena happening within his territory have affected their habits and physical features of their culture. He refers to large-scale sand-dredging in a river near his territory. He explains that a mining enclave has formed around the river since the operation commenced with the national government's approval.

This enclave restricts access to previously open land and river sections, with consequent cultural and economic effects on the community. Their quality of life has significantly decreased since the operation started. All efforts to contact the central government and bring this issue to light have been unsuccessful. He indicates that positive statistics and indicators have overshadowed his community; he explains that most development and quality of life metrics have improved on paper since the mining operation started. Nonetheless, very few members of his community have benefited in actuality; many of them have lost their livelihoods due to a decrease in water quality, which is of course particularly damaging for a fishing community.

However, he explains that some community members held an opposing view, and were very vocal at supporting the project even before it began operating. These people have left the community and are now located in nearby larger cities with wealth they did not possess before. The interviewee speculates that they were bribed by the owners of the mining operation to persuade the community of its worth and to support the build-up of the enclave.

In the few years since the enclave formed, violence has increased around the community: armed actors, acting as paramilitary forces, have emerged in the interviewee's territory, and have protected and expanded the mining enclave. However, he believes that these forces are either ignored by or hidden from the State. Moreover, these violent acts are considered part of the Colombian armed conflict against of FARC (Revolutionary Armed Forces of Colombia) or other guerrillas.

This is a clear example of how hidden actors push development and economic agendas that directly affect the livelihoods and wellbeing of a community and take part in processes of dispossession, environmental degradation, and exploitation. It also hides community struggles behind a statistical improvement in the region's indicators that can be used to justify policymakers' inaction, something that he thinks is because "we do not exist for the government, we are just a steppingstone for someone else."

Another case that illustrates the presence of hidden actors, as reported by the interviewees from indigenous communities, is that of illicit crop cultivation in some regions of the basin. Indigenous communities have sought to preserve and expand community rights and autonomous land management as part of their political projects. From here, scenarios can arise in which the activities of large landowners with large crop monocultures collide with the indigenous claims for land expansion; this is widely recognized land ownership conflict in the Cauca department. Yet, it hides deep-rooted ethnic violence that can be traced to the colonial era.

Indigenous communities have thus adopted a stance which rejects outsider interference and upholds their claims to the ancestral ownership of the land. This is supported by the presence of cabildos, by which the national constitution permits autonomous management of the land. Indigenous communities consider their ancestral territory a space of memory and continued existence. Their land is a place where they can preserve their culture and pass it to future generations to avoid assimilation and the loss of their ancestral ontologies.

In these circumstances, indigenous communities openly oppose all illicit activities on their lands and disapprove of the use of their ancestral territory as safe havens for illicit actors. In spite of the absence of the government in these areas, these communities actively oppose this intrusion. This resistance model has set the stage for a tripartite conflict. First, the communities think that the government facilitates the exploitation of natural resources. For example, in Colombia, all commercial water usage must be regulated by the central government through the vigilance of Regional Autonomous Corporations; this conception directly creates a conflict with indigenous authorities, who consider all natural resources in their land to be under their autonomy. This situation is aggravated by the lack of a normative framework regulating the interaction between indigenous communities' autonomy and government regulations, a clash of jurisdictions manifested in Article 246 of the national constitution: "The authorities of the indigenous [Indian] peoples may exercise their jurisdictional functions within their territorial jurisdiction in accordance with their own laws and procedures as long as these are not contrary to the Constitution and the laws of the Republic. An Act shall establish the forms of coordination of this special jurisdiction with the national judicial system." It is not clear therefore which of the indigenous laws and procedures are incompatible with the State's, and in any case only the State holds the authority to decide this. Accordingly, the presence of the military on indigenous land is frowned upon by the communities. Armed groups exploit this by infiltrating and misusing indigenous land and cultivating the illicit crops that fund their warfare against the Colombian government. If communities oppose this activity, they are in danger of being systematically murdered or coerced by these illicit hidden actors.

Despite the peace deal the Colombian government signed with FARC in 2016, hidden actors still play a determining role in territorial development and water resource management. Their actions affect the quality, access to, and distribution of water. The State has great difficulties identifying these actors and taking effective measures to protect the communities and avoid intensifying conflicts in the basin. It can therefore be argued that the role of the hidden actors in the UCRB is one of opposition to the State and one of territorial control to enable the management of resources according to the hidden actors' economic interests.

Our findings and observations suggest that the influence of hidden actors and stakeholders on water governance in the Cauca department is heightened by different factors associated with socio-ecological systems, as explained above: (a) the low capacity for follow-up action by and participation from the State in the regions to promote efficient governance of public policies associated with water resources; (b) disruptions within communities seeking to develop their own organizational processes related to water governance and social control; (c) and the absence of a culture of collaboration and cooperation for accessing quality technical information that supports decision-making. But there are additional factors that require further research, since they were found to be likely related to the presence of hidden actors yet fell outside the scope of this research. These include: (d) the prominence of the monetary value of water in institutional processes; and (e) environmental conditions, such as climate variability and change.

5. Conclusion

We have proposed that hidden actors, who consciously endeavor to remain invisible, play a determining role in territorial development and communities' ways of life in regard to water resources in the UCRB. The hidden actors' deeds, which are part of their effort to enforce their will on the political agenda, directly affect the communities, who are subjected to violence if they attempt to oppose these actions. Inevitably, the activities of hidden actors seriously disrupt water governance and impede the establishment of government policies. The lack of clarity in national normative standards and the deficiencies caused by an ill-considered implementation of IWRM policy have created places from which these actors can safely emerge and gain force. Besides, institutional arrangements still lack the strength to mitigate the degradation of water resources in the Cauca region. The State's lack of legitimacy in the eyes of communities makes it difficult to create adequate participatory spaces that truly represent the diverse nature of the territory. This, by itself, is evidence of the problems in policy implementation by the State, which are magnified by hidden actors' workings in the regions that lack State presence.

We have also contended that problems of recognition and representation by the State have favored the emergence of hidden actors due to the lack of a comprehensive notion of the constituent elements of rural society. This creates a vacuum that favors illicit stakeholders on the ground and hinders long-standing efforts by different ethnic and campesino communities to be represented and recognized on a larger scale. However, while we have sought to incorporate awareness of hidden actors and their invisible power influence over water governance, there remain other questions meriting further investigation: how do hidden actors exercise their power to influence decision-making? To what extent might the communities give priority to the activities of hidden actors? How do the hidden actors' illegal activities correlate with broader political corruption in Colombia and beyond also influenced by broader global capitalism?

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AF-B: ground research and initial discussion based on the findings. MN: problem and aim definition, coherence editing, and literature support. AF: methodological approach. JA: literature support, overall structure and review, and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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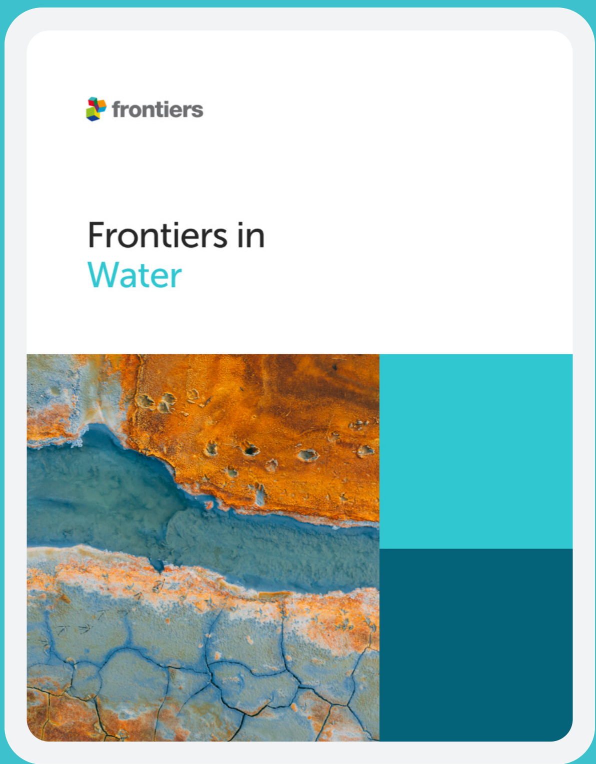

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