SUSTAINABILITY CHALLENGES FOR OUR URBAN FUTURES

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SUSTAINABILITY CHALLENGES FOR OUR URBAN FUTURES

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EDITORIAL
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Editorial: Sustainability Challenges for Our Urban Futures

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Editorial on the Research Topic

Sustainability Challenges for Our Urban Futures

Today, more than 50% of the human population lives in cities. This percentage is expected to rise to 70% by the year 2050 (United Nations, 2016), and will probably keep increasing for the foreseeable future. By enabling accumulation of resources and knowledge, urbanization has had a great impact on improving quality of life, but it also poses difficult challenges for planning and management of the built and natural environment, the provision of urban services, and the design of equitable economic policy (Dye, 2008; UN-HABITAT, 2017). The complex historical, socioeconomic, political, and biophysical drivers of urban growth result in significant spatial heterogeneity in terms of social and demographic characteristics, natural resources, and social, economic and physical infrastructure. This heterogeneity reinforces inequalities in the provision of urban services and exposure to hazards. Such inequalities are exacerbated by biases in the responses and interventions of city managers and infrastructure providers (McGranahan et al., 2001; Ahern, 2013; Eakin et al., 2017; Pickett et al., 2017; Zhou et al., 2017). In cities, social and political processes are created and reinforced through actions of residents, governments, and decision-makers, who in turn influence the creation of the built environment, its socio-economic heterogeneity and the concomitant, uneven vulnerability to hazards (Eakin et al., 2017).

In this Research Topic we present papers that provide novel ideas and empirical results on how decision-makers can better govern urbanization and urban well-being in the context of globalization, climate change, and inequalities. In particular, articles in this collection include methodological and empirical contributions that illustrate the importance of social-ecological and technical coupling in the urban context. Collectively, these contributions support an expansion of the domains in which urban decisions and planning strategies must take place to promote more sustainable, and more equitable expressions of urban life. All articles in this Topic highlight the unequal participation of different actors and stakeholders in the process of making decisions in the face of an array of urban sustainability problems, and stress the major importance of inclusion of all relevant actors and stakeholders when planning for sustainable cities.

In the context of climate change, hydrometeorological events that hit cities have increased both in frequency and in intensity, and the impact of these events and urban strategies for recovery are a focus of investigation for better planning and management. In this respect, the contribution of Beckingham et al. provides a critical overview of the evolution of stormwater management approaches in urban centers in Southeastern USA, arguing in favor of better socio-ecological design that incorporates transdisciplinary work. The authors make the case for the critical importance of engaging different actors and stakeholders to conceive and implement sustainable solutions, including not only the biophysical and technical aspects of building infrastructure, but also the

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appropriate management and social appreciation of the provision of ecological services. In their article, Aguilar-Barajas and Ramirez describe the impact of, and recovery from, a major hurricane hitting northern Mexico. Their contribution focuses on the transdisciplinary work of the "State Reconstruction Council," a government taskforce especially designed to deal with the crisis. In a matter of weeks the Council reinstated infrastructure and services that were severely damaged or destroyed. The authors advocate for the creation of this type of institution as a permanent vehicle for sustainable urban planning and management.

Beyond creating institutions charged with promoting transdisciplinary work for urban management, sustainable cities require the generation and availability of relevant and credible information for stakeholders. Three contributions of the Topic deal directly with the production and analysis of information relevant for decision making in urban planning settings. The article by Mazari-Hiriart et al. characterizes the quality of water in supply wells in Mexico City, while considering the potential for contamination due to their closeness to geological fractures. This work reflects on and makes visible water vulnerabilities that go beyond the availability and exploitation of water sources, serving as a reminder of the importance of locally salient analyses of urban vulnerabilities. Another contribution dealing with the challenges of information for planning is presented by Estrada et al.. In their work, the authors advocate analytical approaches that can unveil critical aspects of urban sustainability in the context of climate change. Their methodological proposal addresses the complexity of information characterizing urban realities and climate uncertainties, with the ultimate aim of guiding policy. At finer scale, Zambrano, Aronson et al. present a case study of the consequences for and evaluation of sustainability of land fragmentation in Mexico City, going beyond the biophysical dimension of sustainability to include metrics of human well-being and social benefits of green areas.

A substantial proportion of the contributions to the Topic focuses on the importance of coproduction of knowledge for urban sustainability transformations. These papers address the ubiquitous hegemony of exogenous narratives as a frequent hindrance, and propose the inclusion of a diversity of actors and local narratives for the analysis of the challenges and opportunities of sustainable urban planning and management. Four examples of efforts for transformative, transdisciplinary work in urban planning for sustainable futures are presented in this group of articles: (i) Zambrano, Cano-Santana et al., focus on the management of urban green spaces and the need to identify conflicts and synergies among stakeholder viewpoints, (ii) Priya et al., present a data-informed reflection on the effectiveness of a formal imported model of planning for health provision in India vs. informal solutions, (iii) Eakin et al. explore and document the need to make visible the meta-narratives and associated solutions for urban problems such as water vulnerabilities as means of identifying possibilities for more sustainable management, and (iv) Randhawa et al. present a case study focused on waste management that provides important lessons for the role of transdisciplinary research in urban sustainability transformations.

The multifarious nature of urban realities, urban challenges and urban traditions is evident in this small sample of reports. Dealing mostly with regions in tropical North America, and exclusively on middle/low income cities around the tropic of Cancer, they nevertheless display the bewildering diversity of empirical and conceptual approaches to urban sustainability. One commonality emerges, though, and is that whatever the particular challenges facing cities, it is only through the concert of all stakeholders and decision-makers that urban humans will be able to move toward sustainable goals and supporting transformative change.

AUTHOR CONTRIBUTIONS

AE, HE, and CM proposed the Research Topic, edited manuscripts, and wrote the editorial. All authors contributed to the article and approved the submitted version.

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REVIEW
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Stormwater Ponds in the Southeastern U.S. Coastal Plain: Hydrogeology, Contaminant Fate, and the Need for a Social-Ecological Framework

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In lowland coastal regions of the southeastern United States, stormwater ponds are being built as the "green infrastructure" best management practice of choice for addressing the hydrologic changes associated with rapid urban and suburban development. In addition to dampening storm flows, stormwater ponds may provide pollution control and other ecosystem services. However, ponds are not native to this landscape. This review summarizes what is known about the effectiveness of these engineered ponds, which take many shapes and forms, in the context of hydrology, contaminant fate, and management. Research needs are identified and include evaluating pond performance and redesign options more comprehensively and applying a social-ecological framework for the future of stormwater pond management.

Keywords: stormwater, pond, green infrastructure, urban development, coastal plain, best management practice

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INTRODUCTION

The southeastern coastal plain areas of the United States, comprising North Carolina (NC), South Carolina (SC), Georgia (GA), and Florida (FL) (**Figure 1**), have experienced population growth in recent decades that exceeds the national average (**Table 1**). This growth is expected to continue, and within a coastal area that is already more densely populated than inland counties (NOAA, 2013). According to the National Oceanographic and Atmospheric Association (NOAA) Coastal Change Analysis Program, between 1996 and 2010 the Southeast had the fastest rate of change in developed land of any coastal region in the country, and experienced development at a pace of 1 football field (∼5,350 m^2, or ¾ of a standard soccer field) every 13 min (https://coast.noaa.gov/digitalcoast/training/regional-land-cover-change.html). This region also supports many industries, including recreation, tourism, and fisheries, which are closely linked to numerous ecosystem services and depend on well-managed water resources. In 2015, each state in the region attributed 9.5–14.5% of total jobs on average in coastal counties to "ocean jobs," primarily tourism and recreation, but also including shipping activities and living resources (although not counting self-employment) (https://coast.noaa.gov/snapshots/). Altogether, coastal counties contributed 25% of the 2014 total gross domestic product of the states in the Southeast region (NOEP, 2016).

Impacts of increasing population, economy, and the resultant land cover and land use change expected for this region into the future (Terando et al., 2014) include changes to the social and political fabrics of the region as well as alteration in coastal geomorphology, increased pollution and eutrophication, and biodiversity loss (National Research Council (NRC), 2008). Stormwater runoff

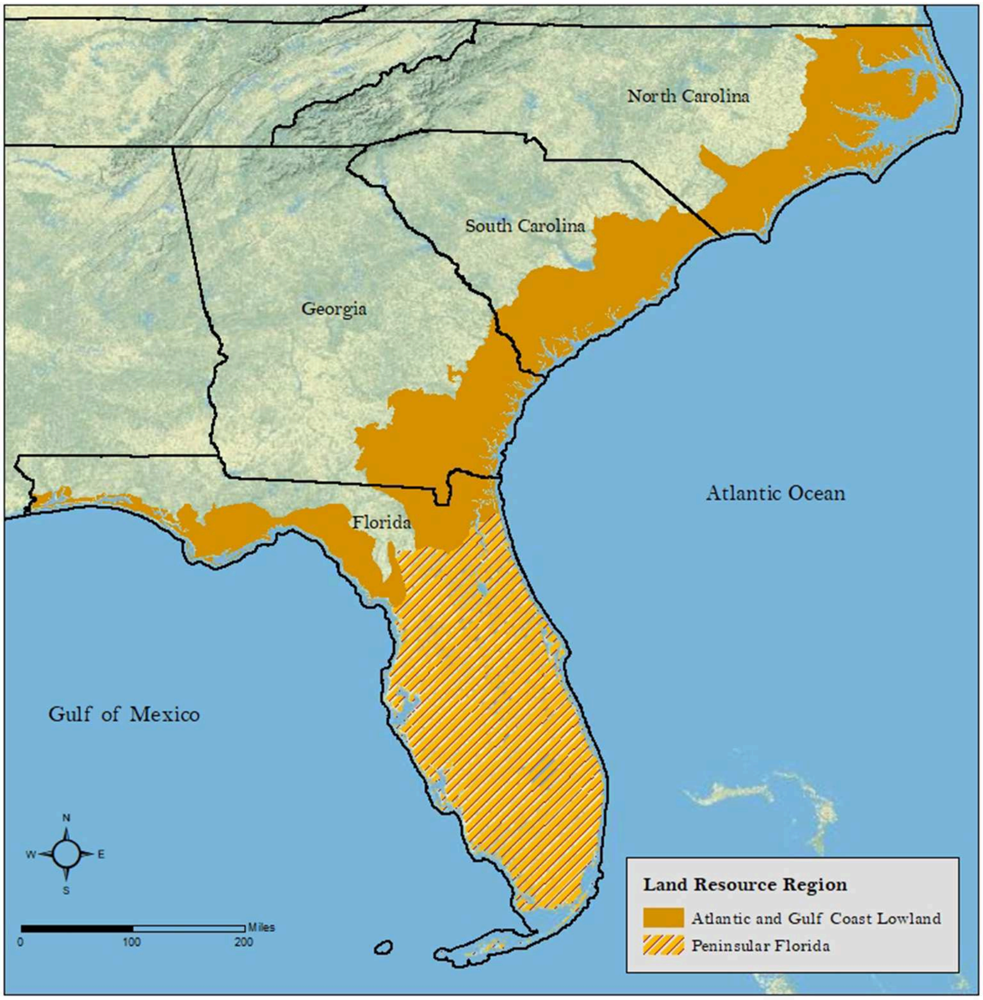

FIGURE 1 | Coastal regions of the Southeastern United States defined using the U.S. Department of Agriculture-classified Land Resource Regions of the outer coastal plain (Atlantic and Gulf Coast Lowland) and peninsular Florida (Map data source: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/nra/nri/?cid=nrcs143_013721).

from impervious surfaces, specifically in urban and urbanizing land uses, is widely considered the primary stressor to aquatic ecosystems around the world and there is, therefore, a need to mitigate these impacts using stormwater control measures (National Research Council (NRC), 2008). Urban development along coastlines worldwide is leading to increased reliance on various types of best management practices (BMPs) to mitigate water flow and water quality concerns, and guidance is increasingly available to planners and builders (e.g., Ellis et al., 2014; Chang et al., 2018).

Over the same period from 1970 to today when U.S. coastal populations have risen dramatically, there have been shifts in structural controls used for stormwater management reflecting various regulatory, technological, and economic drivers (Anderson et al., 2002; National Research Council (NRC), 2008; McPhillips and Matsler, 2018). In many cases, conventional stormwater pipes and conveyances discharging directly to receiving water bodies, often termed "gray" stormwater infrastructure, have fallen out of favor due to unintended consequences associated with the drastic alteration of streamflows and water quality (e.g., Walsh et al., 2005). Where space was available, and where encouraged by stormwater control regulations passed primarily since the 1980s, preference shifted to softer engineering controls, or "green" infrastructure that aims to alleviate changes in water flows and quality post-development, while simultaneously providing other potential societal benefits. While there are a number of emerging green structural stormwater BMPs, such as constructed wetlands, bioswales, and infiltration basins, stormwater ponds are currently the most widely used for peak flow reduction and runoff treatment (National Research Council (NRC), 2008).

In the coastal plain regions, which are characterized by relatively shallow water tables and low hydraulic gradients, stormwater ponds with a permanent pool, typically referred to as wet detention ponds, dominate and are widely visible landscape features. For example, demonstrating the proliferation

TABLE 1 | Population change in the southeastern U.S. coastal plain states.

State	Coastal plain (Figure 1)*		Coastal counties (NOAA, 2013)		
	2010 population	1990–2010 historical change (%)	2010 population	1970–2010 historical change (%)	2010–2020 projected change (%)
NC	1,406,816	46	999,064	92	10
SC	1,507,518	40	1,241,048	127	23
GA	948,607	44	563,967	82	19
FL	18,214,732	42	14,468,197	165	16
U.S.	–	24	–	52^	–

**Census data obtained from U.S. Census Bureau (2011) and Manson et al. (2018). ^Average population change of all U.S. counties.*

of stormwater ponds during development, an estimated 10,000 wet detention ponds have been surveyed in urban areas in southwest Florida, most being constructed since 1980 (Thomas and Lucius, 2016), and there are over 14,000 stormwater ponds in the 20 coastal counties of North Carolina (Gona, 2016). In a study of 511 ponds in SC, wet detention was the most frequently used type (Drescher et al., 2007). Further, analysis of aerial imagery-based inventories of wet detention ponds has found about 100 ponds were created per year on average in both the Myrtle Beach and Charleston metropolitan areas of SC between 1994 and 2013, with annual rates of change in pond area roughly tracking the rate of change of total developed land area (Smith et al., 2018). Ponds are often a highlighted feature of residential developments that have been designed over the past few decades (**Figure 2**).

Green stormwater infrastructure provides a host of potential ecosystem services, although these have been mostly unquantified (Prudencio and Null, 2018). Traditionally engineered with the objective to control flooding, stormwater ponds act as reservoirs to collect water and soil erosion from the surrounding landscape and to dampen the storm pulse to receiving water bodies. This function is important for integrity of downstream structures, and ecosystems therein (Persson and Wittgren, 2003). Over time, it has been shown that ponds can serve many functions; they provide ecological habitat for birds and aquatic life (Hassall and Anderson, 2015; Greenfield et al., 2018), either trap or act as a gateway for the transport of various environmental pollutants to receiving bodies (Van Metre et al., 2000; Thapalia et al., 2010), sequester carbon (Schroer et al., 2018), provide cultural and ecosystem services (Moore and Hunt, 2012), and can serve as a valued, aesthetic feature of a community (Ghermandi and Fichtman, 2015). By averting and storing runoff on-site, ponds open up the possibility for rainwater use, such as for landscape irrigation, saltwater intrusion barriers, drinking water aquifer recharge, augmentation of potable water reservoirs, non-potable water use in buildings, and baseflow augmentation to improve freshwater habitat and recreational use depending on water quality and need (Grebel et al., 2013). Stormwater ponds therefore serve as a public good, although they are often privately owned and managed. How ponds perform hydrologically and biogeochemically influence how they are viewed as either environmental assets or liabilities.

In this review, we aim to illustrate that the water quality and quantity functions of stormwater ponds, as an environmental engineered landscape feature, have important implications for the social and ecological systems of the southeastern United States, and vice-versa, that require further multidisciplinary study. The case for recognizing stormwater infrastructure as a social-ecological system has been made recently (e.g., Flynn and Davidson, 2016), and the southeastern U.S. coastal plain region offers a unique hydrogeologic, ecologic, and socio-political setting to study the functioning of stormwater ponds and their impact on coastal ecosystem services. Here, discussion of "stormwater ponds" is in specific reference to "wet detention basins." We recognize that other designs such as dry detention basins also provide similar services, but dry basins are ephemeral in their water-holding characteristics, usually due to higher soil permeability and/or deeper water table conditions. Thus, dry basins operate differently to affect the routing of stormwater and fate of contaminants in the landscape (Ellis et al., 2014). We focus on the southeastern Atlantic coastal plain within NC, SC, GA, and FL, as well as the FL peninsula because of cohesiveness in landscape topography, ecology and land management (**Figure 1**). Namely, the region spans the U.S. Environmental Protection Agency Level III Ecoregions of the Middle Atlantic Coastal Plain (NC, SC), Southern Coastal Plain (GA, FL), and Southern FL Coastal Plain. The region is also identified as the Southeast region for the U.S. EPA/NOAA Coastal Change Analysis Program and comprises the Outer Coastal Plain and Florida Peninsula Land Resource Areas defined by the U.S. Department of Agriculture Natural Resources Conservation Service.

DISCUSSION

Geologic and Hydrologic Context

There are generally few natural lakes and ponds in the southeastern coastal plain. Water resources in this region include large reservoirs on dammed rivers as well as deep, confined aquifers in carbonate formations of Eocene Epoch (34 million years) or older age. This region is characterized by a generally flat topography, with beach ridges or terraces (modern and ancient, dating back to past high stands of sea level through the Cenozoic Era) separated by lagoonal back-barrier areas between the terraces. One example of natural "ponds" includes Carolina Bay wetlands (Pyzoha et al., 2008); however, these coastal plain features are uncommon because of well-drained soils in the former beach ridge systems and the tendency for concentrated flow on poorly-drained clay-sized sediments

FIGURE 2 | Land use transitions to residential development highlight the use of wet detention ponds for stormwater management in the coastal zone. Upper panel: outside Charleston, South Carolina, 33°3'33.01"N, 80°8'48.85"W in the Sawmill Branch Creek watershed (HUC12: 030502010601); lower panel: outside Boca Raton, FL, 26°30'35.22"N, 80°11'29.72"W, in the Hillsborough Canal watershed (HUC12: 030902061101). Stormwater ponds in the two developed panels to the right side are visible in the form of dark areas surrounded by homes/buildings. In the upper-right panel, two large ponds are visible near the center, while many ponds (round or elongated) are visible in the lower-right panel. Upper-right panel, through partial cloud cover, also shows expansion of new developments with clear cutting and re-grading of the pre-existing managed-forested landscapes, and a borrow pit is found in the top-left corner. The lower-left panel also shows (at bottom-center) prior agricultural use of ponds.

to form streams. Another example are karstic depressions in peninsular Florida (Galloway et al., 1999), which are more common, as are coastal lagoons (Lapointe et al., 2015; Barile, 2018), and both are important water resources in a region of near-surface carbonate lithology. The better connections of surface water and groundwater in peninsular FL result in important differences of water resources, both natural and engineered, compared to that of the rest of the southeastern coastal plain.

Another factor for sparse natural littoral surface water systems in the region is the relatively balanced water budget. Average annual rainfall in the southeastern U.S. is about 110 cm in the upper (inner) coastal plain to about 130 cm in the lower coastal plain of South Carolina (Amatya et al., 2018) to 150 cm in northern Florida (NOAA, 2019). This water input has been, on average, approximately balanced by evapotranspiration (ET) of coastal plain forests (Harder et al., 2007; Callahan et al., 2017; Amatya et al., 2018). Freshwater runoff from any undeveloped uplands of the coastal plain is relatively small in volume because of the relative ease of water infiltration into the sandy upland soils, however, with land development in and around metropolitan areas, increased impervious surface coverage has led to larger volumes of stormwater runoff to receiving water bodies, including streams and rivers, tidal creeks and marshes, and the coastal ocean (Sanger et al., 2015).

To handle the increase in stormwater flow, stormwater wet detention ponds have been built across the southeastern U.S. coastal plain, as described above. Stormwater ponds of varying size now exist across the region where previously only a small collective area of impounded streams and creeks existed, which was typically for the purpose of freshwater resources for rural needs (livestock, waterfowl, irrigation and recreation purposes; see for example **Figure 2**). Stormwater ponds are classified generally according to the way they store and route runoff. In the broadest terms, ponds are either wet or dry—having a permanent pool of water or not. Whether a pool is permanently wet or dries up between rain events is a function of connectivity with surface and ground waters, soil properties, and design of outlet structures. For instance, under similar geologic settings a permanent pool of water can be retained by setting outlet structures at higher elevations than for a dry detention basin and/or by lining the bottom of ponds with a low-permeability material (Persson and Wittgren, 2003; Weiss et al., 2007).

Stormwater routing patterns have received some study in the lower coastal plain of South Carolina (Harder et al., 2007; Epps et al., 2012), with some attention placed on calibrating runoff models like TR-55 or Curve Number Approach to the low-gradient topography (Blair et al., 2014a,b; Blair and Sanger, 2016). The variable soil drainage characteristics of this region may explain the wide range of runoff fraction of precipitation for individual storm events. For example, Epps et al. (2012) found for a natural forested watershed with sandy soils and shallow water table condition, total storm runoff was as little as 0%, and up to 93% of precipitation for different storm events, with a median value of 18% (see Table 3 in Epps et al., 2012). Such variability in this area with little disturbance of forest systems (albeit with past drainage structures such as ditches, constructed decades ago) leads to uncertainty in the stormwater dynamics of developed lands and the engineering of stormwater retention structures. Site details such as topography, development soil fill material, ditching, and pond design details, together with runoff predictive models that include soil data (e.g., Fennessey et al., 2001), should inform stormwater managers to plan for and mitigate stormwater inputs.

Nuisance flooding (Fennessey et al., 2001; Underwood, 2018) and major storm event flooding are hazards to property near ponds that may be exacerbated by a lack of understanding of the hydrology of ponds in the coastal zone. Property can experience nuisance flooding following the construction of large adjacent impervious areas when a pond is constructed directly upslope, as is done for in-fill residential or commercial development. This may instigate a local increase in the water table if the pond is not lined with low permeability clay or geotextile to minimize groundwater seepage, or if an extreme event causes pond overflow or bank failure. These hazards can occur when the site plan mispredicts the predevelopment runoff of a watershed and/or uses property boundaries to define the catchment area for the ponds, as is commonly done (Fennessey et al., 2001). This can additionally impair a pond's ability to operate to design standards. This region is also uniquely prone to hurricanes/tropical storm precipitation events and bears the most risk from hurricanes compared to other coastal U.S. populations (Wilson and Fischetti, 2010). The hydrologic cycle is expected to intensify under scenarios of future climate change. Changing patterns of precipitation in the Southeast U.S. includes an expected increase in heavy downpours (Carter et al., 2018). Although stormwater ponds are not designed to alleviate flooding from major storm events, one can conclude from this that climate non-stationarity may ultimately affect the size of a "design storm": the event return period and amount of rainfall that policy dictates ponds should be able to hold and slowly release. The ultimate result of improperly located or sized stormwater basins may be additional financial burden on community residents impacted by flooding or increased maintenance, as well as broader watershed-scale impacts.

Many stormwater ponds could be conceptualized as engineered "headwaters" connecting landscapes and larger water bodies– and in the coastal zone, these water bodies can be tidally influenced. For instance, 57% of the development-related ponds surveyed in coastal SC are found within 3 km of a significant receiving water body (i.e., "river, tidal creek, or other coastal water body >66 feet in width, as defined by the National Wetland Inventory") (Smith et al., 2018). The water budget of ponds in proximity to tidal creeks will dictate whether or not pond salinity may be brackish, which may be the case if there is significant surface water exchange (via "outlet" structures) or groundwater connectivity, or especially during drier seasons coinciding with periods of higher evapotranspiration. Ponds in coastal SC that are tidally influenced, especially with direct surface water connections, have been observed to range from low brackish to marine salinities (DeLorenzo and Fulton, 2009). Salinity dynamics in freshwater ponds in proximity to tidal bodies have also been observed due to groundwater connections (Wisniewski, 2014). The incidence of high tide flooding is increasing in the southeastern Atlantic coast region (Carter et al., 2018; NOAA, 2018), which has implications for stormwater management. For three coastal counties in SC where location of stormwater ponds was mapped, it was estimated that up to 20% of ponds were at or below the elevation of mean higher high water, indicating likelihood of tidal groundwater exchange (Smith et al., 2018). Contributing to complicated dynamics of storm water flows, the southeastern U.S. coastline has a geographically variable tidal range, with two high tides and two low tides occurring over a 25-h cycle. The tidal amplitude ranges from about 1.2 m in both the northern coast of SC and along the Atlantic coast of Florida, 2 m in the central coast of SC, and 2.8 m in the southern coast of SC. While not conducting a complete water budget, Thomas and Lucius (2016) estimated a significant groundwater contribution (up to ∼15%) to a stormwater pond in southwest Florida. Pond construction details (depth and whether the pond bottom is lined or unlined) will control this subsurface flux.

Stormwater Flow and Pollution Control

Wet detention ponds hold a permanent pool of water, have additional capacity to temporarily store water above the permanent pool to a design depth during storm events, and trap contaminants predominately through settling and biogeochemical transformation within the water column and sediment bed (see conceptual diagram, **Figure 3**). Hydrological, physical, and biogeochemical processes operate in concert to drive the function of stormwater pond systems. Stormwater runoff and groundwater interflow entering ponds carries with it an array of contaminants of concern, including inorganic (e.g., nutrients and metals) and organic chemicals (e.g., pesticides, herbicides, flame retardants, phthalates), particulate matter (e.g., sediments, oxygen-consuming substances, and anthropogenic litter including microplastics), and pathogens (e.g., bacteria and viruses), all of which are removed with various efficiencies depending on pond- and contaminant-specific attributes (Vulava et al., 2018). For example, concentrations of pesticides in stormwater ponds in coastal South Carolina have been correlated with temperature and rainfall, and to concentrations in adjacent tidal creeks (e.g., pyrethroids and imidacloprid), which demonstrates connections between runoff, stormwater ponds, and receiving waters (DeLorenzo et al., 2012). Significant groundwater fluxes of nutrients (ammonium and nitrate) to and from stormwater ponds have also been observed (Bunker, 2004).

Broad ranges in pollutant removal efficiencies from stormwater runoff by wet detention ponds are reported in published literature. Wet detention basin performance cited by

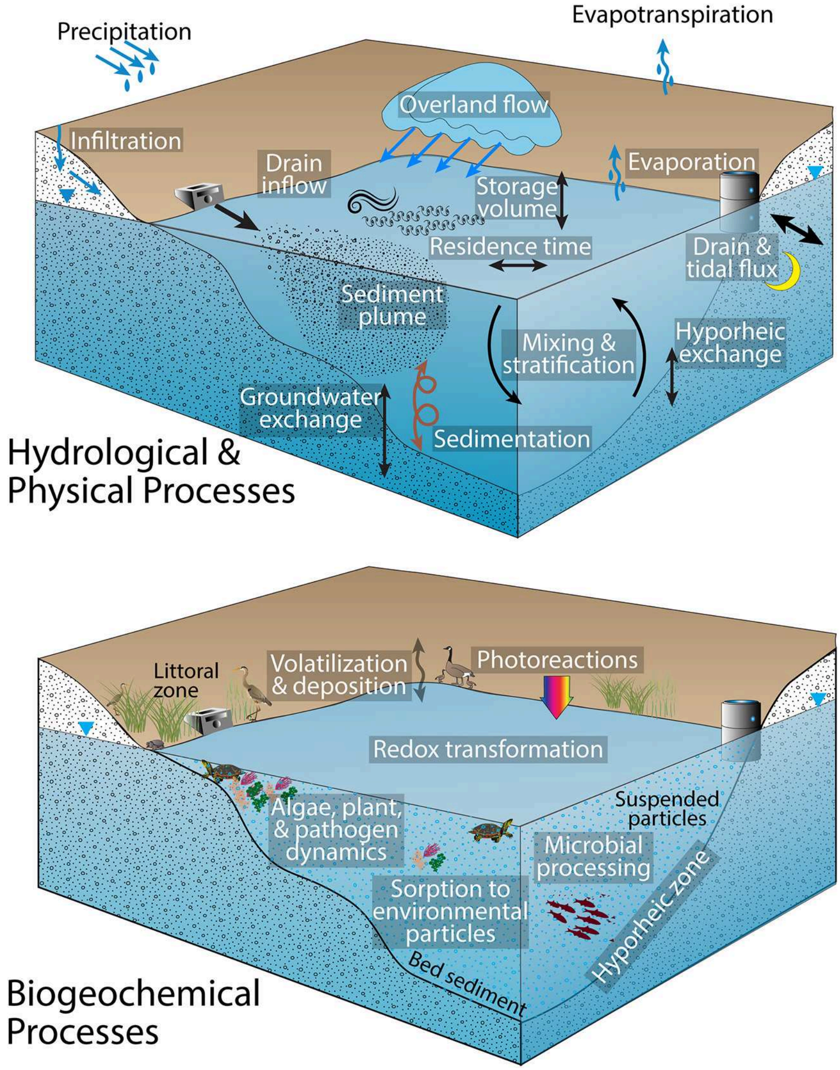

FIGURE 3 | Conceptual model outlines hydrological and physical (upper), and biogeochemical processes (lower) that occur in stormwater ponds. The hydrological and physical processes reflect a typical hydrologic cycle as well as stormwater runoff and associated sediment and contaminant transport. The biogeochemical processes reflect various consumption, sequestration, and transformation pathways of contaminants in stormwater ponds. (Acknowledgment: some elements of this conceptual model are courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science, ian.umces.edu/symbols/).

BMP guidebooks for South Carolina and Florida, as examples, are presented in **Table 2**. These ranges reflect "typical" behavior but may not capture the range of removal efficiencies across storm events of different magnitudes, and are not specifically taken from studies of wet ponds in the coastal plain. For example, negative removals indicating ponds as sources of pollutants to receiving water bodies are also reported in coastal case studies (e.g., Messersmith, 2007; Gold et al., 2017b). Also, the ranges in total nitrogen removal in **Table 2** for SC and FL case studies agree with the average of 40 ± 31% for wet ponds in a recent comprehensive data synthesis (Koch et al., 2014), but it's important to note that efficiency depends on nutrient form (e.g., nitrate or ammonium vs. organic-N) and this applies to other contaminants of concern as well (e.g., metals). It is also worth cautioning that comparing storm-by-storm pollutant removal efficiencies is complicated by variation in study design, data analysis and site hydrology, and it has been recommended that alternative measures for evaluating effectiveness, such as statistical comparisons of longer-term influent and effluent data and evaluation of effluent water quality, be more routinely applied (Strecker et al., 2001).

While serving to alleviate flooding and downstream water quality concerns when operating effectively, stormwater ponds may also present localized human and ecological health risks. Because ponds capture pollutants from stormwater runoff, removal and disposal of these sediments represents an opportunity to reduce contaminant loads to receiving water bodies; however, pond sediments may contain concentrations of trace metals or organic contaminants of concern above sediment quality guidelines (Weinstein et al., 2010; Baalousha

TABLE 2 | Average pollutant removal capabilities summarized in Best Management Practice manuals for wet detention ponds based on studies conducted in South Carolina and Florida.

Pollutant	Average percent removal	
	South Carolina (SC DHEC, 2005)	**Florida (Harper and Baker, 2007)**
Total suspended solids	65–80%	55–94%
Copper	40–65%	1–92%
Zinc	50–75%	32–96%
Lead	60–85%	40–96%
Total nitrogen	35–45%	4–63%
Total phosphorus	50–70%	39–93%
Biochemical oxygen demand	Not reported	50–90%

et al., 2018). In addition to receiving pathogenic organisms in non-point source runoff, stormwater ponds may also provide the ideal conditions for their proliferation or attract wildlife leading to in-pond sources (Hathaway et al., 2009; Greenfield et al., 2018). Emergence of harmful algal blooms in ponds can impact immediate or downstream human and ecological communities (Lewitus et al., 2003, 2008; Serrano and DeLorenzo, 2008; Greenfield et al., 2017). Developing a framework for human and ecological health risk assessment for engineered stormwater ponds is complicated by having to define endpoints of impairment and appropriate indicators (Tixier et al., 2011).

The factors that are critical to influencing pond function, specifically hydraulic detention and contaminant sequestration, are based on mechanistic and empirical knowledge from the fields of engineering and natural sciences (see for review, Blecken et al., 2017 and Vulava et al., 2018). Stormwater pond design and maintenance manuals outline and regulate critical features (such as dimension, slopes, hydraulic head, depths, pipe structures and ways to maintain them; e.g., U.S. EPA, 2009). Pollutant removal processes occur through a variety of mechanisms, including physical (e.g., sedimentation), chemical (e.g., sorption, photodegradation), and biological (e.g., uptake and transformation of nutrients, or particulate trapping by vegetation) (**Figure 3**).

Sedimentation in particular is an important process that protects downstream water quality, and is influenced by pond design (e.g., geometry, forebay or other installation), hydrology (e.g., retention time, potential for short-circuiting), the nature of suspended solids (e.g., allochthonous, autochthonous, and carbon or mineral composition), management activities that impact particle capture (e.g., vegetation planting/control or dredging maintenance), and even storm event-specific characteristics (e.g., hydrograph, wind speed and direction) (Greb and Bannerman, 1997; Anderson et al., 2002; Scholes et al., 2008; Vezzaro et al., 2011; Gold et al., 2017a; Moore et al., 2017). In a study of 14 stormwater wet detention ponds in coastal SC in residential urban and suburban communities, Schroer et al. (2018) measured sedimentation rates spanning 0.06–0.5 cm y^{-1} and detected sequestration of carbon and nitrogen through burial. However, in another case study in SC, Messersmith (2007) observed a single stormwater pond lost 36% volume and the last pond in a series of 5 linked ponds lost 15% volume in 5–7 years post-construction. Sedimentation in stormwater ponds is beneficial for improving water quality in downstream receiving water bodies; however, over time the reduction in effective settling depth, water storage volume and residence time of stormwater in ponds can lead to ineffectiveness at removing pollutants or buffering storm pulses.

Residence time (RT) is a parameter that controls sedimentation and biogeochemical transformation and has been cited as the factor that is most limiting to water quality improvement in stormwater ponds (although other factors, such as light penetration, redox environment, and plants are notable for certain constituents) (Mallin et al., 2002; Weiss et al., 2007, 2008). Residence time is determined by pond volume and water discharge rates. Longer residence times over 7 days tend to result in more improved water quality through greater reduction in nutrients (N, P) and biochemical oxygen demand (Harper and Baker, 2007). However, residence time alone does not necessarily allow prediction of pollutant removal efficiencies (AMEC, 2012). Size, depth, and shape are important design criteria that have been observed to affect pollutant removal in stormwater ponds (e.g., Chiandet and Xenopoulos, 2016) and are a part of wet detention pond design criteria in states across the study region (SC DHEC, 2005; Harper and Baker, 2007; GA EPD, 2009; NC DEQ, 2017).

There are also seasonal variables that can affect wet detention pond performance. For instance, stratification or eutrophication are phenomenon that are often observed in stormwater ponds and lakes in the southeastern U.S., especially in summer, as affected by pond depth, nutrient loads and the sub-tropical climate at the coasts (Lewitus et al., 2003, 2008; Harper and Baker, 2007; DeLorenzo and Fulton, 2009; Gold et al., 2017a). These conditions can impact the availability of oxygen in pond sediment pore waters and subsequently the redox conditions, which control processing of nutrients, speciation of metals, and degradation of organic compounds, or may lead to proliferation of pathogenic microbes and harmful algae. Harmful algal blooms and low dissolved oxygen can result in fish kills in ponds (Kirkwood, 2009), and may augment occurrences of pathogenic Vibrio bacteria (Greenfield et al., 2017). The extent of tidal influence on ponds, which may vary seasonally, can also affect pond ecology and pollutant removal, such as by shifting bacterial assemblages responsible for nutrient transformation (Lewitus et al., 2008; DeLorenzo and Fulton, 2009).

As a wet detention pond (and infrastructure, generally) ages, continued performance is contingent upon maintenance and local stewardship. "Lifetime" represents the duration that the stormwater control structure demonstrates acceptable functionality, after which replacement or significant maintenance would be required. The lifetime of wet detention ponds may be most impacted by rates of sedimentation and infill by organic matter and debris (e.g., Anderson et al., 2002; Gold et al., 2017a; Thomas 2014). These rates are dependent upon many factors, and importantly in the Southeast U.S. could be controlled by relatively low landscape erosional potentials, relatively high year-round primary production (i.e., resulting in high levels of organic debris) and continuing development pressures. For instance, rapid urbanization or development "in-fill" occurring in the region, and the resulting increase in impervious cover within a stormwater pond watershed, can result in increased sedimentation in ponds (Schroer et al., 2018) that could produce accelerated maintenance demands. Maintenance to dredge accumulated sediment is recommended when the pond pool volume has been significantly diminished. For example, in South Carolina a loss of 25% of permanent pool volume is the benchmark recommended for dredging (SC DHEC, 2005). State of Florida requires that dredging be conducted when the specific "water quality volume" designed for sediment capture has been lost (FDOT, 2015). Decisions associated with maintenance activities, such as dredging, are generally borne by individuals, communities, or municipalities in accordance with responsibilities outlined by local systems of stormwater governance and are affected by the costs and perceived benefits of actions (Burnett and Mothorpe, 2018).

Stormwater Pond Stewardship

Environmental governance and stewardship are long-standing, constantly-evolving practices that tie policy with science through communication (Harrington and Hsu, 2018). Approaches are being developed by various "hard" and "soft" scientific communities for improving partnerships/cooperation/coordination among residents/private owners and state- and local-governments for stormwater pond stewardship, including understanding the costs and benefits of investment (Burnett and Mothorpe, 2018), as well as psychological preferences for how information is presented (Callahan et al., 2018), or who within a community is most receptive to messaging (Monaghan et al., 2016). Among insights gained, researchers have found that knowledge and valuation of stormwater pond function alone may not necessarily translate to acceptance of BMPs, especially if change is perceived as going against social norms (Monaghan et al., 2016). Further complicating sharing of knowledge about best practices across regions are barriers (actual or perceived) presented by political and institutional systems, such as governing patterns, legal codes, and funding mechanisms (Dolowitz, 2015).

There are various stakeholders that need to communicate with each other to exchange needs, desires and technical information, from individual homeowners, to homeowner associations, stormwater pond managers, scientists and engineers, and regulatory officials at multiple levels of governance. Multiple government agencies and non-profits may be involved with a municipality's stormwater management. Learning and exchange may stall when parties do not have a history of trust (Fennessey et al., 2001), are not open to fully discussing failures as openly as successes (Dolowitz, 2015), or when the political climate on an issue is contentious (Dow et al., 2013). There may be significant gaps in policy that affect the drive for evaluation, innovation, and transfer of best practices for stormwater pond management at the local level. Funding and staffing can also be an issue (Law et al., 2008). Stormwater professional organizations, watershed associations, and other organized meetings can help facilitate exchange. Web-based resources are also important; in a survey of Atlantic coastal plain communities, websites were identified as the preferred method for learning new information (Law et al., 2008). Interestingly, in a policy scan conducted of coastal South Carolina, information available pertaining to stormwater on county websites was variable, and 6 of 8 counties did not appear to have stormwater incorporated into their comprehensive plans or zoning (Dickes et al., 2016). Equivalent county-level policy scans in the rest of the southeastern coastal plain region do not appear to be available. Some communities, however, are incorporating stormwater into local watershed plans, such as Bluffton, SC, Valousa County, FL, Washington, NC, and Fort Steward, GA (Law et al., 2008). While, as stated by Drescher et al. (2011), "[i]n the past, stormwater practices and their associated regulations and design standards used in the coastal plain were borrowed from the Piedmont physiographic region and were seldom adapted for the coastal plain conditions," that is changing and there are considerations to coastal conditions in some more recent design criteria and guidance (GA EPD, 2009; Perrin et al., 2009; Ellis et al., 2014; NC DEQ, 2017). Design manuals can be a critical link to the public sector (Harrington and Hsu, 2018). Still, decisions related to choosing a stormwater pond as the preferred BMP are often made "upstream" at the permitting agency and developer/homebuilder levels, and maintenance restrictions or requirements are often written into local codes and covenants (such as for a Home Owner's Association), so the "downstream" parties often have limited decision-making power over BMP selection, function, and maintenance plans.

While planning for the future is objectively important, flexibility in top-down policy implementation, such as is the case for stormwater in the U.S., may be beneficial for adaptive management of stormwater practices at the local level. Importantly, government and non-government actors tend to take on different roles for green infrastructure adoption and management; as reviewed by Harrington and Hsu (2018), government acts as "driver, coordinator and capacity-builder," while non-governmental actors often lead in information-sharing. *Ad-hoc* collaborative networks can be key to adaptive capacity in such systems (Dow et al., 2013). Where consumers and other stakeholders are knowledgeable and empowered, there are cases of market forces driving innovation and implementation, such as due to cost savings or home-owner preference for low-impact development (e.g., US EPA, 2013). Further study is needed for how policy and organizational structures may be optimized to integrate water resource management science and practice involving communities.

CRITICAL RESEARCH NEEDS

Increased Monitoring to Understand Pond Function

Data availability is a major limitation on developing an improved understanding of stormwater pond function and their impact on human and ecological health. Persaud et al. (2016), in their study of stormwater non-point source pollutant management, indicate that routine water quality measurements are rarely performed in stormwater ponds, but that this data is desired by community members. Even fewer studies of stormwater ponds collect long-term (DeLorenzo et al., 2012) or high frequency water quality data (Harper and Baker, 2007; AMEC, 2012), and reviews of the existing literature indicate that controlling factors such as bathymetry and hydraulic retention time are not always reported (Harper and Baker, 2007), nor are other pertinent environmental variables (Koch et al., 2014). There is very little data available pertaining to the seasonality of wet detention pond performance, and to the role they may play in either capturing or transferring emerging contaminants of concern (e.g., pharmaceuticals, hormones, microplastics, or antibiotic resistant bacteria).

Community-based or citizen science programs may help increase data availability, but time and resources will need to be made available for these efforts and achieving positive outcomes is not straight-forward—either in the view of quality control and assurance or demonstrating that engagement leads to improved water quality (Betts and Alsharif, 2014; Scott and Frost, 2017). There are several examples of programs within the region that engage citizens in water quality monitoring through collaboration with non-profit or university groups that mostly monitor stream or river waters, but a few programs from Florida have a focus on lakes or ponds (Canfield et al., 2002; Betts and Alsharif, 2014; Hoyer et al., 2014). Establishing a broad, longer-term record of water quality provides citizens, managers and other stakeholders with data that is needed to improve the decision-making process, including changing management practices (Serrano and DeLorenzo, 2008) and formulating state and local codes or ordinances. Surveying the number, location and dimensions of stormwater ponds will also be necessary for understanding their overall impact on hydrology and pollutant fate and transport in the coastal region.

Performance Evaluation and Criteria

Since the implementation of stormwater control regulations and guidelines, careful calculations of stormwater pond design have been enacted in the field, yet audits of design details to measured performance are lacking. Uncertainties in performance and cost of BMPs for different settings is a critical factor that impedes sustainable watershed-scale stormwater management (Roy et al., 2008). One needed area of continued investigation in the southeastern U.S. coastal region is in the design and "lifetime" of ponds with respect to water quantity and quality performance. Many states recommend maintenance activities to restore function that are benchmarked according to maintaining a certain water volume (e.g., SC DHEC, 2005; FDOT, 2015). But, are these recommendations optimal, i.e., suited for the coastal plain physical geography? To achieve a desired pollution removal, changing wet detention pond design criteria to be based on residence time rather than volume, such as recommended for policy updates in the State of Florida (Harper and Baker, 2007), may be more in line with the growing body of research on wet detention pond performance and allow for performance to be maintained under potential changes in environmental conditions. North Carolina recently updated design standards for sizing wet detention ponds to allow the use of hydraulic retention time (NC DEQ, 2017). Keeping ponds in compliance with these criteria is the next step. Looking into the future, analyses are also warranted of how ponds affect coastal community vulnerability during major storm events and how changing climate with alterations in precipitation patterns and tides may impact function under existing design. It is also important to ascertain how stormwater management policy specifically in relation to wet ponds may need to be updated to address undesirable down-stream effects that may occur even during storms that are less intense than "design" conditions (e.g., channel geomorphic change; Roesner et al., 2001; Bledsoe et al., 2012).

Correct placement of wet detention ponds but also evaluation of how they may work in combination with other stormwater management practices (both structural and non-structural) within a site and on a watershed-basis is needed. This is based on some observations that wet detention ponds with close connections to estuarine systems may pose unacceptable health risks to human and ecological receptors as presently designed and operated, such as by transmitting toxic pollutants, algae, and bacteria (Lewitus et al., 2008; Baalousha et al., 2018). Rather than single ponds, ponds of differing designs in series or a "treatment train" of several different BMP types may be required in places in order to achieve the various performance metrics expected for stormwater management. For instance, there are trade-offs in pond design (e.g., depth) that influence phosphorus and nitrogen removal differently (Koch et al., 2014; Gold et al., 2019). Given the complexity of environmental systems and the number of variables involved, site-specific models may help elucidate wet detention pond function. Knowledge of fate and transport mechanisms has been translated into models that aim to predict pollutant concentrations and loads through stormwater systems to inform engineering and management (Elliot and Trowsdale, 2007; Vezzaro et al., 2011, 2012; Fletcher et al., 2013; Bell et al., 2019). However, it has been reviewed that improvement of biophysical models will require more monitoring data for calibration and field testing, and improved understanding of fate processes and management outcomes for a wider selection of environmental contaminants (Bertrand-Krajewski, 2007; Elliot and Trowsdale, 2007; Gold et al., 2019). Convenient modeling tools are also being developed to enhance the ability of planners and construction engineers to determine the best site location for wet detention ponds in coastal regions (Johnson and Sample, 2017).

Yet, the question still remains whether some coastal plain areas may be better served by other stormwater management approaches. The approach to install wet detention basins throughout the coastal plain is a narrow technological solution to stormwater control and may be built on history of use and confidence in the absence of information in tandem with certain motivations, such as the benefit of using excavated soil for fill material elsewhere (Law et al., 2008) and the basin for sediment trapping during construction activities, the potential for stormwater ponds to be perceived as amenities by home-buyers, and the convenience and potentially lower cost relative to other approaches. One manner by which wet detention ponds may be failing on the landscape-level is in the way routing of stormwater directly to ponds via street drains and pipes results in limited soil infiltration and processing potential of nutrients and organic matter. Infiltration may remove pollutants found in urban stormwater by various mechanisms, including filtration, sorption, and biochemical transformation (Grebel et al., 2013). Lack of soil infiltration additionally may starve coastal waters of the dissolved minerals and organic matter profile that characterizes the pre-development blackwater streams of much of the southeastern U.S. coastal plain watersheds (Gold et al., 2017b). Cycles of vegetation blooms and control via herbicides represent a manmade ecological system severely out of equilibrium and can have down-stream effects through connections with groundwater and/or surface waters. One study which evaluated implementation of wet ponds in coastal North Carolina on a watershed scale found a failure to mitigate many negative water quality impacts of development (Gold et al., 2017b)—more such studies are needed. Among a sample of stormwater pond professionals in coastal SC there was mixed response as to whether stormwater ponds were the best tool for management (Dickes et al., 2016). Need for more research into alternative management methods, incentives for low impact development and improved design criteria were commonly cited among survey respondents (Dickes et al., 2016).

Arguably the largest opportunities for redesigning stormwater management systems lie in currently developing areas (e.g., National Research Council (NRC), 2008). Although infrastructure "lock-in" (Markolf et al., 2018) presents barriers to change, retrofits are also possible, especially considering that many older stormwater detention ponds may be approaching major maintenance milestones. Stormwater ponds and other green infrastructure designs may be adapted for coastal plain hydrogeologic conditions (e.g., Gregory et al., 2011). Non-structural controls, such as through upland management and community engagement around stormwater issues (e.g., pollution reduction, disconnecting downspouts, vegetative buffer management, etc.), are also important elements that could be advanced in many areas of the southeastern U.S. (DeLorenzo et al., 2012; Persaud et al., 2016). It is important for watershed management to be an inclusive process, and to not have "debates around [development] strategies… materially and discursively reinforce forms of inequality on the landscape" (Finewood, 2012). Evaluating practices and encouraging a multi-pathway approach to management is not a novel recommendation (e.g., Roy et al., 2008), but we emphasize that prioritization of resources and policy mechanisms are needed toward this goal.

Science and Practice: Multidisciplinary Frameworks

As researchers and stormwater professionals move from documenting water quality and quantity performance and engineering design and into the realm of scientific outreach, restoration, or advocating for structural and non-structural changes to urban development, success will depend on how well place-based social, political, and economic factors are interwoven (Thornton and Laurin, 2005; Barbosa et al., 2012; Betts and Alsharif, 2014; Young et al., 2014; Monaghan et al., 2016; Persaud et al., 2016; Dhakal and Chevalier, 2017; Markolf et al., 2018). Thornton and Laurin (2005) aptly refer to the prerequisite for social sciences and marketing in environmental sustainability as "soft sciences and the hard reality of lake management." Improving stormwater management in general, and wet pond implementation in particular, will undoubtedly require collaboration between a variety of professional fields. Venn diagrams have been used by other researchers to conceptualize the interdisciplinary nature of integrated stormwater management, for instance by illustrating overlapping economy/regulatory, ecology, and society/institutions (Thornton and Laurin, 2005), or with engineering/technological, environmental, and social components (Markolf et al., 2018; Prudencio and Null, 2018). Markolf et al. (2018) describe bidirectional interactions between these infrastructure system components. Going further, Flynn and Davidson (2016) describe urban stormwater social-ecological systems by defining key attributes in 9 tiered categories relating to: social, economic, and political settings, ecosystems, resources, governance systems, actors, interactions between components and outcomes. Examples of attributes modified specifically for green infrastructure in this framework (and category) include: stormwater ordinances, funding scheme and management plans (governance systems); local ecological knowledge, technical expertise, operation and maintenance, and perceptions/attitudes (actors); and soil characteristics, imperviousness and functionality (resource systems) (for expanded list and definitions, see Flynn and Davidson, 2016).

Given the multiple dimensions involved, social-ecological (e.g., Flynn and Davidson, 2016) or social-ecological-technological systems (e.g., Markolf et al., 2018) frameworks are the next step toward recognizing interactions between system components in order to realize pathways for communicating and attaining shared development goals in concert with environmental protection. These system frameworks may help identify system vulnerabilities and advance sound management by elucidating interconnections among stakeholders and influential factors in the decision-making process, since feedback mechanisms operate between technological, social, and ecological domains. Coupled socio-biophysical models are computationally and methodologically challenging but represent a critical opportunity for understanding vulnerability in stormwater management systems (Eakin et al., 2017). As a precautionary example, within current practices, stormwater ponds morphed in design to accommodate mostly economic goals of increasing lake-front property, in Florida for instance, have been termed "ticking time bombs" for coastal water quality (Thomas, 2014). Failure to thoroughly evaluate stormwater pond performance (technological and social) reflects the barriers to full green infrastructure implementation that have been outlined by others, including social acceptance, availability of expertise, and leadership (e.g., Dhakal and Chevalier, 2017), the inherent complexity of environmental systems (Drescher et al., 2011) and the growing complexity of infrastructure systems (Markolf et al., 2018), and the methodological challenges in interdisciplinary systems research (Eakin et al., 2017; Partelow, 2018). Avenues are needed for supporting this type of collaborative work around stormwater management, such as in the southeastern U.S.

CONCLUSIONS

In summary, the ability of wet detention ponds to attenuate peak flows and remove pollutants to protect downstream water bodies are affected by stormwater pond position in the landscape, how this impacts hydrological and biogeochemical processes, policies on design, and management practices. Where the existing knowledge base needs to be expanded to suit the needs in the southeastern U.S. coastal plain is to recognize how the unique hydrogeologic and climatic setting, in addition to socio-political factors, may differ regionally, and perhaps in contrast to other climatic and topographic zones where stormwater pond research and management case studies have been conducted.

A large number of ponds, and various engineered designs, uses, and management approaches, together make the overall impact of stormwater ponds on water flow and quality in the southeastern coastal plain difficult to ascertain. Due to practicality and scaling issues, and the need for even the most fundamental of performance data, studies have typically focused on individual or parcel-level pond observations. There is a need to integrate engineering, chemical and biological sciences with hydrology to better understand pollution removal capability and to forecast functionality, from the unit-scale to the watershed-scale, under changing hydrologic conditions. However, the socio-political aspects of stormwater pond design preference, use, maintenance and stewardship cannot be overlooked. In the dynamic and rapidly-developing coastal zone of the southeastern U.S., combining knowledge areas with a systems perspective is needed.

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Health Implications of Diverse Visions of Urban Spaces: Bridging the Formal-Informal Divide

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In the past 200 years, urban spaces have been imagined as neatly laid out, well-planned, sanitised and civilised places of dense human habitation with regulated economic activity, where political power, financial capital, the frontiers of knowledge and technology thrive. This has been the urban planners dream, even while it does not reflect the full reality, whether of cities in the LMICs or the HICs. In the face of such homogenising visions arising from Euro-American models, formal urban systems fail to provide adequately for residents' needs, who then carve out their own resources and processes for meeting them, largely within the domain of urban "informality." While large part of literature presents urban informality as reflected in the slum, others have shown how it is found in relation to all classes (1). The concept of informality has largely been applied to the core dimensions of economic life of the city. Applied to people's "ways of life," intermingling of the formal and informal becomes distinctly evident in everyday practices in locations such as the peri-urban, and in activities such as health care. This paper opens up the sphere of health care for urban planning that has, in recent decades, left it largely untouched. It uses data from a rapid assessment of health seeking behaviour of three socioeconomic groups—the middle class, slum-dwellers, and homeless— in Delhi, the capital city of India. The findings, relevant beyond the specific location, reveal that people of all sections resort to myriad informal arrangements for their health care, challenging the dominant connotation of the formal-informal denoting a legitimate-illegitimate dichotomy. This provides potential directions to bridge the formal-informal divide, to re-configure urban planning towards more sustainable futures with plural visions of land use and urban greening for healthier urban conditions and for health care provisioning. The analysis posits that, besides the economic and political relations shaping the formal and informal, the politics of knowledge must be factored in if the informal has to be adequately understood for building sustainable futures.

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FORMALITY, HOMOGENISATION AND CENTRALISATION VS. INFORMALITY, PLURALITY AND DECENTRALISATION IN URBAN PLANNING

While cities have been the locus of urbanisation, over the past century the urban mode of life has penetrated much deeper, changing everything in its wake. The benefits and opportunities have no doubt been astounding, reflected in the rising longevity of human life across the globe. But no less have been the challenges, including environmental degradation and loss of well-being. Having a higher density of population, higher level of consumption and higher number of industries, urban spaces usually exert a greater pressure on natural resources, frequently leading to greater environmental degradation. Cities account for 75% of energy consumption, more than 60% of greenhouse gas emissions, and 67% of the waste generated (2). South Asian countries present with even more complicated challenges, given their histories of colonisation, underdevelopment, and neglect of these issues in urban planning. Cities run chronically short of water, but their roads routinely get submerged in the rains. High levels of unemployment make people clamour for precarious jobs in industries that pollute air, water and soil, endangering life, and health. As they endanger the environs and economy of the rural areas, the cities also result in enhanced rural-urban migration and further increase in urban densities and needs. Inequalities and insecurities have come to define urban life. Though recognised as major urban problems that are often severer than in rural areas, inequalities in socioeconomic status and consumption, access to services, and in being recognised as legitimate members of the space, remain largely unaddressed or are typically dealt within silos in urban planning. Despite urban populations having better health status indicators on aggregate than the rural and higher density of doctors and medical institutions than in rural areas, health indicators of the urban poor are often not better than of the rural and access to affordable and quality healthcare continues to be severely restricted (3, 4).

A large part of the problem seems to lie in the tunnelled vision of urban planning by the state. Over the past century, with colonial hegemony affecting all spheres, the Euro-American model has provided the imagination of the urban landscape and its planned development world-wide. The local historical social and infrastructural specificities, of course, then bring diversity in its translation on the ground. This has been well-demonstrated in land use planning, housing, water and sanitation systems (5, 6). Planning for catering to urban populations has generally meant formal public services by municipal and other agencies even while land use is decided by technocratic Master Plans and builders' lobbies. In low-and-middle income country (LMIC) contexts, the capital intensive, centralised models of, e.g., water supply and waste disposal, always remained short of demand and resulted in a never-ending chase of targets and counting (and often under-counting) of under-served/un-served population segments. "Informal" mechanisms were adopted by both, the public agencies and the private builders and individuals to meet such basic needs.

Much literature has emerged in recent years on urban "informality," contrasted with the planners' dream of the manicured formal city. Some scholars view informality as the underbelly of an inequitous development path where large sections of people attempt to find informal means of meeting their basic needs (7, 8). Buoyed by scholarship and experiences from third world cities, urban informality has become an important lens to capture the nuances of urban life, from being a "driver of growth" in De Soto's neoliberal framework, to a liminal space between the structural and everyday practices (9–11). However, other scholars present informality as an integral part of the "planned city" in a grossly unequal social reality, as not restricted to the marginalised, but also part of the way of life of the better off and even evident in the developmental actions of the state, where it flouts it is own master plans, rules, and regulations (1).

In this paper we examine urban informality related to health through a brief discussion on the implications of peri-urban areas, and to health care service utilisation through empirical data from Delhi, the capital city of India. We hope to demonstrate how crucial recognising the informal is in attempting to build people-centred and sustainable futures through planned development.

URBAN INFORMALITY

Challenging the dominant Euro American perspectives on urbanism, such as the "modernist" perspective of the Chicago school or the post-modern urbanism of the Los Angeles school, urban informality has emerged as an exciting analytical framework from the experience of the third world cities (12). While beginnings of the informality discourse can be traced back to emergence of the economic concept of the "informal sector" in the 1970s, articulating the movement of labour to the cities in the preceding decades, informality, now as an analytical lens, has opened up newer ways of understanding the mode of the production of space in the urban context. Hart's definition (1973), "Formal incomes came from regulated economic activities and 'informal' incomes, both legal and illegal, lay beyond the scope of regulation" (13) reflects that "regulated" or "unregulated" is the demarcating line between the formal and informal. Therefore, Kanbur (7) submits that informality can be examined only in relation to particular legislation and regulations.

However, a large body of scholarship from the third world has contested this idea of the informal as unregulated sphere, outside the purview of the state and a refuge of only the poor and marginalised. Scholars like Alsayyad and Roy have shown how governments themselves actively produce informality, by facilitating practices and land use which are contrary to their own regulations and plans. Roy cites the process of rapid peri-urbanisation as an example of informalised process that despite transgressing official plans and norms, often receives tacit sanction from the state. She goes on to identify informality as an idiom of urbanisation in India, as in other countries (10). For example, formal land use planning and regulation in India regularly push the poor outside the formal system, but later accommodate them flouting the same regulations and policies. This gets more pronounced with the inclusion of service provisioning, such as water and waste management, within the domain of informality. Due to incomplete urban infrastructure development, informal networks have been observed to be operating in cities and peri-urban areas to ensure water supply. The formal waste disposal system is vastly supplemented by the informal system of rag pickers and other informal agents. Use of waste water for agriculture in peri-urban areas is well-documented in Indian and other Asian cities as an informal means of waste water disposal and irrigation (10, 14). Hence, informality, contrary to the idea of an unregulated domain, has been argued to represent constant negotiations between various forms of "extra-legal, social, and discursive regulation (10)."

Further, contending the idea that informal cities only represent domains of survival for the urban poor, scholars have highlighted the ingenuous ways in which informality stretches formal limits, opening up newer possibilities for sustainable urban planning. The fluid informal city foregrounds local wisdom in the modern world in opposition to the attempts of its erasure (15). Informality makes visible the ways in which the urban "informals" shape the city fundamentally through their everyday acts of resistance and the processes that negotiate the formal and the informal. Thus, questioning the state centred definition of formality and informality as well as the strict dichotomy in urban configurations, as in the case of land use, water systems, transport systems and so on, they require us to rethink the neat sanitised image of the planned urban space and its urbane civility (9–11).

Informality as "the Other" Way of Life

Regulatory frameworks related to collective resources such as land and employment play a pre-eminent role in designating entitlements and property relations in urban areas. Healthcare lying in the sphere of "the personal that is political" is somewhat different. The health care industry is part of the formal regulated sector, as represented in modern hospitals and health centres, modern health care professionals, pharmaceuticals, and insurance agencies in the public and private sectors (even if the regulation is often merely notional in third world settings, and often leads to increasing costs and exclusions). However, a large segment of health care that is undertaken in homes and communities, with traditional and new evolving knowledge in addition to the modern conventional providing the basis, lies outside this formal sector and forms the informal healthcare. Since health care includes "ways of life" and application of specialised knowledge, state support and regulation of only a segment of both these makes what is left out, the "unregulated," seem "illegitimate." The plurality of knowledge traditions in health care, included in both the formal and informal segments in countries such as India and China, suffers as the traditions with ontology and epistemology differing from that of modern bio-medicine, get delegitimised over the years. While the codified traditions that have adapted to modern institutional forms, are officially recognised and regulated, the officially unrecognised traditional folk practices and practitioners undergo processes of decline. Yet their use, renewal, and innovation continues in efforts to adapt to the challenges of changing conditions (16). While their practice continues, they are pushed to the background in public discourse, propagating perceptions that link them to cultures of ignorance of the uneducated poor and rural.

In the context where urban spaces include a large component of the rural-urban interface (whether as tracts of agriculture that is conventionally viewed as rural activity or by the immigration of rural populations into urban areas), other seemingly rural elements also acquire such an illegitimate characteristic. Studies across third world cities show that peri-urban areas host large concentrations of the rural immigrants in search of livelihoods. In such areas agricultural activity and animal husbandry attracts the poorest and the women, allowing them to find their feet in the urban context with more familiar economic activities and lifestyle. They also provide several other innovative possibilities for urban resilience and sustainability. For instance, peri-urban agriculture has been documented across Asian cities as an informal mechanism devised by local communities to deal with problems generated by an incomplete shift from rural to urban: of mixed land use, unsatisfactory occupational mobility of the local population, domestic waste water disposal, and an influx of rural migrants. Studies show how it allows for retention of green spaces and ecosystem services that provide for increased incomes of the most vulnerable social segments (the poor, women and migrants), food security and waste management (17). However, this urban/peri-urban agriculture tends to be obliterated from public view and not factored into urban plans as a provision for urban green spaces as well as livelihoods, poverty alleviation, food security and the like. In fact, as documented, urban agriculture is completely outside the ambit of the suburban aspirational middle class's vision of an urban area (18).

Simultaneously, the peri-urban space acquires an ambiguous administrative identity, and tends to be left out of public services and amenities. The rural agencies withdraw as the area gets declared to be within the urban boundary, and the urban municipalities take time to reach it since it is peripheral and last priority for distribution of scarce resources. However, since it contains a continuity with traditional ways of life and at least some elements of the eco-system, the possibility of practices such as of food production and herbal medicine are preserved more than in the urban core. Thus, "informality" in itself can be a reflection of deprivation and exploitative relations, or an opportunity for assertion of agency and innovation.

Perceived as spaces with no legitimate identity, peri-urban areas have been conventionally used for dumping the city's waste or its polluting industries for planned sanitisation of the formal city-space. An alternative view is emerging that considers peri-urban spaces as constituting the diversity of urbanisation and providing possible solutions for urban resilience (17, 19, 20). The "urban sprawl" vs. intensive vertical urban infrastructure is central to the debate about urban and regional development models, reflecting the formal architectural urban planning vs. informal land use patterns (21). All these need to be viewed as plural options to be used appropriately as suited to the multiple objectives, needs and contexts even within one city/town/urban agglomeration. Studies on people's innovations that link peri-urban agriculture, waste water disposal, and food security indicate how changing social composition with rural-urban migrants constituting a large part of the residents, livelihood patterns that still depend on eco-system services, and traditional folk practices co-exist. They also demonstrate how the governance structures are completely out of sync with such realities and the many challenges they pose that the formal systems must engage with (14, 17, 20). A holistic view of urban health would do well to examine such systemic issues as central to health systems thinking for improving the health of urban populations.

CHALLENGES IN URBAN HEALTH

Public health has been central to urban planning historically and continues to remain a need just as important in the present day urban scenario. Tracing global epidemiological trends of urban health and disease reveals the seriousness of ill-health generation in these most economically endowed areas. Thereby, focusing on urban health behoves us to examine the pathways through which inequality and ecological unsustainability manifest in urban life and shape health and disease. While inequalities permeate every society, the severe lack of resources make matters far more complicated in the LMICs, and attempting to mimic the development models of the high income countries (HICs) has compounded the problem. Nearly a billion people live in slum conditions, with 90% of the urban slums located in the LMICs (22).

The urban space, layered across different socio-political-cultural-economic axes, is mediated differently by different sections of the population, which in turn also shapes their health differently. For instance, Urban Health Resource Centre in New Delhi, India, drawing on data from National Family Health Survey 2005-06, classified urban populations according to their wealth and observed that for almost all indicators on health, healthcare or key social or housing related determinants of health, the poorest quartile fared far worse than the rest of the urban population. Under-five mortality for the poorest quartile was 73 per thousand live births, significantly higher than 42 per thousand live births in the rest of the urban population. In nutrition too the poorest quartile cut a sorry figure with 54% of children being stunted and 47% underweight, whereas the figures were 33% and 26%, respectively for the rest of the urban population. Women receiving at least three antenatal check-ups among the poorest quartile was only 54% compared to 83% for the rest of the population. In terms of living conditions, 81.5% among the poorest quartile lacked access to piped water supply at home and 52.8% did not use a sanitary flush or pit toilet. By contrast, 62% had access to piped water at home and 96% used sanitary toilets among the rest of the urban population (4). Clearly, the inequality is stark, but equally important is the fact that even the non-poor have not achieved health conditions that can be called acceptable in the twenty-first century.

While the urban environment, especially in the slums, offer ground for infectious diseases to flourish, non-communicable diseases (NCDs) are also increasingly laying claim to morbidity and mortality among the urban poor. Precarious employments and exploitative employment relations, poor housing conditions, overcrowding, lack of basic amenities, growing inequalities of consumption lead to deteriorating well-being and rising social strife and violence. Fast-paced life, sedentary work, stressful conditions, unhealthy food habits predispose urban inhabitants of all sections to NCDs like obesity, diabetes, and hypertension. Road traffic accidents, diseases due to environmental pollution are also on the rise. LMIC countries such as India are still in the phase of epidemiological transition where the urban better-off are more affected by the NCDs, but the poorer sections are bearing a disproportionate triple burden—communicable diseases continuing, NCDs emerging and injuries rising rapidly. While socioeconomic vulnerabilities expose them to unhealthy conditions, inadequate, fragmented and expensive health systems rob them of the chance of receiving good quality services. The lack of community outreach of health services in urban areas and poor referral services have only compounded the problem.

The above description of inadequacy of the formal systems to provide for the urban poor, creating conditions of health inequalities is well-documented across the world. Yet, what is often overlooked in discussions of urban health is the fact of the formal systems being limited by their very centralised, mono-solution based, homogenised, bio-medical imagination in catering to human needs. The ignored plural solutions are then resorted to through informal pathways, supporting the existence of a majority of the urban residents. Underlying this problem is international and local political economies, with industries pushing their technological ware (including now the medical and infrastructural "green technologies") and real estate making its fast buck. But what is less recognised is an epistemological divide that underlies the modern tools of planning— for assessment, validation and regulation of technologies, models, and systems.

India, despite its own experiences in urban planning— for example the city of Shahjahanabad in what is now "Old Delhi"— chose to borrow from western models. Lutyens Delhi in the colonial period or the planned city of Chandigarh post-independence stand testament to that fact. The theoretical assumptions underlying the dominant policy-making knowledge frame, e.g. the Garden Cities of Europe based at least in part on notions of environmental health, led to parks and wide roads at the cost of housing for the poor. Public health needs of the different sections of the population got side lined in the quest for real estate management, often for the benefit of the affluent class. Thus, it has been shown that the inadequacy of urban infrastructure in Independent India, especially for the underprivileged, primarily resulted from the elitist class bias and decontextualised planning of the public administration. Resettling the city's poor from more central locations to the peripheral areas (that had been declared "inhabitable" in the Delhi Master Plan 1962) so as to decongest and beautify the city required official flouting of the masterplan. This led to dismal environmental conditions in these planned colonies of the poor that resulted in endemic water borne diseases and a full blown cholera epidemic in 1988 (23). Adopting decontextualised models from the developed countries meant affording low priority to the common citizens and their specific needs as well as their appropriateness to local contexts. These fail not only the poor but also other residents and frustrate the efforts of sincere administrator-implementors. All of them then flout the rules laid down by the technocratic planning machinery with its globalised elite visions. Given the complex interplay of all these factors, unless the political economy and politics of knowledge is simultaneously acknowledged and issues addressed in a holistic manner, sustainable solutions are unlikely. Whether urban planning, in its theory and in practice, incorporates or can incorporate such an approach is the moot question.

The displacement of polluting industries from Delhi to its peri-urban areas in the 1990s has increased pollution of water, soil, and air that is returning to the city through the food produced in the peri-urban area (14, 18). Now, as the urban dwellers face the consequences of such planning in escalating pollution and public health hazards, *ad hoc* regulations, and drawing natural resources such as water from further afield are implemented as solutions. Given that these do not adequately address the problems generated by the decontextualised vision for urban spaces and their inhabitants, their effects also remain limited and temporary at best.

Similarly, despite a rich heritage of pluralistic health culture, a monolithic health system was imposed upon the Indian people, centred around conventional biomedicine and its doctor and hospital centred institutional model. The system has resulted in a never-ending chase of targets and counting of under-served/un-served population segments. While it responded to the unmet need for services by incorporating para-medical based health centres in rural areas, for urban areas, the imagination remained fixed on hospital and dispensary based medical services until the 1980s. It was in 1983 that a committee recommended urban primary level services with outreach in the community, and even this has been only partially implemented to date (3).

Implementation of the medical institutional model formally adopted suffered from the imperatives of the choices made, with an increasing delegitimisation of the informal. Besides its being too resource intensive, the lack of adequate priority and funding compounded the resource constraints that did not allow the formal plans to be implemented in full (23). Given that the middle class could afford private healthcare and the poor had little bargaining power, there was little public pressure for a strong public service system. As a result, the public system remained anaemic while private healthcare flourished, hurting the vulnerable the most. While strengthening rural health services received some attention through the National Rural Health Mission (NRHM) in 2005, it's counterpart, the National Urban Health Mission (NUHM) is yet to take off in any substantial manner (24). That people still found ways to survive even in these adverse conditions, albeit not in what are considered the best of ways by the formal system, bears witness to their way of life and support structures that existed before state-planned health care, as well as their sheer determination and ingenuity to adapt to changing times. What often came to their rescue in these difficult situations are the informal arrangements that exist and are constantly evolving.

THE FORMAL AND INFORMAL IN URBAN HEALTH CARE

Literature abounds on plural forms of health care in the rural context in India, with almost an implicit assumption that the informal practitioners and practices are located there because of the gross lack of institutional medical services. At present, with 32% of the Indian population in urban areas, about 80% of registered doctors and 80% hospitals are located here, of both the modern conventional and other formal systems. The registered, 5-year degree holding doctors represent the formal health care practice in public and private hospitals, dispensaries, and clinics.

Formal healthcare in India includes eight knowledge traditions recognised by the state— modern medicine and seven other codified health knowledge systems now officially brought under one acronym—AYUSH (Ayurveda, Yoga and Naturopathy, Unani, Siddha, Sowa-Rigpa and Homoeopathy). Each has its texts, colleges for professional education, research councils, hospitals, and dispensaries. However, this has been an "undemocratic pluralism," with dominance of conventional biomedicine such that it gets over 90% of the government allocation for health while the other seven get 3% (25).

At the other end of the health care spectrum is the practice of home remedies and promotive practices, folk healers and faith healers in the community, as well as family lineages of practitioners of the recognised systems who have been trained inter-generationally without going to college or obtaining degrees. These constitute the "informal traditional" forms of health care, using "free gifts of nature" or easily accessible materials. Folk and faith healers generally provide care as a form of non-commercial community service.

Between these two ends of the informal to formal spectrum newer forms of informal health care have evolved, such as the practitioners of conventional modern medicine who have not been formally educated or are at best trained as paramedics and AYUSH doctors, called Rural Medical Practitioners (RMPs) by some scholars, colloquially called *jhola chaap daktar*[1]. Chemist shop keepers have also become prescribers, thereby becoming another category of informal modern medicine providers. In addition, people have evolved an informal mechanism of preserving the prescriptions of a formal medical professional to use repeatedly in other episodes of the same or other illnesses, by just using it to buy from the chemist. Some modern medicines have also become part of common knowledge and self-care, bought off the counter, such as paracetamol as an anti-fever medicine. This "folkisation" of conventional medicine can be viewed as a market response generating informal providers to fill the gap created by state generated demand which public services could not adequately fulfil, and/or the adoption of industrial products available in the market into self-care practices. "Folkisation" is the term being coined for diffusion of elements of conventional modern biomedicine into everyday

[1]"*jhola chaap daktar*" refers to the non-MBBS practitioner of conventional medicine who often travel to settlements of the poor and rural, carrying medicines and basic equipment with them, but also includes those who set up clinics in the areas of the poor.

popular practice and varies in form and extent across socio-economic sections and regions. Much literature demonstrates the generalisability of this phenomenon across continents (26). Thus, we use folk medicine for whatever people practice at individual, family, and community level without any form of state legitimisation, with "informal traditional" and "informal conventional modern" indicating the knowledge traditions they draw from. While this seems to collapse the folk and the "informal," there is another form of informal that is not "folk" but embedded in the formal.

Forms of informality are evident within the formal medical institutions, for instance the widespread use of lesser trained nurses and paramedics in private clinical settings with "training on the job" instead of hiring trained professionals who may be in short supply and have to be paid more. Cutting corners or over-prescribing in patient care by private hospitals for enhancing profits often flout professional clinical guidelines. In the over-crowded public sector institutions, scarce resources or time lead to rule-of-thumb practices that do the same (27). Outreach services are often designed to be conducted by paramedics when they ideally require medical supervision. Thus, the formal private and public services too are composed of a spectrum from the formal to the informal providers and practices.

It is generally assumed that the urban areas are devoid of informal health care or that it exists only in slum areas. However, studies in different cities find that all forms of informality among health care providers exist and thrive in urban areas, as does the utilisation of herbal medicine. We would argue that this spectrum of informality in health care and the overlaps between the formal and informal processes reflects what recent scholarship on urban systems has started theorising in other spheres. Also that they are not restricted to India, but are ubiquitous in their presence in all continents and countries, to varying extent and in varying forms.

Studies conducted in Ahmedabad and Cuttack from India found that in urban areas many people still perceive faith healing as an alternative treatment for psychiatric disorders. Faith healing was available easily and locally, in contrast to psychiatric treatment for which most patients and families had to travel a considerable distance (28, 29). Studies from urban areas in Western Nepal, Riyadh, Brazil had observed that in conditions ranging from childhood illness to asthma to respiratory infections, people used home remedies and folk medicine. Knowledge on home remedies was found to be usually inherited from mothers, grandparents, relatives and neighbours (30–32). González-Stuart's (33) study in Mexico's third largest city Monterrey, and Ranjikar and Rajbhandary's in urban areas of Kathmandu valley in Nepal found that despite the widespread use of modern pharmaceuticals and the availability of mainstream medicine in the city, many people still rely on traditional healers and also use medicinal plants to treat diverse variety of ailments (33, 34).

Thus, health care planning for the urban setup, just as urban planning itself, needs to account for the wide spectrum of needs and diverse activities that can cater to them. Mere service provisioning of the conventional type or administrative enhancement of the dominant model of services, out of touch with people's contexts, is unlikely to meet the healthcare needs of the population and for all its segments. People's health seeking and health creating practices are shaped by the myriad of identities they embody. Instead of ironing out such plurality the state needs to address the varied needs and practices of populations.

In India, as in most parts of the world, this, unfortunately, has not been the case. The state's planning for healthcare has completely ignored the traditional community, family and individual based health care. The codified systems that have been officially recognised have a large network of educational, service delivery and production institutions in both the public and private sectors, including a separate Ministry of AYUSH. Folk health knowledge and practices, however, still remain largely bereft of state support. Devoid of the state's patronage, these non-state, non-modern knowledges, and practices have only been able to sustain because of their continuing utilisation, the experience of benefit., and continuing trust that people have placed in them.

Health Seeking Behaviour Across Three Different Population Groups in Delhi

If urban healthcare planning wants to be truly informed by people's practices, the health seeking behaviour of people relating to both the formal and informal health services need to be examined, keeping in mind its dynamicity and evolving nature. While there have been several studies exploring urban health seeking in the formal health system and fewer in the informal segment, the continuum of care seeking for different sections of population has rarely been explored in the urban context of India. National household level data gathering on health and health care is conducted by several agencies in multiple forms, such as decadal surveys by the National Sample Survey Organisation (35) and the National Family Health Survey (36). While the former categorises treatment sought by any source other than formally trained professionals as "untreated," the latter documents traditional medicine use only for a few selected conditions as part of a larger survey for health related indicators. Thereby, with extremely limited health seeking behaviour being captured, there has been an invisibilisation of the informal sources of health care by official and public health macro data sets. However, evidence of informal healthcare is widely available from anthropological research and some health systems research studies that demonstrate their pervasive presence across the country, as in a large number of other countries as well (37, 38). In order to begin filling these gaps in information from urban areas, a rapid assessment of health seeking behaviour of different socioeconomic groups was undertaken in 2013-14 in the metropolis of Delhi, the capital city of India.

The methodology adopted for the study was of a rapid survey across three socio-economic classes, the middle-class, the poor, and the homeless. Residential areas of these socio-economic groups were purposively selected, which included a middle-class colony, a slum area and an area with large number of homeless persons. Systematic random sampling was adopted for sampling at the household level in the purposively selected middle class and slum colonies. For the homeless, convenience and snow ball sampling had to be used as they didn't live regularly in any specific location. In total 125 respondents were interviewed (Middle Class—40, Poor Slum Residents—40, and Homeless—45). Majority of the respondents were middle aged women, with diversity in the sampled middle class respondents' educational qualifications while the majority of sampled poor slum residents and homeless were illiterate. A semi-structured interview schedule was used as tool of data collection which was designed to elicit knowledge of all forms of health practices in daily living, including the modern, and traditional modes of care. Previous experience of research among rural and urban communities had shown the importance of the investigator communicating a non-judgemental position on "informal knowledge," and creating a conversation that encourages respondents to speak about it. Open-ended questions were asked in such a sequence that they allowed the "delegitimised" traditional practice and knowledge to be acknowledged and reported as health seeking actions. The first questions were about what plants and food items the respondent knew had medicinal value and for what health conditions. No checklists were provided from the researcher's side. The information generated reflects the respondent's knowledge of medicinal value of food items in 46 health conditions and plants in 51 health conditions that they themselves cited. One hundred two of the respondents reported any knowledge of food items in health conditions while 113 reported knowledge of medicinal properties of plants. The next set of questions were about their healthcare seeking practice in specific illness events in the past 15 days and over the past 1 year. Given multiple responses from each respondent, the total number of illness episodes for which the respondents sought various modes of healthcare, from home to the outer world, came to 1,114 (Middle class: 327, Poor slum residents: 411, Homeless: 376). Finally, a question was asked about their history of ever visitation to the range of health care providers.

The health care activities reported exhibited a wide range of informal arrangements. Starting with self-care at home (consuming healthy and balanced diets, to using diet change and home remedies or self-medication in minor departures from health), it extended to involve folk healers (herbalists, bone setters, dais, vaids etc.) and faith healers as informal practitioners of traditional systems of medicine available at the level of the community. The chemists and "*jhola chaap*" practitioners constituted the informal providers of conventional medical care. Resort to the formal health system constituted of public or private services of conventional medicine and in small measure to the recognised traditional knowledge systems. For a majority of health issues, home remedies were observed to be the first resort.

Despite the expected erosion of such knowledge within households over the years in the rural and urban populations, the survey found that the general breadth of knowledge on the medicinal properties of food items and medicinal plants was commendably rich. The survey documented that the sampled population is well aware of medicinal properties of food items, 115 of them being reported by respondents to address 46 different health conditions. The survey also listed a total of 91 medicinal plants and their medicinal properties that were known to address 51 different health conditions. Of these food items and medicinal plants, the greatest number was reported by the middle class, then the slum residents and least by the homeless (**Figure 1**).

When the home remedies or diet change alone did not prove sufficient, people usually resorted to other modes of care in different combinations. The survey traced illness in the last 1 month for this movement of healthcare seeking from home to the outer sources. It was observed that across the three different study groups, while about 15% of illness episodes were dealt with by home remedies and diet change alone, a larger section of care seeking involved home remedies and/or diet change in combination with care from outside home (36.44%). This means altogether home remedies and diet change, alone or in combination with other modes of care, constituted the largest proportion of care seeking behaviour (51.16%). This was 60% for the middle class and poor, while only about 33% for the homeless (whose homelessness actually makes 'home remedies' a misnomer).

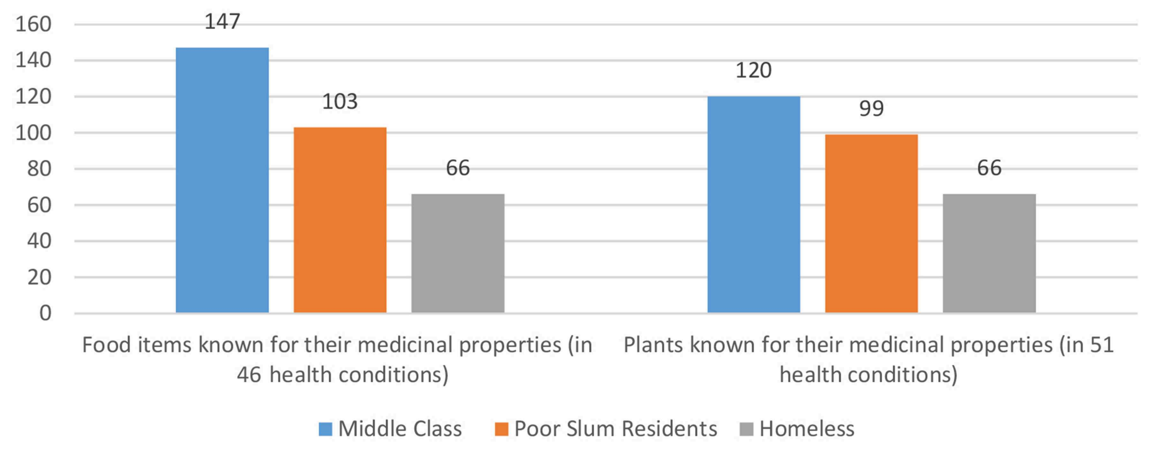

FIGURE 1 | Number of food items and plants used in different health conditions in different socio-economic classes (multiple responses).

The specifics of treatment sought outside the home showed a multiplicity of patterns of resort, depending on the problem and their collective experience of various forms of treatment for it. For a case of diarrhoea in a child, the treatment would begin with dietary restrictions and home-made oral fluids, quickly move to accessing informal modern treatment, and upon that failing, go to a formal medical provider/institution. In case of arthritis, however, the sequence may lead from home remedies to traditional folk healers and much later to the formal, traditional, or modern.

The three socio-economic groups taken together reveal that, informal health care was resorted to in 67% of illness episodes. This included home remedies and diet change (14.72%), traditional informal (14.18%), and modern informal (38.24%). Disaggregating the data further shows that the modern formal system (public and private) was used most by the middle class (in 72.78% of their illness episodes), followed by much lesser utilisation by the poor households (14.84% of episodes) and the homeless (14.10% of episodes) (**Figure 3**).

The data, although from a small sample, underscores that common people are rational enough to seek out different modes of care when home-based care is insufficient. It is also possible that there is more resort beyond the home than necessary due to the delegitimisation of the folk practices and the over-medicalisation of health, but that is only hypothetical and remains for another study to examine. Clearly, they see care seeking as a continuum between the informal and the formal, not in binaries as the state system makes it (**Figures 2**, **3**).

A telling vignette from the field work during the survey illustrates an important dimension of how the informal reflects the possibility of people's control and sense of ownership of the city as against a sense of passive acceptance and falling in line that is expected from the citizens by the dominant top down planning processes.

> While conducting the survey among the homeless, one elderly beggar woman who had lost one arm in an accident was a respondent. She was the strong head of a family of three daughters who were all married with children of their own, but back with her due to widowhood of one, battering and desertion by husbands of the other two. She had come to Delhi almost 25 years ago, searching for a livelihood to feed herself and her daughters after her widowhood. For healthcare she had relied almost exclusively on her knowledge of medicinal plants and other natural home remedies. She gesticulated to where she could find the plants in her surroundings even here in the city, what was available behind the bus-stop and for which plant she had to travel a few kilometres to a greener patch, and so on. She narrated how now, they most often take treatment from the local "jhola chhaap daktar." Upon asking why this shift, she sadly pronounced, "Now we have lost confidence in ourselves." In her narrative she had acknowledged the value of the daktar's treatment but also indicated that she thought there was unnecessary resort to the doctor as well.

This is the psycho-social value of the informal, that it allows a critical and problem-solving approach with questioning of the dominant formal, even among the most vulnerable segments of society. Rather than encouraging such bottom up reflection and action, and examining the worth of its solutions, "community participation" is sought ritualistically to ease the implementation of plans made by technocrats based on the dominant knowledge of the times.

The data on "ever visiting health service providers" found that of the myriad providers in the study areas, the middle class, expectedly, visited the allopathic doctor/nurse at the private sector the most (65%), followed by the chemist/pharmacy (50%). Almost half of them had also visited Homeopaths (47.5%), and the Ayurveda practitioners/Vaids (37.5%). Most revealing was

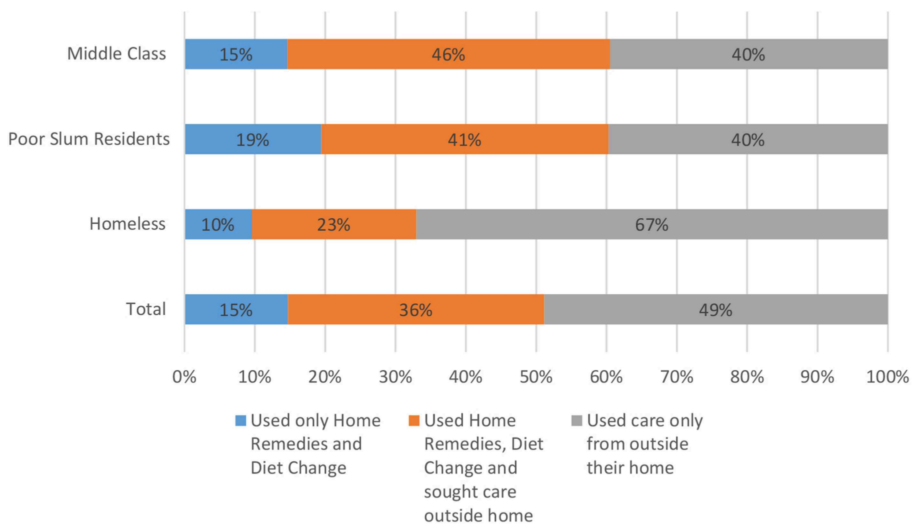

FIGURE 2 | Health care seeking from home to outer world.

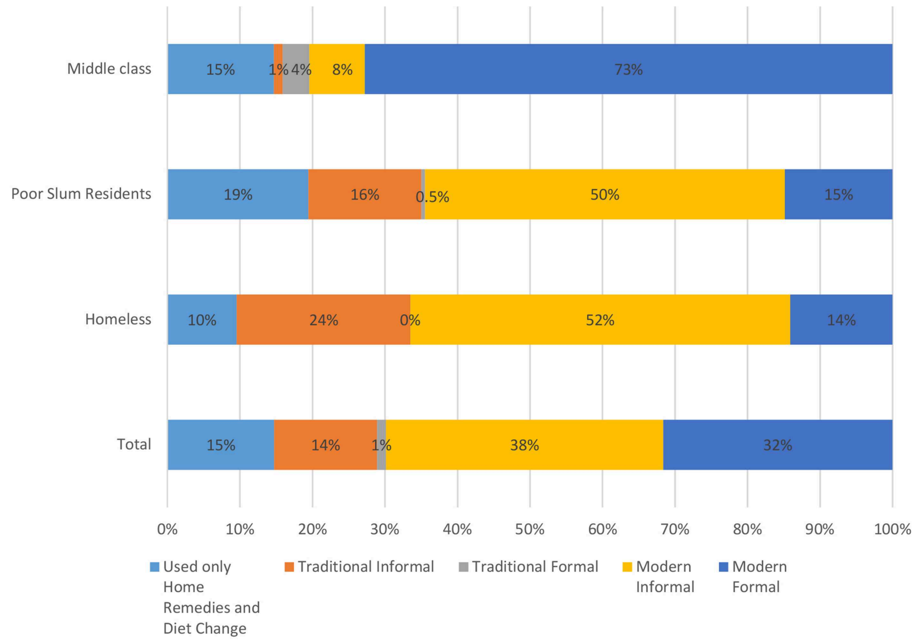

FIGURE 3 | Utilisation of different forms of health care in and outside home. Traditional Informal include, folk healer, faith healer and vaid; Traditional Formal include, AYUSH clinics and dispensaries; Modern Informal include, *Jhola chhaap daktar* and chemist; Modern Formal include, MBBS Doctor/Nurse clinics and nursing homes, allopathic dispensaries, health centres, and hospitals.

TABLE 1 | Ever visited health service providers.

Facility/Health service provider	Middle class (*N* = 40)	Poor slum residents (*N* = 40)	Homeless (*N* = 45)	Total (*N* = 125)
Folk healers	9 (22.5%)	7 (17.5%)	9 (20%)	25 (20.0%)
Faith healers	9 (22.5%)	36 (90%)	17 (37.7%)	62 (49.6%)
Ayurveda/Vadis	15 (37.5%)	9 (22.5)	13 (28.8%)	37 (29.6%)
Homeopaths	19 (47.5%)	8 (20%)	–	27 (21.6%)
Siddha practitioners/Tibetan medicine	3 (7.5%)	–	–	3 (2.4%)
Unani practitioners/Hakeem	–	4 (10%)	1 (2.2%)	5 (4%)
Government dispensary	11 (27.5%)	31 (77.5%)	18 (40%)	60 (48%)
Government MCH centre	2 (5.0%)	4 (10%)	2 (4.4%)	8 (6.4%)
Government hospital	4 (10.0%)	20 (50%)	17 (37.7%)	41 (32.8%)
RMP/Jhola-chaap/Non MBSS practitioner	7 (17.5%)	17 (42.5%)	13 (28.8%)	37 (29.6%)
Nursing home (private)	9 (22.5%)	4 (10%)	–	13 (10.4%)
Allopathic doctor/nurse (private)	26 (65.0%)	21 (52.5%)	10 (22.2%)	57 (45.6%)
Chemist/pharmacy	20 (50.0%)	16 (40%)	32 (71.1%)	68 (54.4%)
NGO/charitable allopathic dispensary/hospital/mobile clinic	9 (22.5%)	1 (2.5%)	2 (4.4%)	12 (9.6%)

the finding that 67.5% of the middle class had also resorted to modern informal providers and 45% had sought treatment from informal traditional providers (**Table 1**).

Of the poor slum resident households 77.5% had ever visited the government dispensary and 50% a government hospital, while 52.5% had gone to the formal private care providers. A much larger proportion (82.5%, 42.5% from Jhola-chaap + 40% chemist) had accessed the informal modern services. It was also observed that reliance on faith healing was the most among the poor (90%) due to the proximity of the slum to a place of worship known for its curative powers. The data also indicates that slum dwellers exercised the greatest "choice" in resort to the range of providers, their number of responses being higher than either the middle class or the homeless, the homeless exercised least choice.

Almost all (99.9%) of the homeless group had sought care from the modern informal providers, and 57.7% from informal traditional care. Care sought from the formal private was the least among the homeless (22%).

While lack of access and affordability would certainly explain in part the limited use of the sources of formal healthcare by the poorer sections, the not insignificant use of informal health care by the middle class testifies to its inherent value as perceived by all classes. Strengthening the formal public services would, of course, be of benefit to the urban residents especially the poor. However, recent fledgling initiatives at health systems strengthening are unlikely to have impacted treatment seeking behaviours in our study population since 2013-14 when our study was conducted. Delhi government's recent initiative of setting up "Mohalla Clinics" (Colony clinics) for providing free diagnostics and drugs has a very restricted population coverage and the Ayushman Bharat initiative of the national government providing social insurance to the poorest 40% of population is restricted to covering hospital care, with both still facing problems of implementation and fragmented design (39–41).

It is apparent from the data above that a majority of illness episodes are taken care of by informal mechanisms, while the state plans only for the formal health care. Pluralism allows the urban residents to exercise their agency to choose between use of the home remedies they know and the informal and formal sources of healthcare outside the home, in various combinations as they are able to access or think appropriate. The implications of this for urban health care and planning need to be understood.

DISCUSSION

Cities encompass multiplicities within themselves, where various concepts of urbanism coalesce and fragment simultaneously to create ever shifting kaleidoscopic arrangements. In the cities of Latin America, Asia and Africa, the situation gets additionally complicated with their histories of colonisation, underdevelopment and the attempts to develop by adopting the expensive and high consumption models of the first world, as well as the presence of a market dominated economy. An exploitative economic system in conjunction with deeply entrenched social hierarchies have created a landscape of precarious employment and perilous living conditions for the urban underclass, all marking the pervasive poverty by the notion of informality. Rapid globalisation, aggressive marketisation and a receding state have further attributed the cities of the third world with the defining characteristics of increasing inequality, rising violence and an unruly politics. While the "informal" urban processes are a response to such inequality in access to basic resources and services, they are also the means of fulfilling human needs of all sections that the formal system is failing to do., What this paper argues is that it is not only an economic inequality, but also the power equations in the politics of knowledge that denies the more local and rural popular epistemologies and ways of life due consideration in the visions for planning urban spaces, "the urban way of life" and urban health care. Informality reflects not only the solutions of low resource settings in urban areas, but also the marginalised epistemologies that resurface even in better resourced settings, and in people's attempts to conserve or continue to practice what they value in their way of life, and in the cultural-moral underpinnings that accompany them. The wide-spread and increasing informal resort to traditional-complementary-and-alternative medicine (TCAM) in HICs is beginning to be formally factored into their health service systems, for instance by medical insurance paying for TCAM services, the teaching about TCAM in medical schools to sensitise under-graduate medical students as well as in specialisations for post-graduate studies. But the prevailing informal traditional knowledge and practices of the urban poor are likely to be lost to them in the prevailing environment in most LMICs. Traditional folk practices continue to be delegitimised, and with increasing "folkisation" of conventional bio-medicine, forms of self-care and informal providers based on use of modern conventional industrially produced medicine replace the more ecologically sensitive understandings of health as a product of the ecosystem and way of life and health care based on natural materials and processes. Implications of these trends need to be examined.

The concept of urban informality that has largely been applied to urban land use as well as to economic activities and livelihoods related to them, has been extended in this paper to the pluralism of health care in people's lives as against the official planning of health care that has ignored such possibilities. The study showed a spectrum of informal and formal-informal sources of health care forming the urban health care system on the ground, even in a metropolis such as Delhi, the capital of an emerging economy. All the sources of formal and informal health care were resorted to by all sections of urban residents, the poor and middle class, in a plural combination of health seeking behaviour varying by socio-economic status. On an aggregate, only 33% of illness episodes led to resort to the formal services (often combined with informal measures) while 67% were dealt with through informal sources of health care. Care seeking for promotion or preservation of health begins from the informal setup of the home across all socio-economic groups. These practices of self or family care, although constituting the largest proportion of healthcare, receive very little attention from the state which arranges all its planning and activities around formal sources of healthcare even when its use is much limited in comparison. Outside care for the poor and the homeless comes mainly from informal health service providers, but they are sought out even by the middle class. Clearly people make choices across the wide spectrum of informal to formal depending on the nature of their ailment and experience with different systems, influenced by their location and belief systems. The exclusivity of what is legitimised as valid knowledge and its practitioners by the state's vision of health care (through official recognition and regulatory mechanisms that mark out the formal in health care with ignoring of all that is outside it), is rarely observed in real life practice.

The way formal urban health care is planned in India carries common attributes with urban planning in general, The models tend to get adopted uncritically from international contexts. While there is a diverse set of health services and practices available in the urban culture of Delhi, the state reserves its support for only institutionalised biomedicine, which has become the standard the world over, or that part of traditional medicine that has moulded itself into the dominant model of doctor-and-institution centred health care. Solely a disease centred approach limits the biomedical system to primarily curative services and that gets reflected in the state supported health services as well. A more democratic and comprehensive approach to health planning in the urban setup would make use of not only the plurality of knowledge and practices available, but also link health with its various other determinants, such as employment conditions for the urban worker, livelihood and food security, living conditions etc. Urban planning, instead, driven by the desire to implement universal solutions, creates an abstract homogenisation of urban life, mostly out of touch with reality of the majority of the citizens. Rather than learning from local wisdom of diverse people and communities, "the formal" attempts to centralise systems of knowledge and of production and application, clearly evident in water supply, sewage and institutionalised healthcare provisioning in the urban areas. This creates inappropriate services and wastage of valuable resources. Being far removed from the local context the models adopted are more aspirational of the "development standards" of the global north rather than mindful of ecological sustainability, economic viability, and social justice.

The observation of widespread resort to informal modern conventional health care in cities, towns and villages has led to the proposal to officially institute 3-year courses for training "community-level accredited practitioners—not full-fledged doctors" who can practice independently and provide basic health care at low cost (42). However, this policy measure has not found favour with the regulatory bodies in the country even when attempted by some states for rural areas (43).

Moreover, the dominant politics of knowledge overlooks, even delegitimises, these alternative sources of knowledge coming from the common people of all sections. Thus, even though the most marginalised of the population primarily depended on informal sources and the public services for their healthcare needs, there's little reflection of that in existing plans that favour promotion of private medical services. People taking care of themselves, with locally available resources, is a reality that is usually ignored in our formal health services planning. The whole articulation is geared only towards medical service provisioning and demand generation for the products of the medical industry, creating dependency rather than facilitating people's own health creating practices.

It must be admitted that folk medicine like any other system of medicine has its own strengths and limitations. While it is mainly used in present times for promotion of health and treatment of common everyday health problems, its value as beneficial for health promotion, prevention, palliation and cure has been well-recognised by pharmacology since the discipline has evolved on the basis of traditional medicinal plant knowledge found especially in the "developing" world. The pharmaceutical industry too has depended on it as the source for leads to identify medically effective molecules for its research and development activities, and continues to do "bio-prospecting" even in the present (44). In recent years, the state has opened up to civil society initiatives attempting some form of recognition of the folk practices and practitioners—for instance, the Indian Public Health Standards set by the Ministry of Health and Family Welfare for rural health services that stipulate cultivating herbal gardens in the compounds of Primary Health Centres and Sub-centres as "desirable" (45, 46). Evolving systems for certification of traditional folk healers such as herbalists, and bonesetters and their practices by the Quality Council of India (a quasi-statal agency) (47) is another initiative relevant to bridging the formal-informal divide. However, even this is targeted at the rural areas, with no acknowledgment of the existence and practice of folk medicine in urban areas. Codified systems other than the modern conventional too are growing in their scope of urban practice and integration into modern health care by adopting modern forms of institutions and regulation. Yet, even this component of the formal in major Asian countries is not factored into most of health systems research or design, either in the Primary Health Care of 1978 or in Universal Health Coverage of the 2000s or the international slogan for attaining the Sustainable Development Goals (48). Even those advocating for addressing the Social Determinants of Health as part of UHC for South Asian cities do not seem to envisage plural forms of health care as a relevant component (49). In contrast, Cuba, a country well-recognised for the large number of doctors it produces and its well-developed modern health services, is, some may think paradoxically, also a pioneer in the scientific research and use of Homeopathy as well as teaching of herbal medicine to school children (50). This seems to embody the healthcare system with what Knutstadt had hypothesised in 1975, that "pluralism of medical beliefs, choices, and therapeutic strategies offer adaptive advantages to health care systems. Instead of producing negative effects, as some proponents of the symbolic unity of cultural systems have led us to believe, cognitive dissonance (multiple and competing health care strategies), at least in the health care system, may well have distinct advantages for biological survival, the resolution of psychosocial tensions, and the evolution of adaptive cultural strategies" (51).

Our study shows the possible benefits of providing urban populations access to traditional medicinal plants by promoting urban forests and herbal gardens in public spaces as well as encouraging cultivation and use of medicinal plants and herbs by all sections. Urban/peri-urban agriculture and cultivation of medicinal plants in public spaces for citizens to access is possible with a vision of urban green spaces that may not be neat or sanitised but are of use in the way of life of all, and especially of the poor and migrant. Learnings can come from initiatives such as undertaken in Cape Town, South Africa that brought together disparate groups who share interests in the city's biodiversity—formal economy, predominately middle class conservation managers and policy makers, and informal economy, predominately working class Rasta herbalists—to develop herbal gardens in public spaces (52).

State can play an important role therefore in reviewing the popular practices and facilitating those that prove beneficial. In terms of strengths beyond biological efficacy, it is important to note that folk traditions are commonly an integral part of the social and physical environment of the communities, making them more conducive for adoption and treatment adherence. Facilitating home remedies which are usually low cost, prepared from locally available materials, and constituting a significant proportion of care seeking, could have not only brought down the cost of care but also taken the load off the formal public services, allowing them to improve their quality of services. In the face of exorbitant rise of medical care cost, increasing incidence of antimicrobial resistance and deaths due to iatrogenesis globally, as well as the polluting nature of the pharmaceutical industry, the traditional systems of medicine and folk medicine do hold promise of contributing to evolving more democratic, plural and sustainable health systems.

An integrated, comprehensive, and ecological planning would have optimised the existing resources and practices in providing people good quality care that is need based and sustainable on a longer term. Epidemiological logic in consonance with people's need and service provider's opinion, should inform decisions regarding provision of institutional care. An earlier study covering rural populations spanning 18 states of India had found that 80% items listed as self-reported household level knowledge of medicinal value of plants and food items was verified and validated to be rational by the codified knowledge and scientific principles of the recognised AYUSH systems (37). Building on urban people's existing knowledge of medicinal properties of food and plants, as demonstrated by the data in this paper, should create an interface of the formal institutional with the informal that remains sensitive to people's agency and innovation (53). Documenting and researching home based remedies, disseminating useful knowledge about them, creating herbal medicinal gardens in urban localities, teaching children in schools about the value of medicinal plants and involving them in their cultivation and use, could go a long way in re-legitimising this knowledge and bringing its benefits to larger numbers. Such measures are rarely resource intensive and due to their dependence on nature, also provide people with a reason to preserve the natural habitat.

The challenge to such folk knowledge and practices that tend to be location specific can pose challenges when practitioners migrate to urban areas. Our study found that there is continuity of the regional flora across rural and urban, which gets eroded as construction and concretisation of open spaces increases. While this problem can be resolved, the issue of folk healers is more complex. The folk healers were traditionally regulated by the norms and ethics of their community of healers. As they migrate to the city, they can get cut off from their community and its regulatory system. That is why wider propagation of the peer assessment based certification mechanisms for folk healers becomes important even in urban areas. Further, their skill upgradation through senior healers would ensure survival of such valuable knowledge and its practice brought to better benefit larger numbers. Inter-disciplinary and trans-disciplinary research could also provide systemic mechanisms to rationally increase the element of self-care and community level care so as to decrease resort to institutional care, thereby decreasing costs and time of both the users and institutional providers. Further, based on studies of the urban poor in different parts of India and a wider literature review, it has been argued that their perceptions of quality of care, understandings of the social determinants of health and ways of dealing with them can provide learnings for more appropriate assessment criteria and designing of health systems (54, 55). In the 1970s, based on Chinese health culture, Kleinman famously depicted the health care system as being composed of three distinct spheres—"the popular" (individual, family and community-based) as the largest, with smaller spheres of "the professional" or formal and "the folk" composed of folk practitioners (51). While finding that this holds true even in the twenty-first century urban context (though we use "folk" to include the popular practices and the non-formal providers), our analysis shows that there is greater complexity within and inter-digitation between them. The relationship between these spheres is therefore better depicted as concentric circles, as in the paper by Ghodajkar et al. (53). This has implications for how the health care system boundaries are to be drawn and how regulatory as well as institutional structures are to deal with the various spheres.

Thereby, the informal can (i) be analysed to understand what features suit people in diverse conditions and build them into system or intervention designs, (ii) demonstrate pathways to sustainability in diverse contexts, and (iii) be analysed for evolving normative principles for planning. All these are valid activities even while they need to be undertaken with the recognition that the informal mechanisms may not always be the "best solutions" of the elite, but responses for coping with situations full of constraints. The constraints themselves have to be recognised as those of societal resources, as relevant considerations for any efforts at sustainable development encompassing all socio-economic sections and thereby questioning the criteria for assessing optional solutions including those of the elite. The interface between the informal and the formal is the junction we are hoping to address for examining and contributing to building sustainable systems.

People's health seeking practices show that there is place for both the formal and informal. The how, where and what of that gets reflected in the choices that people make which vary by specific contexts. Making the process of urban planning people centred should therefore create conditions that empower people's solutions emerging from the ground. This can help capture the complexities of real life, as well as show us how to make the urban environment healthier by ensuring fulfilment of basic needs and promoting resilience (e.g., with promotion of peri-urban agriculture) and the health care system more responsive to people's needs and suitable to local context (e.g., promoting people's access to medicinal plants in public spaces). Sustainable cities, while upholding the three pillars of social equity, economic prosperity and environmental integrity, need to place democratisation of knowledge and people's practices upfront as the fourth pillar. Exploring urban informality can provide us with some clues on how to do that, so as to reflect the diversity within urban areas and provide more sustainable options for organising the high urban densities into more livable spaces for health and well-being of all.

DATA AVAILABILITY

The datasets generated for this study are available on request to the corresponding author.

AUTHOR CONTRIBUTIONS

The empirical study was conceptualised by RP. Methodology and tools prepared by RP and RS. The survey was coordinated and data managed by RS. Data analysis was done jointly by RP and RS. RP and SD jointly conceptualised and wrote the paper based on an earlier draft by RP and RS.

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Evaluating Socio-Ecological Interactions for the Management of Protected Urban Green Spaces

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Protected urban green spaces (PUGS) are exposed to numerous disturbances and threats since they are immersed in highly dynamic socio-ecological systems. PUGS in highly urbanized cities require particular conservation strategies. Here, we propose an approach for PUGS management which integrates three components: (i) scientific knowledge (monitoring/restoration), (ii) community interaction with the environment, and (iii) management decision. Based on the perception of stakeholders, we searched for evidence that these components are well-integrated in PUGS management and decision-making. The intersection of these components should produce a solid management program, provided that the obtained multidisciplinary knowledge meets the needs of information required by the community and decision makers. We tested this in a small PUGS located within Mexico City at the National Autonomous University of Mexico campus that holds the Ecological Reserve of Pedregal de San Ángel. Through a participatory approach we elicited mental models and represented group beliefs using Fuzzy Cognitive Mapping (FCM). This, in turn, produced evidence of effective integration of the three components in terms of management and decision-making. Our findings provide insight into the actors' perceptions and concerns and suggest that the interactions among the three components, although important, are not self-generated and must be constructed. The findings also suggest that one of the management problems is the mismatch between scientific knowledge and conservation programs.

It is paramount to include generated knowledge into management and monitoring programs. The complexity of the PUGS requires an active collaboration among actors and monitoring the development of management strategies using the three components while taking the conservation goals into account.

Keywords: cities, Mexico City, UNAM main campus, urban conservation, socio-ecological system, Ecological Reserve of Pedregal de San Ángel, community perception, fuzzy cognitive map

INTRODUCTION

In most cities urban green spaces (UGS) are subject to urbanization pressures and ecological disturbances (Ernstson et al., 2010), such as the reduction of green areas, the introduction of invasive species, increased pollution, and soil compaction in pathways (Alberti et al., 2003; Andersson, 2006; Yang et al., 2017). The establishment of protected urban green spaces (PUGS) can reduce urban pressures upon these areas if they are properly managed. However, devising effective management programs for PUGS is a challenge in highly dynamic and populated areas. Outside of cities, the management of natural protected areas is based on multidisciplinary scientific information that generates tasks to increase the efficacy of conservation strategies. This strategy is focused on simultaneously maintaining ecological processes and the activities carried out by local people in rural communities such as forestry, gathering, hunting, harvesting, or cropping (e.g., Kharel, 1997).

Human and nature interactions are integrated systems in which people interact with natural components (Liu et al., 2007), thus, the resources used by humans are embedded in complex social-ecological systems (SESs) which are composed of multiple subsystems and internal variables at different levels (Ostrom, 2009). Due to intense interactions with humans, PUGS in urban areas with complex socio-ecological dynamics must generate new management strategies. For example, restoration projects in rural regions are normally controlled by few people who have minimal contact with local settlers (Mangun et al., 2009; Davenport et al., 2010). In cities, restoration programs such as the eradication of exotics—plant or animal—may be misunderstood by numerous citizens who are in daily contact with those protected areas (Leong et al., 2009). This may culminate in protests against eradication measures (e.g., Gaertner et al., 2016; Novoa et al., 2018), and ultimately reduce program achievements (e.g., Madden and McQuinn, 2014). In addition, there is an increase in the number of people who are adopting pets, especially dogs and cats near PUGS (e.g., Sepúlveda et al., 2014; Paschoal et al., 2016). Exotic pets like fish, turtles, and frogs are also being released into PUGS (e.g., Taniguchi et al., 2017), which can generate human health issues and harm native biodiversity.

Land is one of the critical limiting resources in cities for both society and nature (Lambin et al., 2001). The large influence of UGS in urban ecosystems is based on the amount of land they occupy within cities (Xu et al., 2016). Parklands in New York City cover 21% of the area, containing 85% of the flora diversity (Schewenius et al., 2014), while in Chandirgah they extend over a third of the city's surface (Chaudhry and Tewari, 2010; Shen and Fitriaty, 2018). This land occupies a key role in ecological processes such as biodiversity maintenance and ecosystem services (Aronson et al., 2017; Sirakaya et al., 2018). The PUGS often undergo fragmentation, which in turn modifies ecological/evolutive interactions as well as provision of ecosystem services (Tian et al., 2011; Mitchell et al., 2015a,b). Fragmentation not only modifies ecological dynamics but also change social interactions in the neighborhood of green spaces (Hansen and DeFries, 2007). Therefore, to increase conservation success, management practices in PUGS should pay attention to the socio-ecological interactions generated in and around PUGS.

An assessment of the factors and interactions comprising each component is critical to evaluate PUGS management, which may vary from areas to areas. We studied a small PUGS, the Ecological Reserve of Pedregal de San Ángel (REPSA, as it stands in Spanish; hereafter it might be also referred as "Reserve"), situated in the National Autonomous University of Mexico main campus, Mexico City. We analyze PUGS management based on three components that have been traditionally used to manage protected areas: (i) scientific knowledge (monitoring/restoration), (ii) community interaction with the environment, and (iii) management decisions (**Figure 1**).

In order to answer the research questions "Is there evidence that these components are well-integrated in REPSA decision-making, according to stakeholder perceptions?" and "Is the intersection of the three components enough to create a solid foundation for management of any green space within this university?" we described the characteristics of the three components in this PUGS, elicited mental models and represented group beliefs (including students, academics, and administrators) using Fuzzy Cognitive Mapping (FCM) (Kosko, 1986; Gray et al., 2014). We evaluated the connections among these components based on activities, perceptions, and ecological variables within the university campus. The intersection should be critical since both decision makers and those who generate the scientific information come from the same community. Then, the FCM will show that the key concepts for the solid management of the REPSA will fall exclusively in the intersection of the three components.

STUDY SITE

In the middle of the last century, the Federal Government bought 723 ha of lava field far away from the city center and gave it to the National Autonomous University of Mexico (Morales-Schechinger and García-Jiménez, 2008). The land lies within a xerophytic and thornshrub ecosystem established over volcanic material generated from the eruption of a monogenetic volcano (Xitle) in 280 ± 35 BCE, which covered roughly 70 km^2 in the

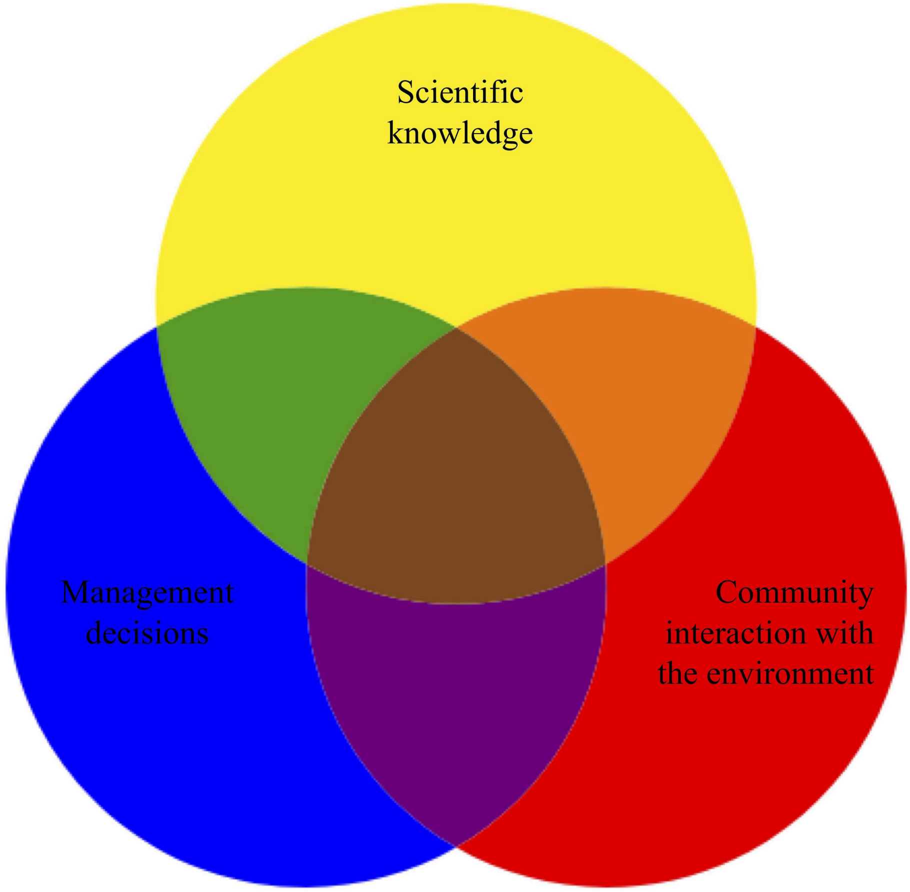

FIGURE 1 | PUGS management using the three components. The intersection of the three circles is in which elements of a proper management should arise.

south of Mexico City (Siebe, 2009), which is known as Pedregal de San Ángel (hereafter will be also referred as "Pedregal"). It generates diverse habitats, depending on the flow and cooling conditions, resulting in a heterogeneous interstitial matrix. It has a high gradient of light and temperature within few meters, allowing only xerophytic species of plants to survive (Rzedowski, 1954; Peralta-Higuera and Prado-Molina, 2009).

The University moved its main campus in 1953 to this land in an attempt to generate a development pole at the south of the city, but occupied only 178 ha of the total area (Zambrano and Cano-Santana, 2016). Soon afterwards, regional urbanization spread along the area outside of the University, reducing the lava field ecosystem. The University had development plans that would urbanize the rest of the lava field landscape (Morales-Schechinger and García-Jiménez, 2008), threatening the geoheritage of this ecosystem and a large number of species.

Academics and students mobilized to protect this area and the university authorities established a protected 124 ha area within the campus in 1983, naming it Ecological Reserve of Pedregal de San Ángel (REPSA) (García-Barrios, 2014). During the past three decades, the Reserve has been expanded and now occupies a third of the campus area (237 ha). Scattered along the campus there are also 40 ha of non-protected patches of original ecosystem. It comprises a complex basaltic volcanic field that is the base for a large biodiversity of pioneer plants and animals (Cano-Santana et al., 2008). The REPSA is now home to 1,849 native and 317 exotic species (REPSA, 2017). As other PUGS, this area is inserted in an urban matrix and provides ecosystem services such as high-water infiltrations to the city and flood regulation (Vargas, 1984; Delgado et al., 1998; Nava-López et al., 2009; Palacio-Prieto and Guilbaud, 2015).

THE THREE COMPONENTS APPROACH

First Component: Scientific Knowledge

The constant generation of scientific information of a protected space is essential since most parts of ecosystem interactions can be explained by long term ecological monitoring (Brown et al., 2001) and ecological restoration programs, which give information about ecosystem processes. Long-term ecological data provide baselines for evaluating environmental change (Rustad et al., 2007), help to detect and evaluate changes in ecosystem structure and function, and help to distinguish the ecosystem's response to changes in environmental trends from those responses to changes in the intensity and frequency of episodic events (e.g., by drought or wildfires).

Two examples are understanding fire causes or eutrophication trends due to pollution accumulation within a reserve (Welch, 1998; Radeloff et al., 2010), and understanding the interaction among species in different areas. Information on native and exotic species is critical to understand the ecosystem functioning in an urban space. For example, understanding ecological interactions such as competition or predation is critical for management (MacKenzie et al., 2004). Monitoring represents a challenge but provides reliable estimates of demographic and population variables (Yoccoz et al., 2001; Nichols and Williams, 2006). Recent methodological advances, such as occupancy models, allow demographic estimations with simple observation of presences and apparent absences of species and should be implemented in long-term monitoring programs (Buckland et al., 2015; MacKenzie, 2018). Ecological monitoring studies in the REPSA have revealed that occupancy of exotic species occupancy may have both negative and positive effects on native species (Ramírez-Cruz et al., 2018, 2019). Likewise, the analysis of genetic erosion (e.g., de Oliveira and Martins, 2002; Moodley et al., 2017) of the species is necessary given the small PUGS size where populations are intended to continue their evolutionary processes (Sherwin and Moritz, 2000; Moritz, 2002). Factors that maintain diversity should also be considered, like plants with their pollinators, seed dispersers, and other ecological interactions (Tylianakis et al., 2010; Jordano, 2016).

Restoration ecology programs are equally important to the monitoring of PUGS and therefore need to be included in management programs. The first restoration program developed in the REPSA was the reduction of the *Eucalyptus* spp. populations, initially introduced in the campus when it was under construction in 1951 (Segura-Burciaga and Meave, 2001; Cano-Santana et al., 2006; Antonio-Garcés et al., 2009; Estañol-Tecuatl and Cano-Santana, 2017). A current restoration program, which aims to restructure the original trophic dynamics of local wildlife (Kagata and Ohgushi, 2006), comprises two significant actions: (i) the restoration of wildlife populations by the eradication of feral dogs and cats (Zambrano et al., 2016), and (ii) the population re-establishment of gray foxes (*Urocyon cinereoargenteus*) which were presumed to have been extirpated from the REPSA (Hortelano-Moncada et al., 2009) until an individual was photographed in 2017 by Y. Glebskiy (see López, 2017).

Scientific information is critical for a biological understanding of the system, but also, for creating strategies to ensure that current and future generations enjoy an ecosystem and its services (Faith et al., 2010). Therein lies the importance of the interface between generating scientific information and the other two components (i.e., community interaction with the environment and management decisions); it provides the knowledge that authorities and the community require along with information on community-nature interactions needed for management.

Second Component: Community Interaction With the Environment

The university community's perceptions regarding the green spaces on campus have changed, particularly the perception of the REPSA being either a problem or a solution. This has modified the position of stakeholders (authorities, students, and workers) toward these green spaces. In the early stages (1951–1983), only aesthetics aspects were valued for campus management. Most of the community was essentially unaware of the natural area (Morales-Schechinger and García-Jiménez, 2008; García-Barrios, 2014). In a more recent study from 2014, a poll showed that <30% of students and academics knew the type of ecosystem in the campus (Pérez-Escobedo, 2014). Nevertheless, in recent years there has been a change in perception about what it means to have this ecosystem amidst buildings and avenues.

In order to understand this second component based on the conflict between urban land use and conservation at the university, different perspectives (other than those used for the traditional biodiversity conservation studies) have been employed. For example, social cartography is one tool that has been applied on specific areas of the campus to uncover collective ideas of urban nature (Amin, 2007; James, 2015). Cartography studies helped to evaluate if the university community is willing to balance conservation vs. infrastructure needs, without compromising social cohesion. In this sense, the environmental game theory approach (Dinar et al., 2008) has been also implemented as a tool to represent and manage the conflicts arising from the interaction of the various REPSA stakeholders (researchers, students, administrative workers, authorities, and citizens in general), whose acts are guided by their own interests (Kreps, 1990). The third employed tool is participatory modeling through FCM (e.g., Gray et al., 2015). There are many experts in several disciplines, focusing on specific species, processes and knowledge of history, working within or closely-related with the REPSA (academics, students, and administrators) whose perceptions and knowledge are important to capture, integrate, and facilitate the decision-making related to the management of the Reserve (Gray et al., 2012).

Because each stakeholder of this particular socio-ecological system plays a fundamental role and has different perceptions, a clear communication and close interaction between the community and the decision-makers are critical. Frequently, plans to change the infrastructure are communicated late by the authorities. This shows opposite interests among stakeholders and induces difficulties in each stage of the process. The result in the long term turns out exhausting to each part of the community. Nevertheless, the authorities of the REPSA have a role only in cases when a project is carried out on the Reserve land. For the rest of the projects (even in those that affect the Reserve) they do not have decision capacities. A constant interaction of the second component with the other two is relevant as it can potentially contribute to the social-environmental dynamics. This is a basic relation for the establishment of programs and actions that effectively allow the transfer of valuable information to the community, and thereby increases the chances of better management.

Third Component: Management Decisions

Urbanization of the campus since 1953 has increased according to the development projects of each Dean and the economical capacities of the country. Historically, for the first few years, no consideration was given to landscaping from an architectural point of view (Morales-Schechinger and García-Jiménez, 2008; García-Barrios, 2014). Since the PUGS was established, a series of conflicts between the community and the campus authorities have surfaced. The result is a campus with fragmented and scattered areas, some of them well-planned, while others seem poorly-planned (Zambrano et al., in press). Even though there is a protected area, the green space is divided by buildings, roads, and fences, therefore, the ecosystem is highly fragmented with biotic communities poorly connected.

The REPSA had a difficult start as a PUGS since it resulted from a dispute between university authorities, had limited planning to urbanize the total area in a short period of time, and students and academics promoted the protection of the native ecosystem (García-Barrios, 2014). This generated confrontations for decades, and surprisingly the result has been an increment on the protected space on the campus and the strengthening and institutionalization of the office in charge of its protection (Carrillo-Trueba, 1995; Zambrano and Cano-Santana, 2016). Volunteer programs, political gatherings and social mobilizations to stop the destruction of the remaining native ecosystem in the Pedregal areas, and the institutional work based on the people in charge of the Reserve have helped to save it from destruction (Carrillo-Trueba, 1995; García-Barrios, 2014).

Nowadays, the campus is facing a new challenge since the university needs to grow to meet the demand for education in the country. The remaining space is highly reduced and, hence, the opportunities to increase the infrastructure are severely limited. Similar to other universities, such as Oxford or Cambridge in the UK (NIC, 2018), a university needs to increase its facilities without affecting its landscape or monuments. With these challenges in mind it is necessary to ask if it is possible to manage a PUGS under this type of pressure. The information generated on each of the parts is crucial to guide management decisions. Consequently, the integration of the three components (scientific knowledge, community interaction with the environment and management decisions) may provide the building blocks for the authorities and decision-makers to define actions for the university and the reserve.

Assessment of the Three Components

Typically, knowledge is generated by different and very specific disciplines; collaborators work together and produce information within each one of the three components explained above. Once the information is available, selection, and organization processes are carried out to develop Reserve management plans that could facilitate decision making regarding its management.

Therefore, it is expected that the intersection between the three components should lead to the proper management of a PUGS. That is, the union between all of the disciplines is crucial to generate effective management regarding the Reserve. This should be particularly true in a PUGS within a university able to generate scientific knowledge needed immediately by academics in constant communication with the authorities and the community.

METHODS

Participatory Approach and Group Fuzzy Cognitive Map Building

Integrating knowledge through participatory modeling has been a successful approach although it can present several challenges (Gray et al., 2012). Through participatory workshops it is plausible to elicit the perception of different sectors of stakeholders. In order to know, communicate and graphically capture the perception of an individual or group of individuals who are part of a socio-ecological system several techniques have been developed, one of which is the mental model. A mental model obtained through the FCM approach (see Kosko, 1986) can be defined as internal representations or beliefs of the external world (Jones et al., 2011; Gray et al., 2012). FMC is a useful tool for understanding the community's knowledge about the university campus and its implications for the REPSA management since it has a bottom-up approach and can integrate in a standardized format several levels of knowledge from individual to community as well as expert knowledge (Gray et al., 2015). After building the FCM, results are analyzed by an interdisciplinary group. The ideas, and perceptions of different actors are merged through an in-depth discussion, which in turn contributes toward better decision-making related to scientific monitoring and restoration, and improvement of the interaction university community—nature and urbanization decisions. The analysis evaluated whether the concepts of the FCM and its interactions fit into the three components (i) scientific knowledge (monitoring/restoration), (ii) community interaction with the environment, and (iii) management decisions.

In order to further understand the factors driving management strategies for PUGS, we applied a participatory approach through which the perceptions of different actors and their social and ecological relationships with this PUGS were elicited and used to prove the integration of the three components. A participatory workshop was conducted in 2018 with 25 members of the university community to discuss the main concerns, management plans, and decision making around the university campus and REPSA protection and conservation. The group of participants was formed by students, academics, and administrators working at the university in different areas of expertise (e.g., conservation biologists, ecologists, restoration specialists, architects, urban planners, veterinarians, and administrators) and collaborating closely with projects related to the REPSA. Specifically, the students (40%) were mostly part of the Postgraduate Program of Biological Sciences although a few undergraduate students also participated. The academics (36%) were from several research institutes such as Biology and Ecology Institutes as well as the Architectural, Sciences, and Veterinarian and Zootechnics Faculties, whose research activities have been focused for several years on the REPSA. In addition, some of the academics from the Sciences Faculty and Architecture Faculty were working on topics related to campus mobility. Finally, the administrators (24%) were part of the Executive Secretariat of the Ecological Reserve of Pedregal de San Ángel (SEREPSA, as it stands in Spanish) which is in charge of the liaison between the Technical Committee and several academic entities, as well as with the university community and society. The percentage of members of each one of these particular sectors was similar to prevent as much as possible specific group bias.

The participatory workshop consisted of several activities (see **Supplementary Material 1** for more details) to build a collaborative model (e.g., Voinov et al., 2018; Cholewicki et al., 2019): (i) construction of a rich picture, or a drawing to illustrate a specific situation (in groups of five people). Since the RESPA is immersed in the campus and what is happening might affect or have influence on the decisions made at the Reserve level, the participants were asked to discuss and to make a sketch based on the question *What do you think are the main problems on the campus and their implications for the Reserve conservation?* Drawing a rich picture provides an understanding process of the central idea, and it is plausible to identify multiple viewpoints as all of the participants intervene; (ii) explanation of the rich picture and collection of the concepts that will be the building blocks of the FCM. In this activity the participants exposed to each other the drawings; concurrently a facilitator was writing on paper cards all of the words and concepts mentioned by the participants; (iii) building a group FCM where the paper cards with the concepts were connected through causal relations. For example, a concept may have a direct influence on another and/or others by increasing or decreasing them. The participants were asked to connect the concepts and to establish the relations among them through positive and/or negative arrows. Here the role of the facilitators was critical to guarantee a mental model that reflected the perceptions of all of the participants through a large discussion and promoting consensus; and finally, (iv) weighting of the FCM concepts, which provides an individual weight of the most relevant components and their relative importance in the model according to each one of the participants. For this activity, the same number of stickers were given to the participants who were asked to put the stickers on what they believe were the most important concepts of the map. Each sticker had a value of one point, and the participants made a freewill to use their points in one or several relevant concepts.

This exercise triggers the communication between parties that need to communicate in a systematic way and to synthesize the community perception of REPSA, the urban green areas, and the urban context. The mental model generated is a first interdisciplinary product to evaluate the management of this PUGS. The result obtained is dynamic and therefore can be used to analyze changes in the perception of the problems of the university campus, to evaluate conservation strategies based on management, population growth, and public safety.

Fuzzy Cognitive Map Analysis

By employing the specialized software Mental Modeler (www.mentalmodeler.org; Gray et al., 2013) and Cytoscape 3.4.0 (Shannon et al., 2003) the mental model generated during the workshop was digitized, visualized and analyzed. The model is visualized as a network in which concepts are connected through positive or negative edges. These programs were also employed to compute the network structure statistics, including number of concepts, type of concept (driver, ordinary, receiver) number of connections, connections per concept (number of connections divided by number of concepts), and the calculation of measures such as density or an index of connectivity determined by dividing the number of connections present by the maximum number of possible connections (Hage and Harary, 1983; Özesmi and Özesmi, 2004), and complexity score calculated as the ratio of receiver concepts to driver concepts (Özesmi and Özesmi, 2004; Gray et al., 2014). In addition, in Cytoscape 3.4.0 a Hierarchical Layout algorithm was applied to the network to help visualize the flow of information from the base to the top concepts.

In order to deeper analyze the concepts and their relations, all of the concepts were assigned to categories regarding the three components as follows: A = scientific knowledge (monitoring/restoration), B = community interaction with the environment, and C = management decisions. Since some of the concepts fell into two or the three categories, the subcategories *A-B*, *A-C*, *B-C*, and *A-B-C* were also included. For instance, concepts that potentially corresponded to both the *A* and *B* categories were included into the *A-B* subcategory. Thus, some concepts were exclusive to a category or fell into two or more categories. The concepts assignment was conducted as part of a group activity that included the complete interdisciplinary work team, who discussed the categorization of concepts and reached a consensus. Finally, the concepts were color coded to be visualized according to the categories (see **Figure 1**) in the hierarchical network. Likewise, the weighting score was visualized as black dots for the corresponding concepts.

RESULTS

The participatory workshop was successful in terms of attendance and participation of members of the university community. Through several activities conducted during the workshop (described in the **Supplementary Material 1**), a FCM representing the participant community's perception was created. This model was the first interdisciplinary product developed by the research project team to evaluate the management of the REPSA.

The FCM developed from the workshop was moderately complex (**Table 1**) as it consists of 45 concepts and 85 connections, whereas the connections per concept (calculated by the ratio connections/concepts) was of 1.88, the density of 0.042, and complexity (ratio of receiver concepts/driver concepts) was of 0.875. Through the hierarchical arrangement of the network a total of 14 hierarchical levels were observed (**Figure 2**) as well as the flow of information which goes from the bottom to the top of the network, and in the same flow, three types of concepts or nodes were recognized: the drivers or those affecting other concepts, the ordinary ones which are affecting and at the

TABLE 1 | Summary statistics of the network.

Metrics	Value
Total concepts	45
Total connections	85
Density	0.043
Connections per concept	1.889
Number of driver concepts	8
Number of receiver concepts	7
Number of ordinary concepts	30
Total positive connections	44
Total negative connections	41
Number of weighted concepts	17
Complexity score	0.875

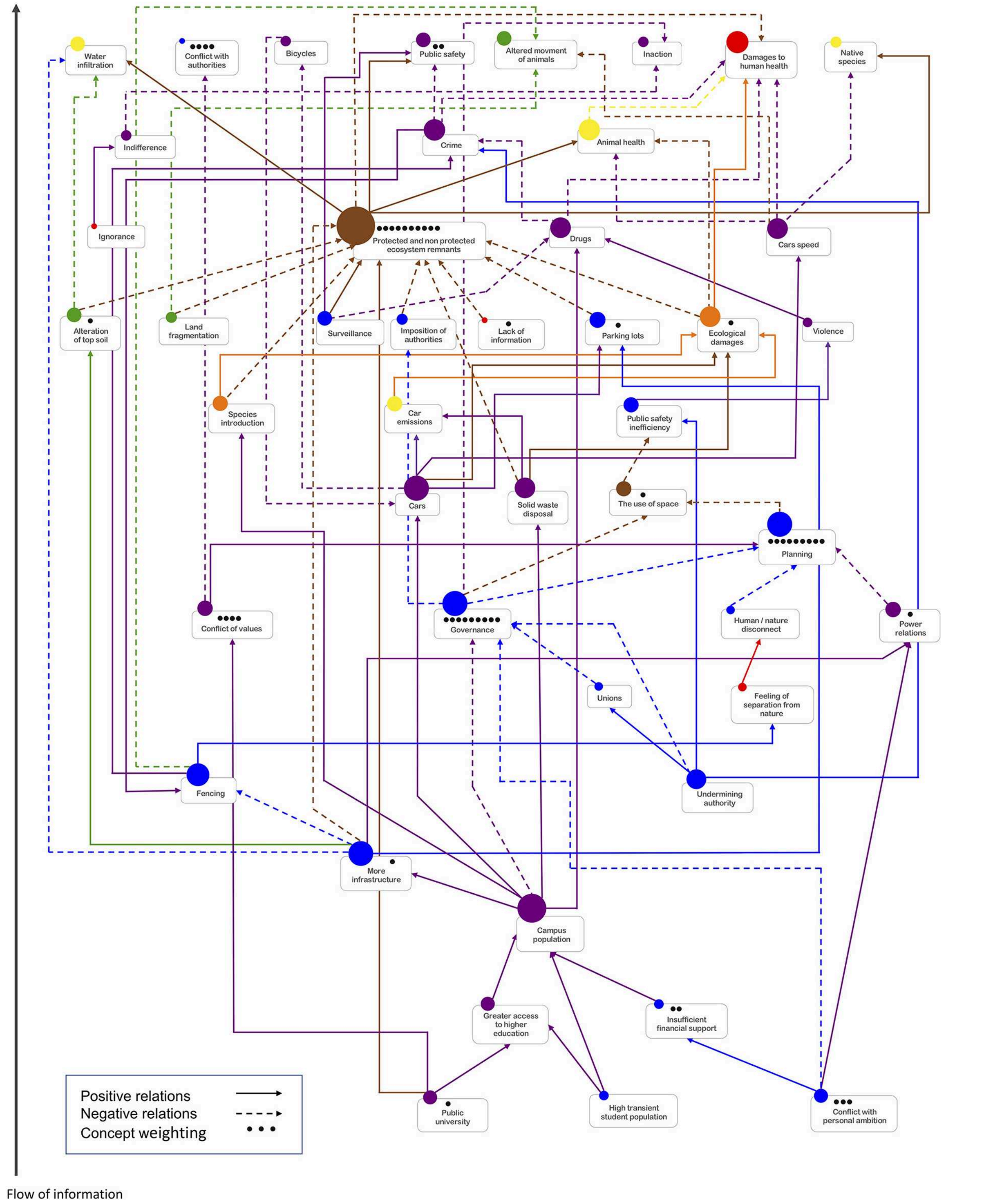

FIGURE 2 | FCM depicting the community's perception. The color of the concepts corresponds to the different categories established: *A* in yellow, *B* in red, *C* in blue, whereas the subcategories *A-B*, *A-C*, *B-C*, and *A-B-C* are in orange, green, purple, and brown, respectively. Likewise, the size of the nodes is consistent with the centrality, hence, bigger nodes have more connections with other nodes, while the smallest nodes contain one edge only. The small black circles next to the concepts indicate the weighting scores, that is, the sum of the points given by each participant to those concepts considered of high relevance for the system. The concepts are connected through causal relations that are positives (solid lines) or negatives (dotted lines). The black arrow to the left depicts the flow of information from the base to the top concepts.

same time are influenced by other concepts, and the receivers not having influence on others only being influenced by others (Özesmi and Özesmi, 2004) (**Figure 2**; for more detail on the meaning of concepts see **Supplementary Material 2**).

With regard to the category allocation, 30 out of the 45 concepts are contained within the category *C* (15 concepts) and the subcategory *B-C* (15 concepts; see **Table 2** and **Figure 3**). The categories *A* and *B* contain four concepts each, whereas

TABLE 2 | Concepts location and characteristics.

Concepts	Network level	Centrality	Input	Output	Weighting score	Component*
Protected and non-protected ecosystem remnants	12	16	11	5	10	A,B,C
Campus population	3	9	3	6	7	B,C
Governance	7	8	4	4	9	C
More infrastructure	4	7	1	6	1	C
Cars	9	7	2	5	–	B,C
Ecological damages	11	7	4	3	1	A,B
Crime	13	6	3	3	–	B,C
Damages to human health	14	6	6	–	–	B
Cars speed	12	5	1	4	–	B,C
Fencing	5	5	2	3	–	C
Drugs	12	5	3	2	–	B,C
Planning	8	5	4	1	9	C
Undermining authority	5	4	–	4	–	C
Solid waste disposal	9	4	1	3	–	B,C
Animal health	13	4	3	1	–	A
Surveillance	11	3	–	3	–	C
Conflict with personal ambition	1	3	–	3	3	C
Public university	1	3	–	3	1	B,C
Alteration of top soil	11	3	1	2	1	A,C
Species introduction	10	3	1	2	–	A,B
Conflict of values	7	3	1	2	4	B,C
The use of space	9	3	2	1	1	A,B,C
Security inefficiency	10	3	2	1	–	C
Power relations	7	3	2	1	1	B,C
Parking lots	11	3	2	1	1	C
Car emissions	10	3	2	1	–	A
Greater access to higher education	2	3	2	1	–	B,C
Public safety	14	3	3	–	2	B,C
Altered movement of animals	14	3	3	–	–	A,C
Water infiltration	14	3	3	–	–	A
Land fragmentation	11	2	–	2	–	A,C
High transcent student population	1	2	–	2	–	C
Indifference	13	2	1	1	–	B,C
Imposition of authorities	11	2	1	1	–	C
Unions	6	2	1	1	–	C
Violence	11	2	1	1	–	B,C
Human/nature disconnect	7	2	1	1	–	C
Feeling of separation from nature	6	2	1	1	–	B
Insufficient financial support	2	2	1	1	2	C
Bicycles	14	2	1	1	–	B,C
Inaction	14	2	2	–	–	B,C
Native species	14	2	2	–	–	A
Lack of information	11	1	–	1	1	B
Ignorance	12	1	–	1	–	B
Conflict with authorities	14	1	1	–	4	C

Components A, scientific knowledge (monitoring/restoration), B, community interaction with the environment, and C, management decisions.

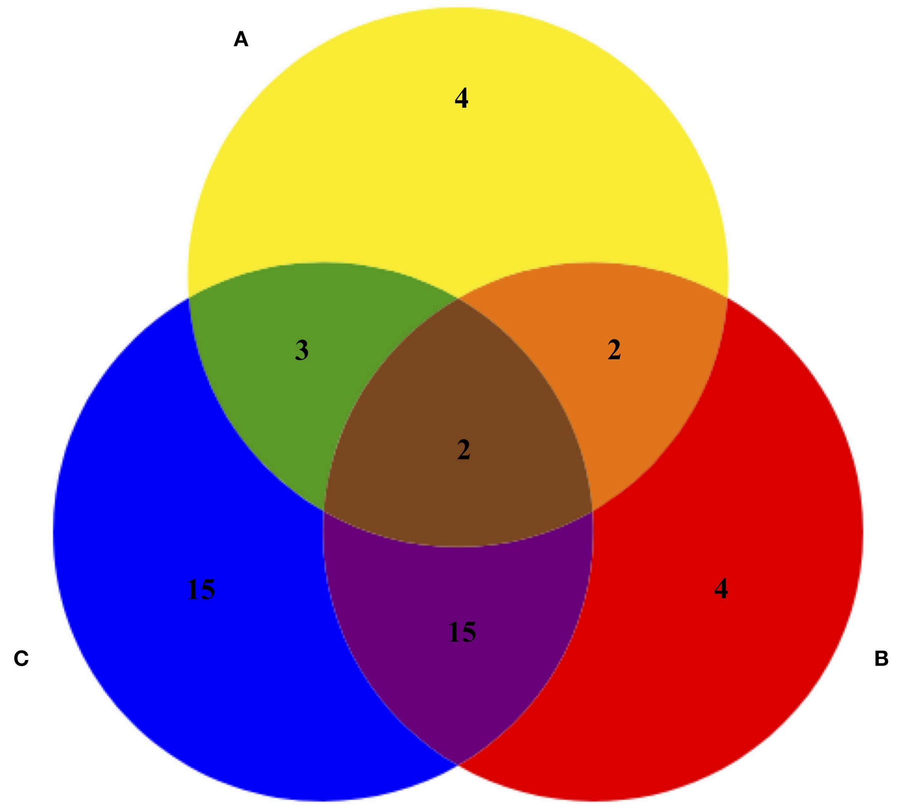

FIGURE 3 | Total number of concepts per component (see **Figure 1**) and the number of concepts within each of the intersections. Yellow circle represents Scientific knowledge, Blue circle represents Management decisions, and Red circle represent Community interaction with the environment.

A-B and *A-C* contain two and three concepts, respectively. The intersection of the three components, the subcategory *A-B-C*, comprises only two concepts, one of these (*Protected and non-protected ecosystem remnant*) presented the highest centrality, however, it is not related with any management action. Category *C* and subcategory *B-C* not only have the highest number of concepts, also, the first seven hierarchical levels of the FCM (**Figure 2**) presented concepts corresponding to these categories only. It is not until the eighth level where a component from the subcategory *A-B-C* (*The use of space*) appears. From the ninth to the fourteenth levels all categories are present. **Figure 4** depicts the centrality for each one of the concepts contained in the categories and subcategories. The polygons are shaped according to the number of concepts per category and subcategory and their centrality. Thus, one of the concepts of subcategory *A-B-C* (*Protected and non-protected ecosystem remnant*) presents the highest centrality while the lowest are for two concepts within category *B* and one of category *C*.

The category *C* is highly connected to almost all of the categories (**Figure 5**), while the category *A* has the lowest percentage of connections (both the number of edges incoming to and outgoing from a node). From the total number of connections (coming in and going out of the nodes), the category *C* and subcategory *B-C* corresponded to 74–89% and 55–60%, respectively. Private relations of a category, that is, those connecting concepts within the same category or subcategory are depicted in brown, and as shown in **Figure 5** a considerable number of such private relations are presented in categories *C* and *B-C*.

The concepts with the highest centrality were *Protected and non-protected ecosystem remnants, Campus population, Governance, More infrastructure, Cars, and Ecological damages* (**Table 2** and **Figure 4**). *Undermining authority, Conflict with personal ambition, Surveillance, Public university, High transient student population, Land fragmentation, Ignorance* and *Lack of information* are the driver concepts, that is, components that influence others. On the other hand, *Damages to human health, Altered movement of animals, Water infiltration, Public safety, Inaction, Native species, and Conflict with authorities* are receiver concepts or those that are affected by others (**Table 1**). The concepts at the end of the discussion of the participatory workshop were weighted up individually (see **Supplementary Material 1**) and the highest score was for the concepts *Protected and non-protected ecosystem remnants* (with 10 points), *Governance* and *Planning* (nine points each) (**Figure 2**). At least for the concepts *Protected and non-protected ecosystem remnants* and *Governance* the highest centrality and the highest weighted score were consistent.

DISCUSSION

The analysis tests three components —scientific knowledge, community interaction with the environment, and managements

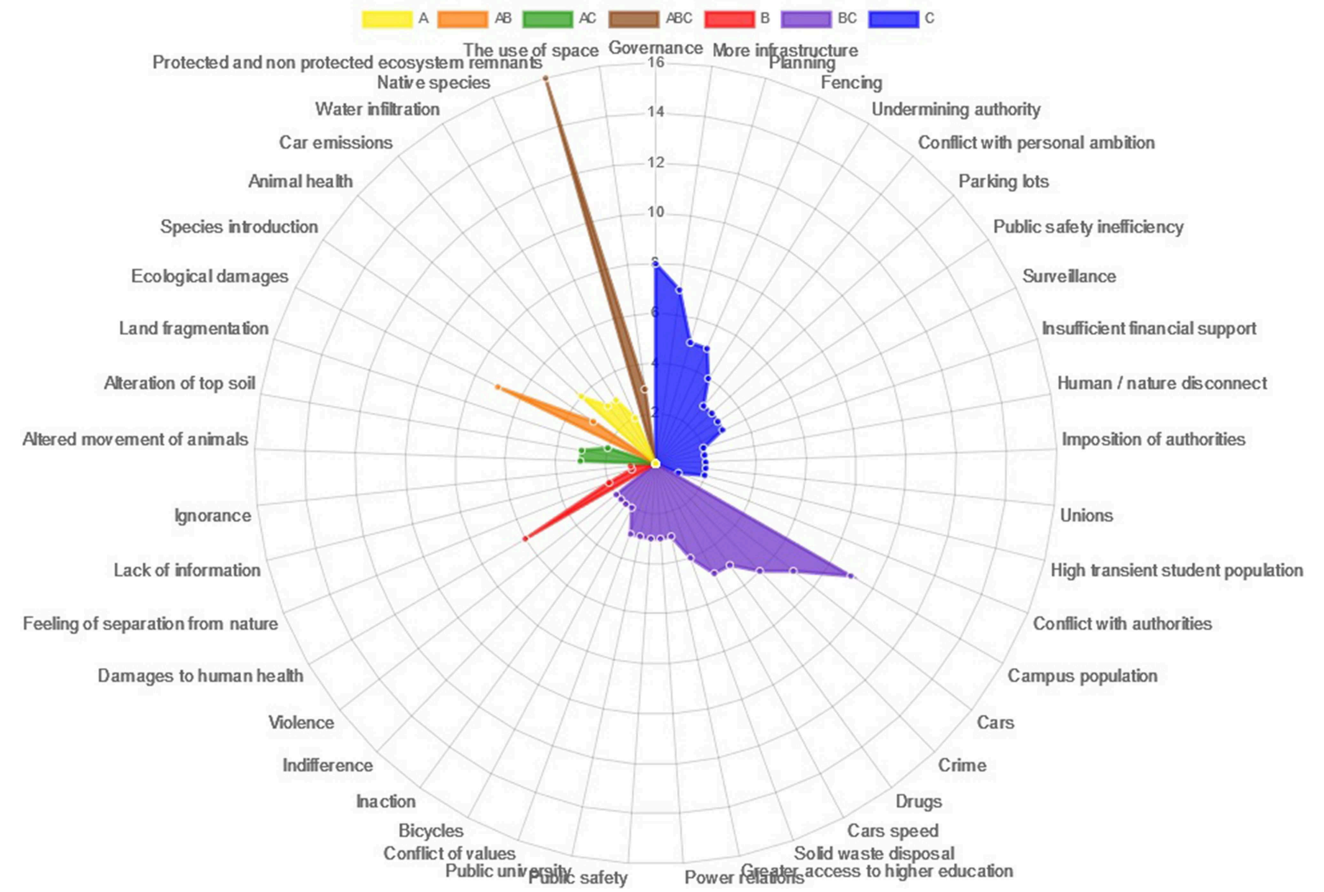

FIGURE 4 | Number of connections for each one of the network components per categories.

decisions—and provides insight into the community perceptions and conflicts between the university campus and the REPSA. There is a prioritization to solve problems in the Reserve, focusing mostly in urban threats. The first seven levels of the network (bottom to top, see **Figure 2**) highlight the urbanization pressure within the campus; showing a society that expects constant growth of the public university. In second place, the main problems are those variables that directly affect the REPSA. The discussion that took place during the participatory workshop and building of FCM revealed that assistants view the campus as being under constant urban pressure; an increase in infrastructure and student population represents a severe threat to the protection of green spaces.

Since the participatory workshop was conducted with similar percentage of participants from each sector (students 40%, academics 36%, and administrators 24%), the power was balanced to hold discussion and dialogue (Barnaud and van Paassen, 2013). Participants were free to express their opinion within the workshop, and the power relations were shown in the mental model. The model—and the moment when it is being built—is unique for the community as it represents a relevant learning experience for participants and detonates the processes of reflection within the group. Nonetheless, participants and executors might validate and use the information in very different ways because each one of the participants has, starting at the same mental model, a particular analysis according to individual interests and concerns. Planning formulas (another of the more weighted concepts), can help absorb complications and disputes if conducted with a long-term vision under a proper institutionalization and balance of power to reduce short term individual actions (e.g., Puchet-Anyul, 2010; Puchet-Anyul et al., 2013).

Several methodologies have been developed to meet different needs in participatory approaches (Voinov et al., 2016), thus, results might be different based on the methodology employed (Jordan et al., 2018). We used FCM to represent a group mental model, nonetheless, as this approach takes a large-scale view of the world (Giabbanelli et al., 2017) methodological limitations dealing with the complexity of a particular problem are recognized (Jordan et al., 2018). In contrast, Agent Based Modeling, with a micro-level view technique (each entity or agent is represented) can be adopted and used in combination with FCM (e.g., Giabbanelli et al., 2017) to obtain an accurate socio-ecological interaction model. As for our study, we found that

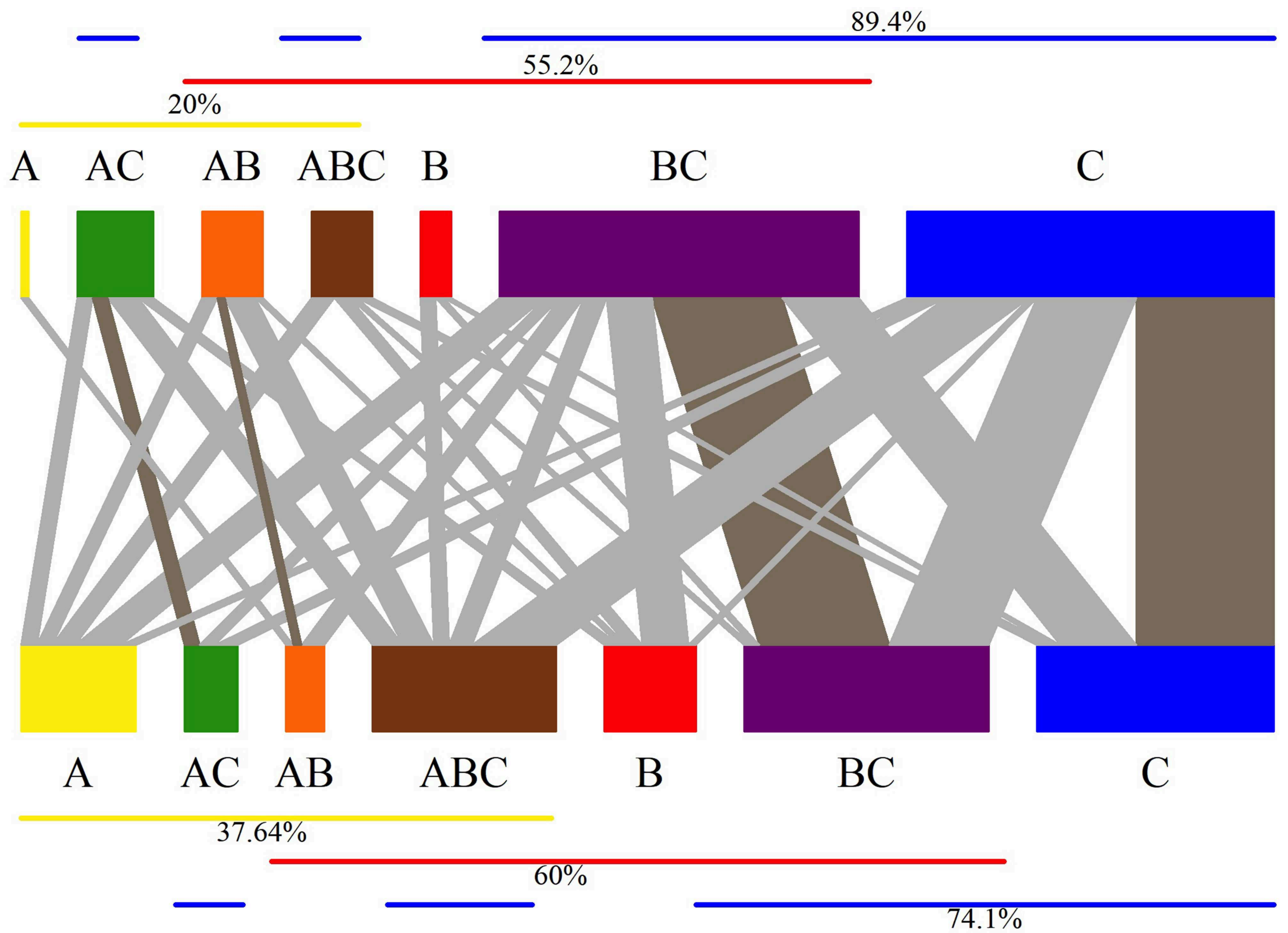

FIGURE 5 | Proportion of connections within and between categories. Darker lines correspond to unique connections or those linking components from the same category.

the FCM approach was useful to evaluate areas where conflicts around the reserve and the university campus occur.

When the concepts of the FCM were classified within the three components, surprisingly there were only two that fell in the intersection: *Protected and non-protected ecosystem remnants* and *The use of space.* The first one, with the greatest centrality, would support our central idea that the intersection of the three components is essential. Nevertheless, this concept does not have any management implication as it only refers to the conserved area. Likewise, REPSA benefits (such as ecosystem services) are not displayed here or in the rest of the model.

The FCM suggests that some reasons why this interaction is reduced are: (i) the lack of feedback links among actors, and (ii) a mismatch between conservation objectives and actual projects generated to preserve the Reserve. The absence of a concept related to scientific generation and the presence of concepts such as *Ignorance*, *Indifference*, *Imposition of authorities*, and *Conflicts with authorities* suggest a lack of feedback on the most important interaction between knowledge generation and management decision.

The lack of links among actors is partially based on the poor communication regarding the importance of the ecosystem services and the biodiversity inhabiting PUGS. Other factors related to the perception of the local community, including academics working on its ecological understanding and authorities that are responsible for the protection of these urban ecosystems, seem to be relevant in the decision process. The mismatch arises from the low number of connections that the ecological scientific knowledge component (Category *A*) has in the FCM. Even at the university, this lack of inclusion of current scientific knowledge in management and conservation programs is as common as in the rest of urban societies (Kim and Byrne, 2006). Some projects fail partially because they are justified under a particular research interest instead of management needs. Also mono-disciplinary scientific research is unable to solve problems in socio-ecological systems for these require interdisciplinarity and transdisciplinarity (Lélé and Norgaard, 2006; MacMynowski, 2007). The lack of feedback loops may generate a spiral of apparently impossible-to-solve conflicts, as well as discontent and general discomfort across sectors coupled with discomfort that falls on individuals rather than institutions.

These conditions can be seen in several examples in REPSA. A first example that shows the lack of feedback links was the elimination of the *Eucalyptus* populations in the Reserve, which generated a series of expressions of disapproval and protests against deforestation by the community. The weak feedback links came from the authorities since a communication channel did not exist to explain the ecological damages being caused by the presence of exotic flora (Segura-Burciaga and Martínez-Ramos, 1994; Segura-Burciaga, 2009). There was no explanation of the importance of their removal or the positive environmental outcomes that accompanied such actions (Segura-Burciaga and Meave, 2001; Antonio-Garcés et al., 2009). The response to these eradication programs by groups of the society is clearly in defense of eucalyptus. Same problem applies to a more recent feral dog eradication program.

Weak feedback links can be seen in a second example based on the efforts made by the academic community to generate information that contributes to educational programs or strategies that promote that the whole community understands and supports the protection of lava relicts surrounded by buildings and roads. The adoption and restoration of a remnant lava field by the Geosciences community called "Geopedregal" (González et al., 2016) succeeded in promoting the conservation and geo-heritage identity, but only at the local community level, and this effort is not acknowledged for larger decisions regarding land use on the campus or for receiving long-term support.

Likewise, the complexity of the misinformation cannot be solved only with informative programs. It is necessary to create a web of connections between components *A* and *C*. There is abundant scientific information produced under robust analysis that can be easily accessed by the community; however, none of it is used in the decisions regarding new constructions, placing fences, and gardening. The application of scientific knowledge requires additional work that facilitates the understanding of authorities to make informed decisions.

One of the examples of the mismatch is based on the monitoring program of several species that provided relevant knowledge on how these species use the reserve, as well as their population and seasonal dynamics (Ramírez-Cruz et al., 2018, 2019). This includes ecological interactions among species and the diverse impacts of humans. These efforts have to be continued to understand ecological interactions in the long-term. Nevertheless, constant monitoring is not considered by funded programs of the Reserve.

Other examples show the mismatch between conservation objectives and the projects in REPSA. There is a social cartography study that aims to understand the time spent by the inhabitants within an area, where these are distributed, and their environment. Results are visualized by mapping territory use by individuals (Fox, 1998; Vaughan, 2018). This information is valuable to decide the land use of the campus and the importance of green spaces and the Pedregal ecosystem, but it is not used for management. This constantly happens when decisions are made without considering the scientific information about land conservation, the genetic diversity, species richness, and the ecological interactions in the long-term. Both projects are part of the responsibilities of the authorities and could be used to evaluate the efficiency of actions taken on *A*, *B*, *C*, and their intersections, but are not used in any of the management programs.

PUGS can be seen as a common resource having different dynamics for their management. An approach for proper management is based on the community's appropriation of the area, thus ensuring that the whole community will protect it (Ostrom, 1990; Matson et al., 2016). In this situation, it is paramount that the community is informed with clear mechanisms of decision and that most members reach an agreement. Decisions must be based on the integration of the new information generated by the community itself (Cook, 2008). Our results suggest this is not happening partly because the scientists should improve the communication strategies (Raymond et al., 2010; Safford and Brown, 2019), monitoring the adequate integration in the conservation programs. Nonetheless, reverting this situation is possible. The constant cooperation and learning between researchers—an important condition to develop innovative research— is key for an organization (Buanes and Jentoft, 2009), an idea that is entirely applicable to PUGS management. Systematic monitoring of the long-term effects of invasive species, acid rain and atmospheric deposition of residues, and species prioritization for conservation plans (Arponen, 2012; Lindenmayer et al., 2015; Wright et al., 2018) must be properly communicated to generate a reaction from different actors. Likewise, the assessment of the ecosystem services provided by the REPSA should be made public. Profitable management of the Reserve depends on the active engagement of several actors as well as a supportive university governance.

Importantly, the model revealed that the REPSA management is only focused on administrative activities. Technical profiles only focus on solving management and administrative problems, without time, or funds to generate or apply academic information for management. Nonetheless, the mismatch can be solved by taking actions directed to specific fields, that is, actions directed to well-localized high-pressure points, for example *More infrastructure* near the base of the FCM and *Governance* in the middle of it (see **Figure 2**). By changing the negative edges to positive ones, the structure of the network will modify the whole FCM by establishing priority actions related to management based on scientific knowledge. This would possibly improve the system's internal management and sustainability.

To modify the interactions based on the FCM, a variable that must be included should be the institutionalization of the reserve management. Even though the reserve operates under specific guidelines that are part of the internal regulations of the Technical Committee of the Ecological Reserve of Pedregal de San Ángel (Gaceta UNAM, 2006), it lacks institutionalization processes for scientific knowledge. There is no liaison group or committee that functions as organizer and facilitator with capacities of linking the great amount of scientific information accumulated about social-ecological systems to the operational groups as well as to other researchers and the general public (Castillo et al., 2018).

The intersection of the three components only had the two concepts *Protected and non-protected ecosystem remnants* and *The use of space*), the first one was highly connected but it does not imply management or applied scientific knowledge. In this particular case, our assumption about the intersection does not apply because the interaction is not naturally given, and even in this university community these interactions do not guarantee the management and conservation goals. Further studies that aim to accomplish this will be developed within the REPSA.

The complexity of the protected urban green spaces in terms of their dynamics within the city requires to actively build the collaboration among actors to reinforce the three components (scientific knowledge, community interaction with the environment, and management decisions).

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

AUTHOR CONTRIBUTIONS

LZ, ZC-S, and AC participated in the design of the project. LZ coordinated the study. AW and DA-L participated in the design of the participatory workshop and the analyses of the mental model. LZ, AW, and DA-L wrote the manuscript. The rest of the authors attended the workshop, included relevant information within their areas of expertise, and reviewed the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2019.00144/full#supplementary-material

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The Consequences of Landscape Fragmentation on Socio-Ecological Patterns in a Rapidly Developing Urban Area: A Case Study of the National Autonomous University of Mexico

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Fragmentation of natural landscapes during urbanization processes has been well-linked to biodiversity loss and changes in ecological and ecosystem function. Fragmentation can also have profound effects on provision of ecosystem services and on human social dynamics and well-being within cities. The ways in which ecological, ecosystem service, and social factors and the interactions among these are affected by fragmentation is not well-studied. Understanding these relationships is particularly important in cities where high densities of human population create intense and dynamic interactions within green spaces. Using the rapidly developing campus of the National Autonomous University of Mexico (UNAM) in Mexico City as a case study, we examine the effects of natural area fragmentation over time on ecosystem services, human well-being, and biodiversity. We compare fragmentation of the campus natural areas between 1954 and 2015 to non-native plant species distribution maps, models of water infiltration, and mobility and citizen-science data. We found that the loss and fragmentation of the campus's natural areas has had varied effects on ecosystem services, and negative effects on human well-being and biodiversity. The relationships between fragmentation and ecosystem services depends on the ecosystem service being measured; water infiltration was negatively impacted by fragmentation but engagement with biodiversity was greatest in areas with a mix of natural and urban land covers. Our human well-being variable, mobility (the average travel time within the campus of walkers, bicyclists, and cars), was negatively affected by fragmentation. Walkers and cyclists spent significantly more time traveling across campus in 2015 compared to 1954. Finally, the most fragmented areas of the campus's natural areas support large populations of invasive exotic species, indicating negative effects of fragmentation on biodiversity. Although campus urban development is necessary for supporting the academic community at this growing university, we suggest a renewed focus on sustainable campus development in which land sparing in emphasized; connecting instructional, research, administrative, and other campus facilities within urban clusters and providing sustainable transport systems. Thus, eliminating further loss and fragmentation of the natural areas on campus, supporting both human well-being and the unique biodiversity of the region.

Keywords: biodiversity, ecosystem services, human well-being, iNaturalist, landscape fragmentation, university campus planning, urban development processes

INTRODUCTION

Urban landscapes are rapidly expanding around the world and one major consequence of the urbanization process is the loss and fragmentation of natural areas. Fragmentation, from large continuous natural areas of relatively undisturbed vegetation to small, increasingly isolated patches of natural land cover, has significant negative effects on ecology, ecosystem function, and human well-being (Savard et al., 2000). The ecological effects of fragmentation are primarily negative on all taxa and have been well-documented, ranging from habitat loss, reduction in species richness of plants and animals (Collinge, 1996; Haddad et al., 2015), alterations to life-history dynamics, dispersal, social systems, metapopulation dynamics, and species interactions to population decline and regional extirpation (Fischer and Lindenmayer, 2007). Ecosystem processes such as nutrient cycling and productivity are also reduced compared to connected landscapes (Haddad et al., 2015), often resulting in diminished ecosystem services provision (Mitchell et al., 2013). The consequences of habitat fragmentation on human well-being are less well-studied, and relatively unknown in urban areas.

It is well-established that human health and well-being are positively influenced by nature, and specifically, biodiversity, in urban areas (Sandifer et al., 2015). Urban development processes, particularly landscape fragmentation, threaten human well-being by reducing the amount of green space in cities as well as the provision of ecosystem services. The importance of urban greenspaces for human physical and mental health has been well-established (Di Giulio et al., 2009) and city planners are utilizing these human health connections to justify increases in parks and other green spaces in cities (Ayala-Azcárraga et al., 2019). However, human well-being may also be threatened by fragmentation in ways unrelated to nature access and ecosystem services. Most work in this realm has examined the effects of roads and traffic on humans, finding that roads and traffic decreases pedestrian movement and divide human communities, limiting interaction and social cohesion (Di Giulio et al., 2009). Additionally, planning focused on car travel often results in sedentary lifestyles, increasing rates of depression, obesity, and heart disease (Sandifer et al., 2015). No studies, to our knowledge, have specifically linked habitat fragmentation to human well-being in urban landscapes.

In cities, the ecosystem services framework has been used to determine the value particular urban ecosystems or habitats offer people and in some cases, has provided an important foundation for decision-making and urban planning (Elmqvist et al., 2015; Nilon et al., 2017; Saarikoski et al., 2018). However, we do not well-understand the links between fragmentation and ecosystem services (Mitchell et al., 2013, 2015). Recently, Mitchell et al. (2015) proposed a conceptual model to explain the probable effects of fragmentation on ecosystem service flow and provision. They propose that relationships among ecosystem services and fragmentation are influenced by the spatial configuration of the landscape (interspersion, isolation, patch size, edge, etc.), the particular ecosystem service in question, and the mechanisms by which that ecosystem service is provided (organism mobility, energy, matter flow, etc.). Thus, the relationship between fragmentation and ecosystem service provision can be negative or positive, linear or non-linear. For example, in a modeling scenario, Chaplin-Kramer et al. (2015) found that the effect of fragmentation of forest landscapes on two ecosystem services differed depending on the type of ecosystem service and the type of fragmentation. Carbon sequestration and biodiversity differed in their responses to agricultural expansion into edge or core forest habitats (Chaplin-Kramer et al., 2015), but both ultimately had a negative relationship with fragmentation. Changes in ecosystem services due to fragmentation can be more intense in urban regions, due to the limited green spaces remaining and greater densities of people relying on these services (Elmqvist et al., 2015). Additionally, the speed and number of people interacting with urban green spaces increase the importance of understanding the effect fragmentation has on ecosystem services provided in cities.

In order to plan and design cities as resilient social-ecological systems, we need to understand the influence of fragmentation processes on not only biodiversity but also on the provision of ecosystem services and on human well-being in cities. While conceptual frameworks have been presented that hypothesize the possible relationships between fragmentation and biodiversity and ecosystem services (Mitchell et al., 2015), very few studies have actually used empirical data to examine these relationships and none, that we know of, have presented the relationships between fragmentation and human well-being not related directly to ecosystem services. Here, we present a case-study examining how urban planning generates relationships among landscape fragmentation, biodiversity, ecosystem services, and human well-being at the main campus of the National Autonomous University of Mexico (UNAM), in Mexico City. Understanding the effects of fragmentation will help to generate knowledge on how ecosystem services and human well-being in urban green spaces are modified during the urbanization process, leading to better management and planning policies in cities.

METHODS

The National Autonomous University of Mexico (UNAM) is the oldest university in America, established in 1551, when the Universidad Real y Pontificia was founded in Mexico City (Coll-Hurtado and Aclántara, 2011). Most of its campus was scattered around the city center in antique colonial buildings, until 1954, when the university moved to its current campus south in which those days was the edge of the city, after two decades of searching for an area large enough to establish the University (Morales Schechinger and García Jimenez, 2008). The area for the establishment became a challenge for development because it was on a lava stone ecosystem—*Pedregal*—generated from the Xitle volcano eruptions 1,600 years ago (Carrillo-Trubea, 1995). These eruptions covered close to 80,000 ha of lava in what is now the southern part of Mexico City (Delgado et al., 1998). After the volcano, a new ecosystem developed along the different type of rocks and cracks. This ecosystem is relatively young and consequently there is very little soil formation (Estañol-Tecuatl and Cano-Santana, 2017), which has generated a highly diverse xerophytic shrubland community (see **Annex 1**; de Rzedowski and Rzedowski, 2001; Cano-Santana et al., 2008). This fractured rock landscape is important for ground-water recharge; almost all precipitation infiltrates to a shallow aquifer encompassing the southern part of the city (Canteiro et al., 2019).

The total area given to the UNAM was 723 ha, but at the beginning the campus was established in <100 ha. Plans in the first decades after 1954 were to use the rest of the campus area to lend buildings to the government (Morales Schechinger and García Jimenez, 2008), but an academic/student protest helped to generate a reserve within the University (García Barrios, 2014) and the Ecological Reserve of San Angel Stone System (REPSA, as it stands in Spanish), was established in 1983, consisting of 124 ha, and is currently 237 ha. However, the existing reserve is highly fragmented by streets, buildings, and other facilities that fragments the once continuous lava stone shrubland ecosystem. The reserve has three core areas divided by wide and highly used roads and highways, and 17 isolated patches that are smaller and more isolated than the core areas. The surrounding parts of Mexico City have also undergone rapid development. Consequently, the REPSA is the last remnant of the *Pedregal* ecosystem in the city.

Building locations from 1954 to 2010 were digitized based on Coll-Hurtado and Aclántara (2011). Data representing 2015 was digitized from an orthophoto obtained from the Geography Institute at National University Autonomous of Mexico. We categorized different types of urban land use: (1) buildings (any type of construction that holds facilities); (2) roads; (3) parking lots; and (4) sports facilities (any court or fields utilized for various sporting activities including: gymnasium, basketball, racquetball, baseball, or football). The rest were considered green spaces, which included gardens and preserved areas. We also gathered data from General Direction of Planning UNAM (Dirección General de Planeación), to evaluate the population growth (student, academics, and workers) of the campus since it was established in 1954.

The fragmentation analysis was generated using "Landscape Fragmentation" (Center for Land Use Education and Research, University of Connecticut), installed in Spatial Analyst ArcGis 9.2. This extension is based on analyses in which fragmentation patterns in the landscape are based on the Morphological Image Processing of a binary image classified as: Forest—No forest (in this case Vegetation—No vegetation), maps algebra and analysis window of 8 × 8 pixels (Vogt et al., 2007). As a result, we categorized the landuse/landcover into five categories, urban land use (as described above) and four fragmentation natural land cover categories: (1) core, which are preserved areas that were either larger than 100 ha (large core shrubland) or smaller than 100 ha (small core shrubland); (2) perforations, perforated shrubland/urban areas within core areas that represent a urban-developed hole in the continuous vegetation generating edge effects, including paths within core areas; (3) edges, which were defined as the border between core areas and other categories, size in this category depends upon the resolution of the analysis, in this case, 10 m width; and (4) patches, which are small areas, smaller than any core areas, that are isolated from any other natural area, and are subjected to large edge effects. We divided the campus area into 1-ha hexagon units, in which the proportion urban land cover and each of the four fragmentation categories were classified. To test if these land use/land cover categories changed in area over time (1954–2015), we used a repeated measures ANOVA in R.

We evaluated the relationship between fragmentation of the campus natural areas and ecosystem services, human well-being, and biodiversity. The ecosystem services (ESS) we examined were water infiltration (provisioning ESS; TEEB, 2011) and biodiversity engagement (cultural ESS; TEEB, 2011). The biodiversity variables we examined were exotic species invasions, and the human well-being variable we examined was mobility (or movement across campus). Since these ES have different responses and a diverse availability of historical data, each had a particular temporal and/or spatial analysis.

In order to predict the effect of landscape fragmentation on water infiltration, we examined the water infiltration capacity of the campus landscape using three scenarios. Water filtration is reduced with increasing urban land cover (Zambrano et al., 2017). Therefore, we first modeled the effect of land use change on water infiltration capacity. Land use change was measured as the hectares that was converted from natural area to urban land use and natural area to anthropogenic green space (grass playing fields and managed gardens) between 1954 and each time point thereafter. In the land use change scenario, we assumed 0% infiltration in urban land uses, 50% in anthropogenic green spaces, and 100% in natural areas. Infiltration capacities were based on land use obtained from Zambrano et al. (2018). The assumption of the null infiltration in urban areas is based on the impermeable soil that was used as fill during construction in order to level the area for infrastructure (buildings, sewage, roads, sidewalks). This assumption was also made because it is common to have floods in lowlands of the campus and adjacent areas during storm events (Zambrano et al., 2018), because of saturation of the

TABLE 1 | Scenarios with different percentages of water infiltration based on capabilities of each fragmentation category to infiltrate rainwater to the aquifer.

	Urban	Perf	Patch	Edge	Small core	Large core
Scenario 2	0	100	100	50	100	100
Scenario 3	0	20	60	50	80	100

100% represent the largest infiltration capacity in these conditions. Perf, perforation.

sewage system, proving the very low infiltration capacity of this category.

There are variables related to infiltration other than precipitation and urban land use, such as temperature, vegetation coverage, and soil (Mohammad and Adam, 2010; Green et al., 2011; Schosinsky and Losilla, 2011; Neris et al., 2012; Wang et al., 2013), but their relative importance to infiltration is not well-known and controversial (Green et al., 2011). However, there is much evidence that these variables change across fragmentation categories (Saunders et al., 1991). Therefore, we modeled the infiltration capacity of the campus using two scenarios by modifying the infiltration capacity of each fragmentation category with assumptions based on the literature (**Table 1**). The first scenario assumes that the rainwater in the "urban" category flows directly to the sewage system (0% infiltration); half of the water in the "edge" category infiltrates (50% and the other half goes to the sewage system; and the rest of the fragmentation categories have 100% infiltration. We assumed that the soil of the other categories have 100% infiltration because the soil of the preserved areas is based on lava stone ecosystem, which has a hydraulic conductivity between 10^{-2} and 10^{-7} m/s (Freeze and Cherry, 1979). This is higher than any soil in the area (Walker, 1993). Because the vegetation communities in the preserved areas is xerophytic, the vegetation cover is low; therefore, with low rates of evapotranspiration. Soil characteristics in perforations are similar to urban category, because they experience compacted soils that make them impermeable. Because perforations are urban land use in the middle of natural areas, the rainwater that falls in perforations results in runoff to the lava soil of the natural areas.

The second scenario modifies those categories that were considered 100% infiltration, assuming that temperature plays an important role in the infiltration and will vary within each fragmentation category. Water that falls in the perforation category, for example, may have higher evaporation rates, because it spends a longer time on surfaces. Therefore, we considered that 80% of the water is lost in this category based on evaporation rates. Patches are surrounded by urban areas with lower vegetation coverage, leading to higher temperatures and higher evaporation rates. The same principle applies for smaller core areas, but with lower temperatures and consequently a higher rate of infiltration. These scenarios are hypothetical and based on the uncertainty of the importance of the size and other effects on infiltration capacities of green spaces. We then plotted the infiltration capacity of the campus in 1954, 1970, 1980, 1990, 2000, and 2015 based on the area of the campus within each land use and fragmentation category.

To examine biodiversity engagement on the UNAM campus, we used iNaturalist (https://www.inaturalist.org/) to evaluate the number of observations recorded in each 1-ha unit. Observations included records of any species of plants (mostly angiosperms, as flowers are an attractive attribute) and animals (mostly insects, birds, and mammals). We then plotted the number of observations in response to percent urban land cover and each of the four fragmentation categories for 2015 only to examine how biodiversity engagement differs across land use/land cover. Most of the 1-ha units in which the campus was divided had <5 observations, therefore we focused our analysis on 1-ha units with more than 20 observations.

For mobility within the campus, we consider that urban planning is highly related to mobility needs. Therefore, moving a school modifies the fragmentation of the area and the mobility of many students and staff faculty around the campus. We used an accessibility model based on friction surfaces, type of transport infrastructure, and a target location, based on Farrow and Nelson (2001). Target locations were seven schools that have been moved around the campus since it was established: Schools of Philosophy, Science, Political Sciences, Veterinary, Engineering, Administration, and Postgraduate facilities. We measured the time spent traveling from their schools to the main building of the campus, using cars, bicycles, or by walking. We used R version 3.53 for a paired *t*-test to evaluate differences in traveling time.

To examine the relationship between fragmentation and biodiversity, we used shapefiles of the distribution of two exotic plants within the campus based on Lot et al. (2012): trees in the genus *Eucalyptus* (particularly *E. globulus*) and the grass *Pennisetum clandestinum.* We then compared the distribution of these exotics to the fragmentation of 2015 only. We used the same 1-ha units to examine the correlation between percentages of exotic cover and percent urban land cover and each of the four fragmentation categories.

RESULTS

The campus has undergone a large transformation since its establishment in 1954. New building construction has been dispersed across the entire campus area and not concentrated (**Figure 1**). Concurrently, population growth within the University has increased (**Figure 2A**). All of the different urban land use types have increased in area since 1954, but the area of buildings in particular surpassed parking lots, streets, and sports, indicating a densification of buildings (**Figure 2B**).

In the first three decades (1954–1983), many schools and facilities moved from the central campus to other regions in the campus, resulting in a landscape of scattered buildings and parking lots. This type of urban development resulted in fragmentation of the natural areas on campus (**Figure 3**). Statistically, all categories in the fragmentation classification changed with p-values below 0.001 among the years and most of these categories showed the important change between 1970 and 1990 (for the statistical analysis, please refer to the table

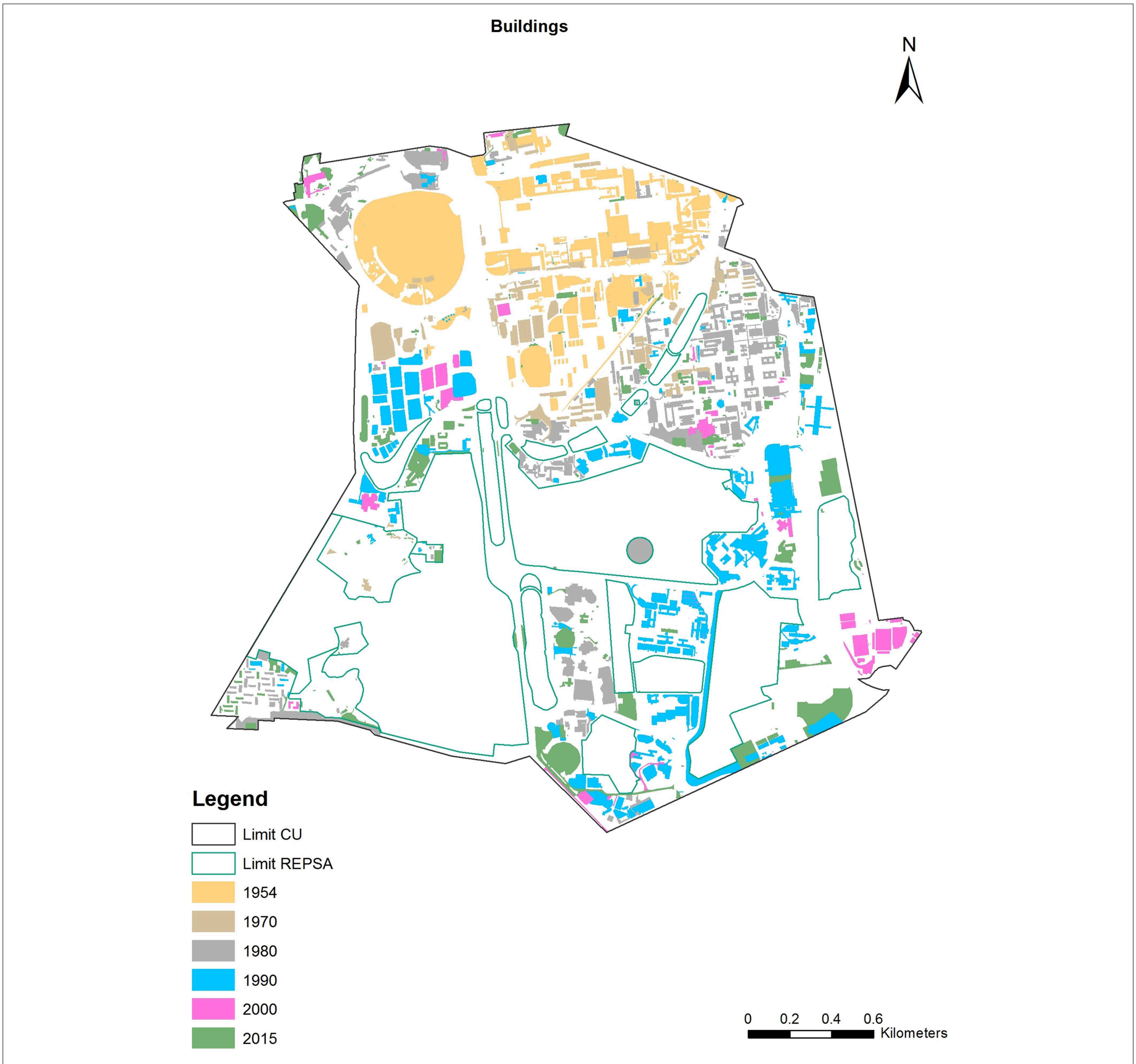

FIGURE 1 | Map of the campus with the new construction from its establishment in 1954–2015.

in **Supplementary Material**). Core areas were reduced, large core areas completely disappeared between 1980 and 1990, as urban areas, small patches, and edges have significantly increased. Patches and perforations show a different pattern, as they are highly dynamic in this type of development, they have slowly increased, and for three decades they have been stable. Furthermore, the dispersion of categories such as urban, perforations, and patches in the campus suggest that fragmentation should generate large modification at different levels of the ecosystem dynamics, and in consequence in the ecosystem services.

Ecosystem Services

Water Infiltration

In the first scenario, considering only land use change, there was a clear reduction in water infiltration capacity across time (**Figure 4**); this reduction corresponds with the urban growth patterns illustrated in **Figure 2**. In all scenarios, the highest infiltration reduction (40%) was during the same time as the most rapid urbanization of the campus. In scenarios 1 and 2, both considering that fragmentation patterns, not just land use change, would affect water infiltration, we found a further reduction in water infiltration capacity (**Figure 4**). All scenarios

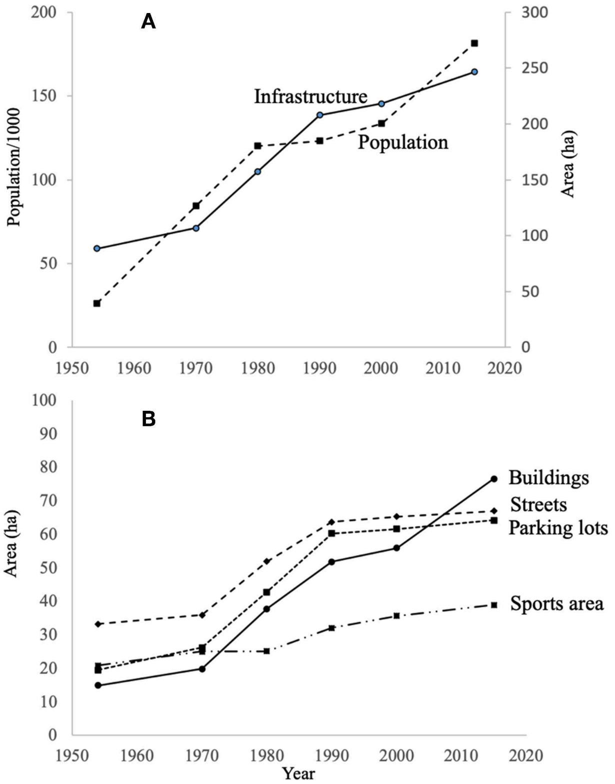

FIGURE 2 | Infrastructure and population of the UNAM campus **(A)** and different types of urban infrastructure growth **(B)** from 1954 to 2015. Population numbers are in thousands and refers to the people (academics, students, and workers).

show a non-linear reduction of infiltration across time. Scenario 2 demonstrated the greatest reduction, where infiltration capacity was at most 60%, due to increases in evaporation compared to scenario 1, in which only urban and edge categories reduced infiltration and the rest of the categories, although fragmented, are capable of infiltrating the total amount of water received.

Biodiversity Engagement

The greatest number of species observations occurred when the urban proportion of any given 1-ha unit was lower than 40%, and the proportion of core habitat between 30 and 50% (**Figure 5**). Additionally, areas with >40% perforations had large numbers of observations. Although, there was also a peak in observations in 1-ha units of ∼100% core habitat and 0% perforations. Therefore, 1-ha units with a mixed proportion of land use/land cover categories had the largest number of observations.

Human Well-Being

There is a clear change in time spent traveling within the campus along years based on the urban planning that generated fragmentation of the campus (**Figure 6**). Traveling by car reduced mobility time ($t = 3.20$; $p = 0.018$), while cycling ($t = 4.02$; $p = 0.007$) and pedestrians ($t = 3.38$; $p = 0.014$) increased almost twice the time of traveling from a school to the main building in the University.

Biodiversity

While urban cover did not appear to be related to exotic plant abundance, other landscape fragmentation categories were closely related to the abundance and distribution of these species (**Figures 7A–J**). The exotic grass, *Pennisetum clandestinum,* abundance was most closely related to cover of perforations (**Figure 7G**); as the proportion of perforation cover increased, so did the cover of *P. clandestinum*. *Pennisetum clandestinum* was negatively related to urban, patch, and edge cover. *Eucalyptus* abundance increased with increasing edge cover (**Figure 7F**). Additionally, *Eucalyptus* cover peaked in areas with between 20 and 50% urban cover (**Figure 7J**).

DISCUSSION

Urban development policies have had direct influences on the fragmentation process since the campus was established in 1954. Some of these policies are related to historical and political trends that the university has been involved. The first urban design suggested a campus planned to avoid any internal movement with cars, considering that most of the students and workers arrived with public transportation. Also, this urban design focused on facilitating the interaction among students and faculty to increase multidisciplinary collaboration and was the answer to separated schools originally scattered across the city center from its foundation (Morales Schechinger and García Jimenez, 2008). However, in the subsequent years, the urban development in which the campus expanded, using the amount of undeveloped area it still had, was the product of three main factors. First, the type of expansion of Mexico City following the international urban development trends of the creation of suburbs and the increment of the use of cars for mobility (Jacobs, 1961). The campus aligned to that type of development, pushing schools and research facilities away from the central areas. Second, those schools that were pushed away were often the ones with larger numbers of student-activists (i.e., political science and sciences students), that were involved in the social movement in 1968 that ended in violence just before the Olympic games. The new distribution philosophy was to reduce interaction among students that could generate further social movements (García Barrios, 2014). Finally, the creation of REPSA along different areas of the campus, leaving scattered areas for development, generated random decision making for placing new buildings (Morales Schechinger and García Jimenez, 2008) and the need of roads and parking lots for each one, to supply the necessities of the gentrified academy able to own a car.

These development processes increased the fragmentation of the large natural areas on campus, which subsequently affected the ecosystem services provided to the campus and surrounding city. The loss of water infiltration, for example, appeared to be highly related not only to the increase of urban land cover over time (Zambrano et al., 2017), but also to fragmentation patterns. Land use change based on urban development is the strongest driver of water infiltration loss. However, our results show that fragmentation, and the size, location, and type of greenspaces, exacerbates the effect of land use change on infiltration, causing

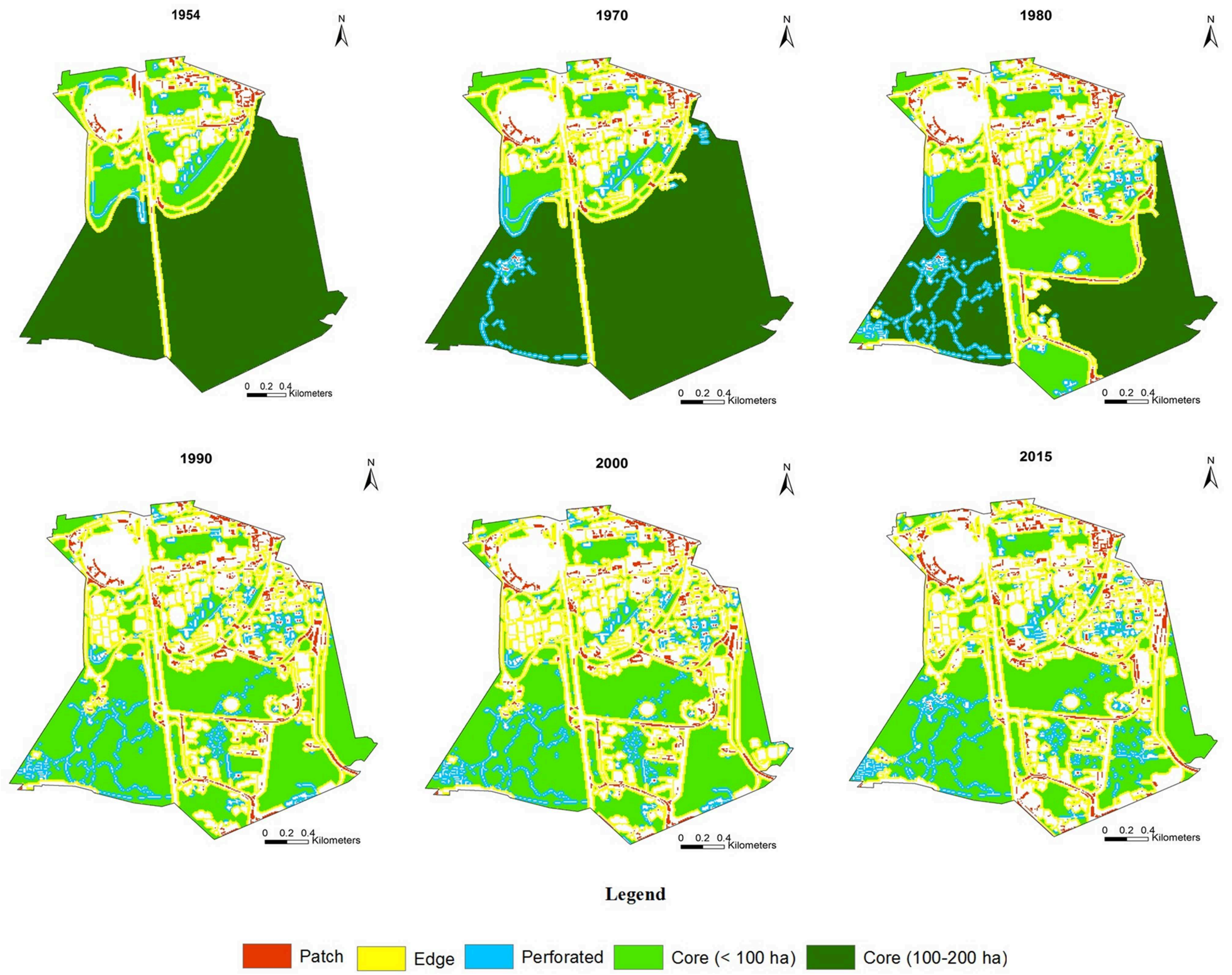

FIGURE 3 | Fragmentation maps of the UNAM campus between 1954 to 2015. For information about the analyses used to generate each category see methods.

a further reduction. Future planning scenarios should consider the ramifications of this loss, preserving large natural areas in order to maintain water infiltration and reduce lowland flooding events. However, future research is needed to consider potential effects of fragmentation on temperature related to local infiltration to confirm or reject these scenarios.

Here we utilized iNaturalist, one of the largest interactive online platforms for recording, sharing, and identifying plants and animals, to measure the UNAM community's engagement with nature on the campus. We found that experience with nature was highest in areas of the campus that have a mix of land cover, indicating that nature engagement may not always be negatively affected by fragmentation. Biodiversity engagement on the UNAM campus was greatest in areas with <40% urban land cover, between 20 and 50% core forest cover, and >40% perforation cover. These are regions of the campus that are on the edges of the core natural areas and that have paths into the natural areas. In fact, the largest number of iNaturalist observations come from the Botanical Garden, which acts as a gateway to trails that traverse the core forest areas on the western side of the campus. University and public community members use these trails and the less remote portions of the natural areas when engaging with nature. Online platforms such as iNaturalist and others (e.g., eBird), have been primarily used for citizen science, such as determining distributions of particular species or groups of species (Sullivan et al., 2014). They have not, to our knowledge, been critically used to measure engagement and the ways in which people engage across different land uses. Data such as these can help us manage and plan natural areas in cities by understanding where urbanites are most likely to engage with nature in the city and where to focus programming to increase education and stewardship.

Urban planning leading to fragmentation effects on mobility is a phenomenon that must be reviewed from the historical perspective mentioned above. As the interactions among students from different schools were to be avoided (García Barrios, 2014), fragmentation has been produced by infrastructure mainly for cars. Routes for cycling and pedestrian were not considered,

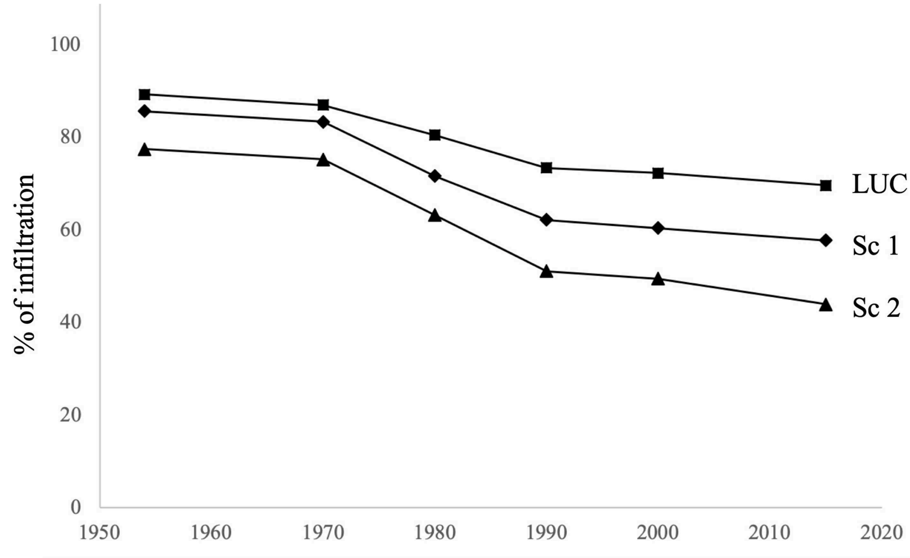

FIGURE 4 | Rainwater infiltration capacities reduction based on LUC across years and hypothetical scenarios, considering fragmentation. Squares represents infiltration changes of infiltration based on land use change (LUC). Rhomboid show first scenario based on fragmentation data (Sc 1) in which urban category reduces its infiltration capacity with edge effect, and the rest of the categories have the highest infiltration rate. Triangles show the second fragmentation scenario (Sc 2) in which edges and perforations also have a reduction in the infiltration rate. See text for specific considerations of each scenario.

and only recently a policy for better cycling routes, but not for pedestrians, has been implemented (many streets do not even have a sidewalk for pedestrians). Roads without sidewalks or cycling infrastructure were built fragmenting all the green spaces. Public transport is also deficient and therefore only cars prevail using this infrastructure. This has produced a large modification of social interactions within the campus (Sheller and John, 2000), making a campus more car dependent with negative social consequences (Kenworthy and Laube, 1999). One of the consequences of increased cars on campus has been traffic jams and scarcity of parking lots, both within the campus. The time spent looking for parking or in traffic is not included in our study of mobility. Therefore, time spent may well have increased for cars over time, in addition to walking and bicycling.

More than 75% of the population (mostly students and workers) within the university move by walking, public transportation, or cycling. If they have to move among buildings at different regions of the campus, they could spend more than 70 min in this activity. Moreover, in the last 5 years, fences have been built in some pedestrian paths as a response of insecurity of some areas of the campus. These fences, surround many areas that could be crossed directly previously, have increased traveling times for pedestrians (pers obs). Therefore, fragmentation based on car mobility influence influenced human well-being in this particular case as happens in cities with fast urban expansion (Travisi et al., 2010; Zhao, 2010; De Vos and Witlox, 2013).

Prevalence and abundance of invasive exotic species are often used as an indicator of biodiversity loss (Butchart et al., 2010). Two metrics of fragmentation were most closely related to exotic species invasions: perforations and edges. Abundance of *P. clandestinum* increased with increasing perforations in the landscape. *Pennisetum clandestinum* is an invasive C4 grass, native to Africa, that is highly drought tolerant (Williams and Baruch, 2000). This species is also shade intolerant (Funk and McDaniel, 2010) and most often found at forest edges, where it spreads rapidly into newly cleared areas via vegetative spread (Wilen and Holt, 1996; Williams and Baruch, 2000; Steffen et al., 2011). At UNAM, *P. clandestinum* is often found along the paths and cleared areas in RESPA. Over time, perforations have increased (**Figure 3**), facilitating the spread of this invasive grass. *Eucalyptus*, on the other hand, was associated with edge habitat on the campus and does not as readily invade the core habitats. Other studies have found that *Eucalyptus* is primarily restricted to edges (Calviño-Cancela and van Etten, 2018), indicating that this species may be less likely to invade the core habitats of RESPA. However, where *Eucalyptus* has invaded, it likely has altered hydrology and nutrient cycling (Dukes and Mooney, 2004), as well as reduced native species establishment (Zhang and Fu, 2009). These data suggest that we can expect more invasions as the campus natural areas continue to be fragmented, and edge effects increase due to both increases in edges and perforations.

One of the most important consequences of the development process at the UNAM was the fragmentation of core natural habitat. In only a decade, between 1980 and 1990, the largest core natural areas of over 100 ha in size were lost. Although we do not have historic biodiversity data, this loss of these largest core habitats, followed by further loss of additional core habitat <100 ha, has important consequences for regional biodiversity. As Mexico City has undergone rapid urbanization, REPSA is one of the only remaining lava stone ecosystems in the region, making it an essential refuge for the plants and animals indigenous to this system (Ramirez-Cruz et al., 2019). The reserve continues to

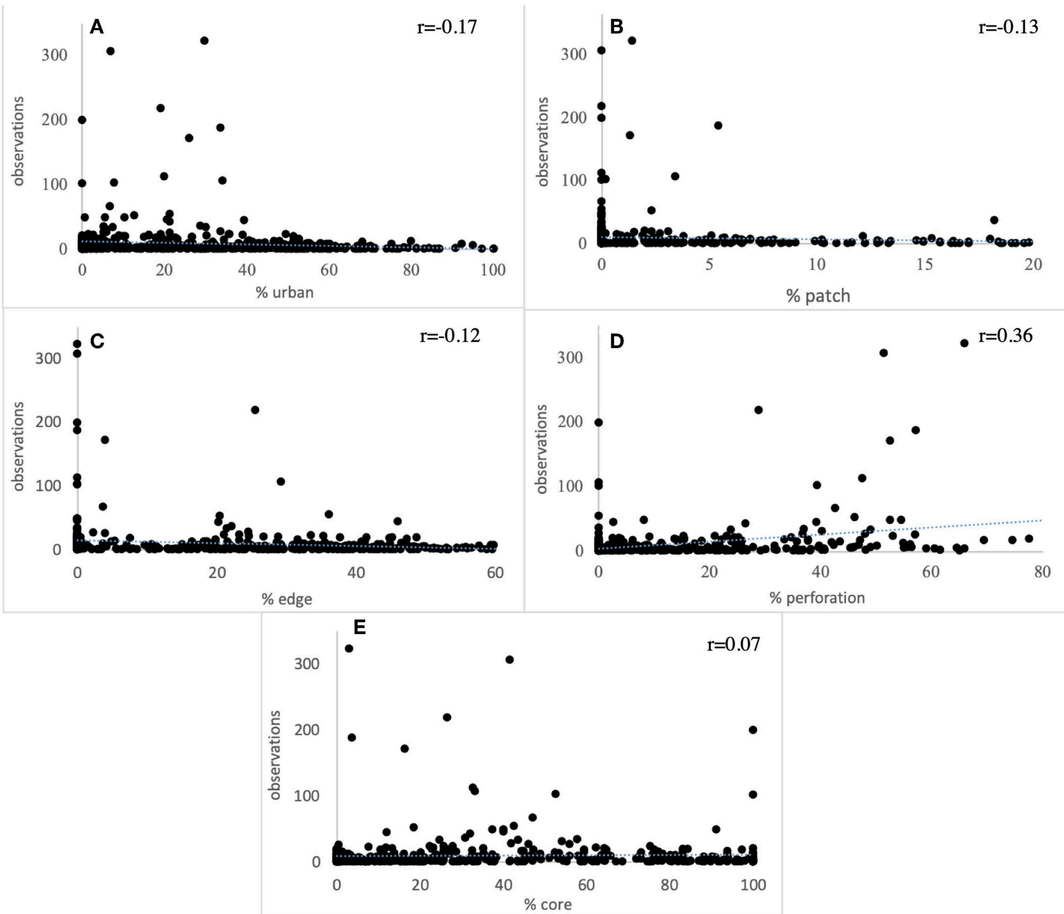

FIGURE 5 | Number of iNaturalist observations compared to **(A)** % urban land cover, **(B)** % patch land cover, **(C)** % edge habitat, **(D)** %perforations, and **(E)** % core habitat in each 1-ha unit.

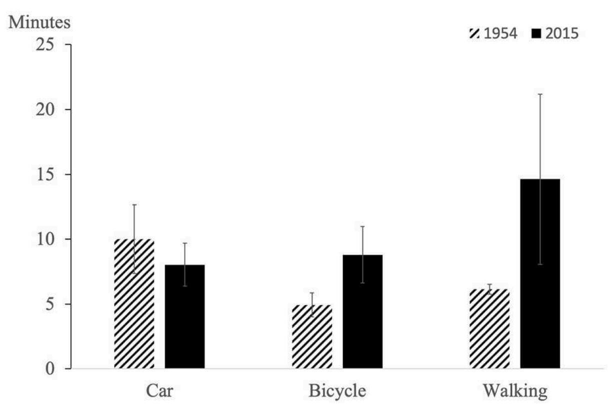

FIGURE 6 | Time spent traveling from schools and other facilities to the main university building in 1954 and 2015. Error bars refer to standard deviation.

be threatened by urban development, human use, edge effects, and invasive species. Managing this landscape to reduce these impacts is imperative to preserving the unique natural history of the region.

For the last 30 years, the rapid campus development has led to conflicts between ensuring conservation of the natural areas and infrastructure needs of the University, leading to discussions among parties whenever new urban development is proposed (Zambrano and Cano-Santana, 2016), as has happened in the rest of the city (Calderón-Contreras and Quiroz-Rosas, 2017). These process, and other factors described above, have led to haphazard development of the campus and construction of campus buildings and other facilities that do not follow the existing master plans. Our results here support the idea that fragmentation promotes different responses in ecosystem services. For this reason, the importance of developing, following, and adapting a comprehensive master plan for a sustainable and resilient campus. Ideally, one in which land sparing is emphasized, as well as connecting instructional, research, administrative, and other campus facilities in dense urban clusters and sustainable transport planning, focusing on walking, bicycling, and public transport (Balsas, 2003). These factors have been shown to lead to better retention and graduation rates, because of positive student experiences (Hajrasouliha, 2017). Additionally, when land sparing is emphasized, biodiversity and ecosystem services,

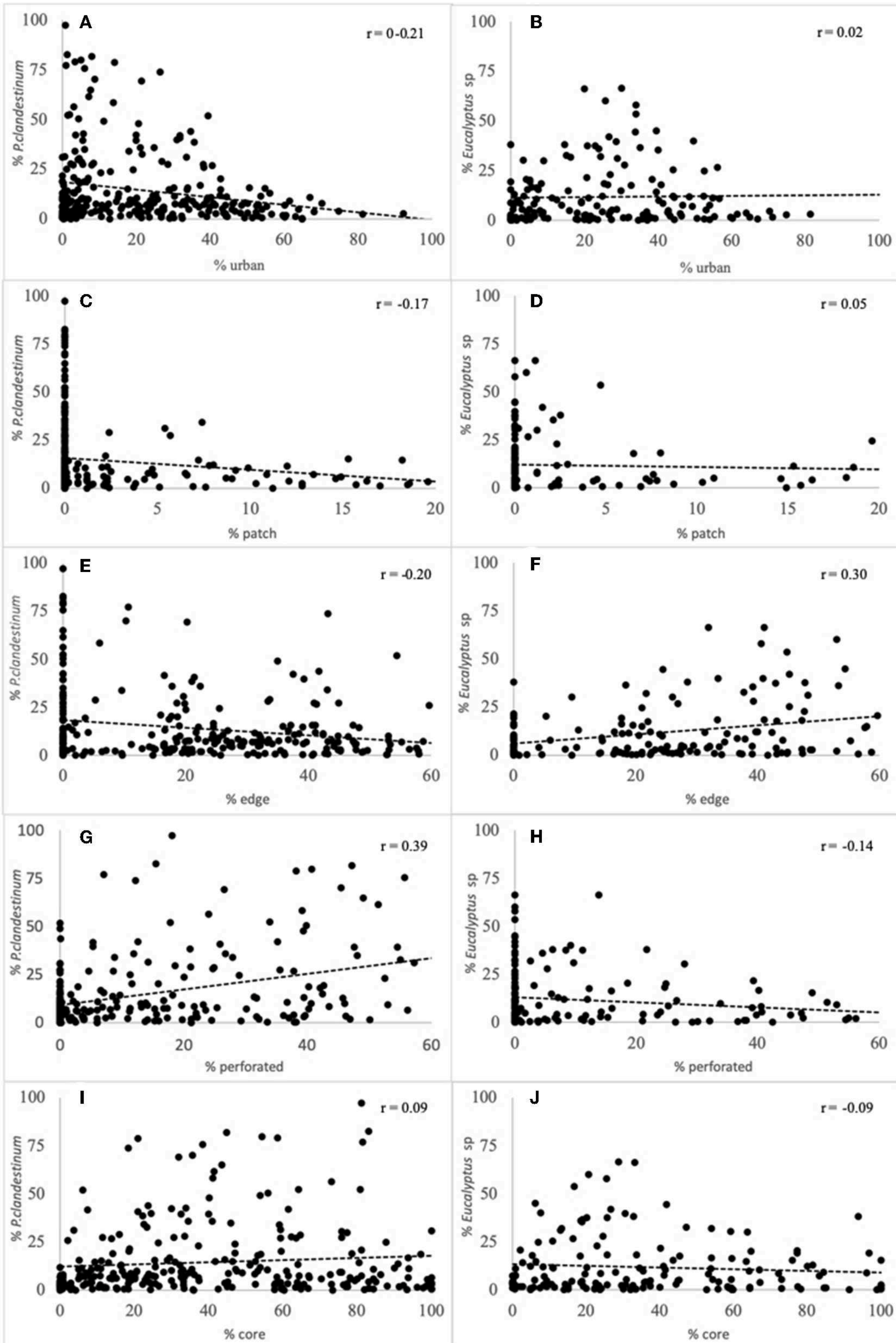

FIGURE 7 | Percent cover of Pennisetum clandestinum **(A,C,E,G,I)** and Eucalyptus spp. **(B,D,F,H,J)** compared to % urban land cover, and % patch, edge, perforated, and core fragmentation categories in each 1-ha unit.

such as water infiltration, are enhanced (Soga et al., 2014; Stott et al., 2015) leading to more sustainable and resilient urban areas.

CONCLUSIONS

Although our study represents urban development processes in a relatively small area in a large mega-city, we show important implications of fragmentation for ecosystem services, human well-being, and biodiversity. These relationships are moderated by natural history, human activities, culture, and socio-political events. We show here that the effects of fragmentation may not always be negative but depends these complex factors. Importantly, we show that the outcome of fragmentation on ecosystem services provision is dependent not only on the characteristics of the landscape, but also the ecosystem service in question and the historical and social characteristics of urbanization. While it is clear that fragmentation has important negative consequences for biodiversity, biodiversity engagement is enhanced with some level of fragmentation. Future research should focus on evaluating general patterns of the relationship between ecosystem services and human well-being under complex system focuses. For the UNAM campus, and cities as a whole, understanding the influences of fragmentation processes on ecosystem services, human well-being and biodiversity can aid in integrating the multiple, sometimes conflicting, needs of people and biodiversity in cities.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

AUTHOR CONTRIBUTIONS

LZ and MA participated on the design of the project, generated the hypothesis, and wrote the manuscript. TF gathered data, performed the spatial analysis, and discussed results.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2019.00152/full#supplementary-material

Supplementary Table 1 | Repeated measures analysis of each category along years.

Annex 1 | Pictures of the described ecosystem in dry (1) and wet season (2).

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Challenges and Opportunities on Urban Water Quality in Mexico City

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Mexico City has a population of 9 million inhabitants and was settled on a lakebed with high seismic potential. It is currently embedded in the Mexico City Metropolitan Area, which encompasses 22 million inhabitants and which was self-sufficient in water in the past, but currently extracts 70% from the regional aquifers and imports about 30% of the water required by this megacity. Groundwater represents its main water source but its water quality is increasingly threatened. The purpose of this study was to determine the water quality in areas related to seismic fractures, which may increase the vulnerability of water provision, and to identify specific zones that could be affected. Official water quality data from the period 2002 to 2017 was analyzed and compared to recent data taken in wells in the city after the September 2017 earthquake. Physicochemical parameters were determined and compared to the existing data. Statistical and temporal analyses were performed in order to understand the evolution and spatial distribution of water quality. The results show that free chlorine was below the limits according to the Mexican regulatory framework, while the presence of fecal coliforms, aluminum, ammonia, iron, and manganese exceeded the standards. The presence of arsenic, boron, and chrome was detected in some areas. Clusters show specific parameters that increase with time: turbidity, sulfates, nitrates, arsenic, manganese, lead, and iron. These tendencies could imply the deterioration of groundwater quality and a potential effect on the health of the exposed population. Spatially, vulnerability was observed in *Iztapalapa*, *Tláhuac*, *Xochimilco*, and *Coyoacán*. Wells coincide spatially with some of the geological damaged areas from the earthquakes in *Iztapalapa* and *Xochimilco*. In addition to water quantity, water quality represents a challenge for the urban future, since water disinfection systems are limited to treating the diversity of compounds detected. The water quality-monitoring program must be changed to improve its capacities within a framework of sustainable water management in different regions of the city, and based on the season, considering the potential exposure to the city's population. This represents an opportunity to propose a strategic plan for the groundwater system in order to improve conditions toward a more equitable and sustainable pathway for Mexico City.

Keywords: water quality, groundwater, Mexico City, urban, earthquake

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INTRODUCTION

The Mexico City Metropolitan Area (MCMA) is a megacity of 22 million inhabitants. It is located within the Basin of Mexico, which covers an area of 9,600 km^2 and is at an elevation of 2,240 meters above sea level. In order to supply water to the city, groundwater exploitation started in the 1800s, with 1,070 wells drilled by 1899 (Ortega and Farvolden, 1989), and by 1990 a total of 3,537 registered wells were reported (National Research Council (NRC), 1995; Carrera-Hernández and Gaskin, 2007b).

Geological and Geophysical Setting

Seismic zones are related to the origin of the lacustrine plain in which Mexico City was built. According to Auvinet et al. (2017) the lacustrine plain was formed by progressive silting of the basin reservoir, due to the rising of *Sierra del Chichinautzin*. Silting with volcanic products and river drift propitiated conditions for the formation of a lake system within the Basin of Mexico. The bottom of the basin was silted up with stratification of different materials; the most important being the lacustrine materials including clays and silts, silts and sands, as well as the volcanic ashes that upon weathering generated highly compressible clays. The erosion of the foothills, river drift and deposits of volcanic origin built up a fill that gives the current variation of the sediments and thickness, therefore increasing the vertical extent of the deposits in a north-south direction. Groundwater quality in Mexico City is closely related to these geological formations, which present different hydraulic conductivities, permeabilities, as well as to the type and depth of the extraction wells.

The geotechnical characteristics of Mexico City have been carefully studied and described since the late 1950s. Marsal and Mazari (1959) presented the first zoning of the soils. Reséndiz et al. (1970) and Del Castillo (1978) updated this first description, including new urbanized areas of the city. A more recent map of geotechnical zones was incorporated in 2004, related to the Technical Norms, and the latest version was developed related to the Metro Geotechnical Design (COVITUR) (Santoyo et al., 2005).

As a result of the different geotechnical studies the areas in Mexico City have been described as Lake, Transition and Hill Zones.

The Lake Zone, with soft clays with large thicknesses, has also been divided in three areas:

> (a) Virgin Lake, in non-urbanized areas that are considered soft clays, (b) Central Lake I, that includes the urbanized areas in the non-colonial area of the city, with small and medium size constructions, representing an intermediate condition, and (c) Central Lake II, limited by the old colonial trace of the city, with a history of heavy buildings from Aztec to colonial periods, with consolidated clays, soft clays in areas covered by plazas and gardens, and very soft clays in the areas where old canals were located. Additionally, it is important to consider the induced consolidation due to groundwater extraction (Santoyo et al., 2005).

The Transition Zone, located in the border of the lake zone where the lower clay area disappears, includes a hard layer at a depth of 20 m with respect to the average level of the plain. The Transition Zone has been divided in:

> (a) High Transition Zone, the one closest to the hills, with stratigraphic irregularities due to the presence of interspersed alluvial deposits, and (b) Low Transition Zone, next to the lake area where the clay layer presents interspersed sandy slime of alluvial origin, deposited during the regression of the ancient lake system, (c) Abrupt Transition in the transition between the lake zones and some isolated hills.

The Hill Zone, located in the surroundings of the city, presents irregular conditions of compactation and cementation.

The described areas were used after the Mexico City 1985 earthquake to generate the Seismic Zonation of the Construction Regulation of the Federal District (now referred as Mexico City), considering all the sources that contribute to seismic risk, and therefore the specific geotechnical conditions in each zone. The map was constructed based on norms of the maps of natural iso-periods of the soil, obtained based on the environmental vibrations, which gives the mean dynamic of the subsoil of Mexico City. Nevertheless, what is considered the most important factor is the local seismic intensity of the subsoil (Santoyo et al., 2005).

Water Extraction and Subsidence

Water is extracted from the regional Quaternary alluvial unit, a pyroclastic and fractured system, overlaid by a compressible lacustrine aquitard (Carrera-Hernández and Gaskin, 2007a; Hernández-Espriú et al., 2014). A regional approach to the groundwater dynamics of the Basin of Mexico has been described by Carrera-Hernández and Gaskin (2007b) and Hernández-Espriú et al. (2014).

Extraction from the aquifer in 1950 was 13.7 m^3/s (Mazari and Alberro, 1990), increasing to 52.2 m^3/s in the 2000s (Jiménez et al., 2004). Groundwater extraction provides about 72% of the total demand (72.5 m^3/s) (Jiménez et al., 2004).

Over the last century, intensive groundwater pumping in this area has led to significant drawdowns and consequentially differential land subsidence, a phenomenon studied since the 1950s (Marsal and Mazari, 1959; Carrillo, 1969; Hiriart and Marsal, 1969), which has effects on urban infrastructure and leads to leakage and potential contaminant propagation to the aquifers (Mazari-Hiriart et al., 2006; Hernández-Espriú et al., 2014). Records show that since the 1900s, some downtown locations have subsided by 9 m (Marsal and Mazari, 1990). Intensive and continuous pumping since the 1940s has caused a differential land subsidence of 6 cm/year in the downtown area to 30 cm/year in the eastern and southern sections of the city (Mazari and Alberro, 1990; Mazari et al., 1992).

The Mexico City Metropolitan Area developed on a lakebed and a highly seismic zone, dependent on groundwater for public supply, a resource that due to its hydrogeological setting is extremely vulnerable (Mazari-Hiriart et al., 2006). This vulnerability not only reflects on water quantity, but also water quality, since often it contains various potential contaminants that are introduced into the aquifer system.

Changes in soil layers due to an earthquake could affect the city's topography; consequently, soil components may come in contact with groundwater, affecting its quality. Important consequences of earthquakes are the fractures in the geologic materials that allow the release of chemicals and may cause other effects, such as change in the groundwater level and the appearance and disappearance of springs (Malakootian and Nouri, 2010). Cities worldwide located in seismic zones have faced changes associated with fractures and variations of soil layers. The natural dynamics of groundwater could be altered in the presence of earthquakes, which has been observed in Santa Barbara County in California (Wood, 2014), the Bam Plains and Baravat in Iran (Malakootian and Nouri, 2010), and in Katmandu, Nepal (Uprety et al., 2017). These changes may be of different magnitudes and may occur at spatially diverse places within the affected areas, which pose complex associated challenges for the city's management authorities. Specifically, attention must be paid on how to prepare to face risks related to water quantity, quality, therefore the availability of water with variations in the water table due to seismic events (Malakootian and Nouri, 2010; Wood, 2014).

Due to the September 2017 earthquakes, some fractures became evident in the contact zone between hard and soft geologic materials in the southern area of Mexico City, where some of the extraction wells that supply the city are located. The aim of this research was to determine the water quality in areas related to fractures, which may increase the vulnerability of water provision, and to identify any change in the condition of water sources that would be important for decision-making in the city.

STUDY SITE

Based on the information generated during several sampling sessions by the *Laboratorio Nacional de Ciencias de la Sostenibilidad* (LANCIS) from June to October 2018 and official databases requested from the Water Authority of Mexico City (*Sistema de Aguas de la Ciudad de México, SACMEX*), we selected sampling sites close to fractures and geologic faults, as well as the frequency of complete datasets, considering water flow (local, intermediate, and regional). Forty-one wells were selected to perform a sampling campaign after the earthquakes (**Figure 1**).

METHODS

Information Systematization

We conducted a search and systematization of the available databases and spatial layers of the following physical characteristics: (i) geology; (ii) fractures; (iii) geological faults, (iv) topography; (v) seismic zoning; (vi) infrastructure; (vii) location of wells, and (viii) well flow (**Table 1**). All spatial layers are in UTM-14 projection and WGS84 datum.

Water Quality Information

Water quality information was obtained from *SACMEX*, and was selected for wells with complete information that was organized and then associated with the Water Quality Guidelines of water supply for urban public use (Conagua, 2016) and related it to the current Mexican Regulation NOM-127-SSA1-1994 (DOF, 2000). Groundwater quality parameters were selected according to the following criteria: (1) Data reported after the September 2017 earthquakes, and (2) Data sequence reports as complete as possible during the period 2002–2017. The water quality parameters that were selected are shown in **Table 2**.

Groundwater Sampling Campaign

In order to have recent information and compare it with water quality before and after the seismic event (19 September, 2017), a single sampling campaign was organized to take samples of 41 wells. The city's Water Authority (*SACMEX*) also accompanied sampling taken throughout the period of June through August 2018.

Physicochemical parameters of water quality assessment were performed *in situ* by multiparametric probe EXO2 (YSI). Physicochemical parameters were flow (L/s), temperature (°C), electrical conductivity (μS/cm), total dissolved solids (mg/L), salinity (psu), dissolved oxygen (mg/L), pH, ORP (mV), and turbidity (NTU). Inorganic compounds were analyzed by spectrophotometry with the HACH method: ammonia (mg/L, Nessler Method, 8038); nitrates (mg/L); cadmium (mg/L, Reduction Method, 8039); organic phosphorus (mg/L, PhosphoVer3®, 8048); sulfate (mg/L; SulfaVer®, 8051), and free chlorine (mg/L, DPD, 10245). Microbiological analysis was performed by Membrane Filtration Technique (American Public Health Association, 2005), and microbiological indicators were Fecal Coliform (CFU/100 mL) and *Escherichia coli* (CFU/100 mL).

Statistical and Spatial Analysis

Cluster Analysis

A cluster analysis was performed in order to identify groups of wells with a similar pattern. Previously, water quality data was transformed to values between 0 and 1, to allow comparison and data analysis. Data transformation was done using the R version 3.5.1 statistical package. Clusters were identified and analyzed applying Normal Mixture Modeling for Model-Based Clustering, Classification, and Density Estimation (Fraley et al., 2014). Bayesian Information Criteria (BIC) was used and graphic visualization to determine the model and appropriate number of clusters. BIC allows the comparison of the different models with several parameterizations or different number of clusters. In general, the larger the BIC value, the stronger the evidence for the model and number of clusters (Fraley and Raftery, 2002). The characteristics of each cluster were identified and visualized with the construction of star graphics (**Figure 2**).

Temporal Trend Analysis

Mann-Kendal and Thiel-Shien tendency statistical tests were performed to detect changes in the groundwater quality information obtained from *SACMEX*.

The tendency statistical tests of Mann-Kendall and Thiel-Sen were applied for the detection and estimation of tendency and magnitude, respectively, in the temporal annual series. Therefore, the presence of an increasing tendency or decreasing monotonic

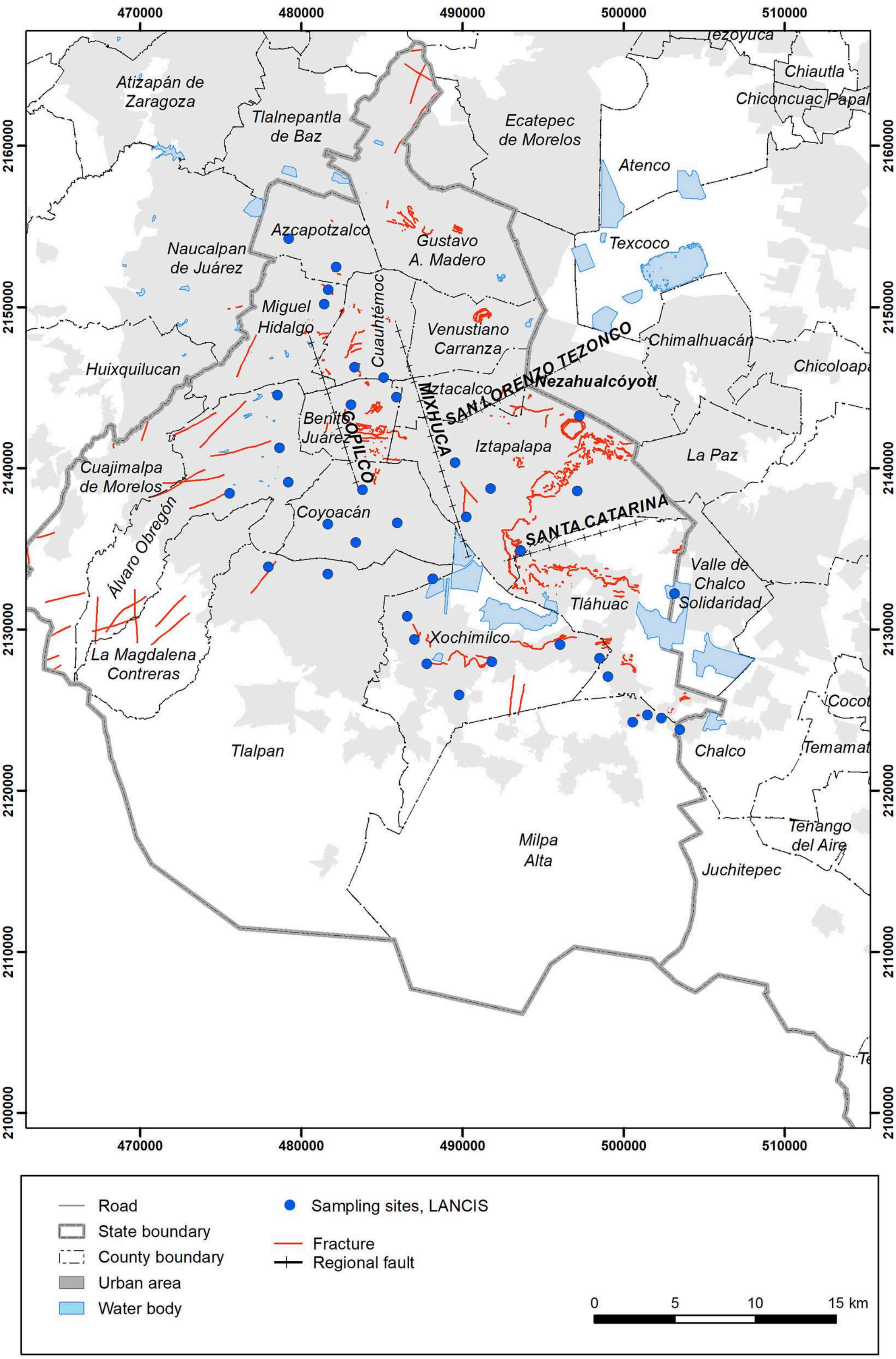

FIGURE 1 | Spatial location of the selected wells (blue dots) to carry out a water quality sampling campaign. Fractures in red and geologic faults in black (based on information in **Table 1**).

TABLE 1 | Mexico City's spatial information.

Digital layer	Descriptor	Data	Scale	Year	References
Geology	Geology (rocks type)	Polygon	1:100,000	1996	Mooser et al., 1996
Geological faults	Faults	Line	1:100,000	1996	Mooser et al., 1996
Geological fracture	Regional fracture	Line	–	2017	Carreón-Freyre et al., 2017
Relief	Delimitation of relief units: mountain area, piedmont and lake plain	Polygon	1:20,000	2017	Carreón-Freyre et al., 2017
Seismic zoning	Seismic zoning: i, ii, iiia, iiib, iiic, iiid	Polygon	1:20,000	2017	Santoyo et al., 2005
Wells	Location of water extraction wells for human consumption	Point	–	2018	Mazari-Hiriart et al., 2018
Water flows	Water flows from extraction wells in three categories: local, intermediate, and regional	Point	–	2018	Olea, 2017

was demonstrated by the non-parametric Mann-Kendall non-parametric test; then, the slope of the linear tendency was estimated based under the Thiel-Sen non-parametric method (Gilbert, 1987). These tests have no distribution assumptions and allow for atypical or missing data or atypical data (Gibbons et al., 2009). The Mann-Kendall and Thiel-Sen graphic visualizations were performed with ProUCL (USEPA, 2010).

Spatial Analysis

Based on information reported by the Institute of Geology (Olea, 2017, unpublished report) regarding underground flux types of the Mexico City extraction wells, we located each well in order to visualize and compare spatial patterns. Each well with the corresponding cluster was mapped and compared spatially. Similarly, we overlapped the well cluster with the geophysical and geological features (regional faults, fractures, reliefs, and seismic zones), as well as zones damaged as a result of the seismic events of September 19, 2017, in order to identify vulnerable areas for groundwater quality. The analysis was performed using ArcGIS 10.2.2 (ESRI, 2014).

RESULTS

Water Quality Information

According to the results obtained from the water quality information provided by *SACMEX* during 2002–2017, we found 107 wells that had the most complete information during this period. From these wells, we observed that free chlorine is the parameter that was frequently found below the recommended limit (**Table 2**) by NOM-127-SSA1-1994 (DOF, 2000). This parameter is relevant given its importance as a disinfectant, and it is one of the parameters of water quality that can be regulated, unlike other parameters (OMS, 2006). A low concentration of chlorine can be related to the presence of fecal coliform bacteria in water, since disinfection is not carried out properly. These results are confirmed by the presence of CF in 44 of the 107 wells. Aluminum, ammonia nitrogen, iron, and manganese were the parameters that mostly exceeded the limits established by the Mexican Regulation in 33, 21, 16, and 10 wells, respectively (**Table 2**, column 3).

Groundwater Sampling Campaign vs. Water Quality Information

One of the main purposes of this research was to exploit the possible differences in water quality parameters that are monitored by the local water authority (*SACMEX*), which have been generating data for many years, as well as data registered after the September 2017 earthquakes.

The analyses performed with pre-earthquake and post-earthquake data only allowed us to identify a significant difference for the pH data. Nevertheless, it is important to note that this research was conducted 9 months after the 2017 earthquakes, due to paperwork and permit requirements. In other reports elaborated in different parts of the world, differences have been reported for oxygen isotopes (Onda et al., 2018), electric conductivity, total dissolved solids, cations, and anions (Malakootian and Nouri, 2010), as well as in microbiological community composition (Uprety et al., 2017). In such cases, water quality monitoring was performed continuously, and when the earthquake occurred, it was possible to have a more solid database.

In this study, even though we did not have access to water quality data of dates close to previous earthquakes, it was possible to observe some tendencies in the variation of parameters registered for 15 years, a topic discussed in section Temporal Trend.

With respect to water quality regulations, it is important to point out that in Mexico, there are specific regulations, such as NOM-127-SSA1 (DOF, 2000), which establish the permissible limits of chemical contaminants and microbiological parameters, as well as the water organoleptic conditions required for human use and consumption. Additionally, regulation NOM-179-SSA1 (DOF, 2010) outlines the monitoring frequencies, considering variation in the parameters, and the measuring methods for each parameter. Both regulations are applicable for water that is to be used and consumed, that is, water that has received some type of disinfection to be able to comply with both regulations (DOF, 2000, 2010) and that is distributed to the population.

The water analyzed in this study during the 2018 campaign (June-August) was groundwater without any treatment; therefore, we reiterate that water regulations NOM-127-SSA1

TABLE 2 | Summary of the results of groundwater quality information from wells located in Mexico City according to the Maximum Permissible Limits of NOM-127-SSA1-1994 (DOF, 2000).

Water quality parameter	Maximum permissible limits, mg/L	Wells that do not comply Mexican regulation
Physical		
Total dissolved solids	1,000	6
pH (units)	6.5–8.5	1
Turbidity (NTU)	5	7
Inorganic		
Chlorides	250	2
Sulfates	400	1
Nitrate	10	0
Ammonia-nitrogen	0.5	21
Metals		
Aluminum	0.2	33
Arsenic	0.05	0
Barium	0.7	0
Boron	–	–
Cadmium	0.005	2
Chrome	0.05	1
Copper	2	0
Iron	0.30	16
Lead	0.01	2
Manganese	0.15	10
Mercury	0.001	0
Zinc	5	0
Disinfection		
Free chlorine	0.2–1.5	92
Microbiological		
Fecal coliforms (CFU/100 mL)	0	44

and NOM-179-SSA1 were only used as reference and not as a standard for compliance.

Statistical and Spatial Trend

Cluster Analysis

Five clusters were obtained during the 2002–2017 period (**Figure 2**). The cluster analysis consisted of 14 groundwater quality parameters from 107 wells. Clusters 4 and 3 group the majority of the data/clusters with 561 and 347, respectively; while clusters 5, 1, and 2 group 254, 231, and 149 data/clusters, respectively. Cluster 4 was characterized based on highest arsenic concentrations and low concentrations of boron, lead, nitrates, chlorides, and high pH. Cluster 3 characterizes low concentrations of arsenic and boron, under low concentrations of nitrates and chlorides, with high pH values. In contrast, cluster 5 was characterized by high concentrations of nitrates and high pH values. Cluster 1 was characterized by high concentrations of ammonia and chlorides, as well as low concentrations of nitrates. Cluster 2 was characterized by a moderate concentration of boron and manganese, chlorides, and residual chlorine, and high pH values.

Temporal Trend

Based on the water quality analyses, we observed a great heterogeneity of water quality characteristics in the Mexico City wells. An important aspect of the analysis are the potential health risks associated with water extraction from these wells, since there is a tendency for the concentration of metals, such as arsenic, boron, lead, and manganese, to increase over time (**Table 3**). Only chrome VI showed a significant decrease, which was observed in 74 wells. Chlorides, sulfates, and nitrates showed a significant increase over time in 32, 32, and 67 wells, respectively. Both free chlorine and fecal coliforms did not follow a significant temporal trend.

Spatial Trend

The spatial analysis of 107 wells classified by flow type -local, intermediate, and regional- as depicted in **Figure 3**. The majority of the wells are of intermediate flow, distributed in the central zone of Mexico City, running from north to south. The local flow wells are mainly distributed in the southern and southwestern counties (*alcaldías*), including *Milpa Alta*, *Xochimilco*, *Tlalpan*, *Magdalena Contreras*, *Álvaro Obregón*, and *Benito Juárez*. The regional flow well area is mainly located in the eastern area of Mexico City, principally in *Iztapalapa* and *Tláhuac* counties. These wells are characterized by high ammonium concentrations, chloride, and high pH values, as well as low concentrations of nitrates.

The seismic zones and clusters on water quality are shown in **Figure 4**, note fractures mainly on zones iiia and iiib of the Lake Zone, and ii of the Transition Zone, as well as most damaged zones in the 2017 earthquake (purple delimitation). The geological characteristics represented by the permeability (%) and different well types according to flow are depicted in **Figure 5**. In order to show spatially the integration of this information and to understand this complex system, an overlap of the two previous maps was performed and presented in **Figure 6**. It is possible to observe the lower permeability zones match with the seismic zones, and the location of the fractures (red lines).

It is possible to observe that cluster 2 is located in *Tláhuac*. Additionally, the well in the *Cerro de la Estrella* piedmont, with a permeability of 20%, which is within the limits of *Xochimilco* and *Tláhuac*, has a moderate concentration of manganese, boron, and chloride, and relatively high values of pH, as well as higher free chlorine concentrations. It is important to note that this is located in seismic zone iiib, iiic, and iiid, but in the lake area with low permeability, such as clay, with high water content, which favors seismic wave transport.

In the central area of *Xochimilco*, north of *Tlalpan* and the northeastern area of *Milpa Alta*, it is possible to observe cluster 4, which presents high arsenic concentrations, low boron and lead values, as well as high nitrates and chloride. In *Xochimilco*, this condition coincides with the spatial location of fractures and interspersed materials of the Lake and Transition Zone with permeabilities of 20–25%.

Wells in cluster 3 are distributed mainly in the Lake and Transition seismic zone ii, iiia, and iiib, presenting low concentrations of nitrates and chlorine, as well as relatively high pH values. These wells are mainly of intermediate flow

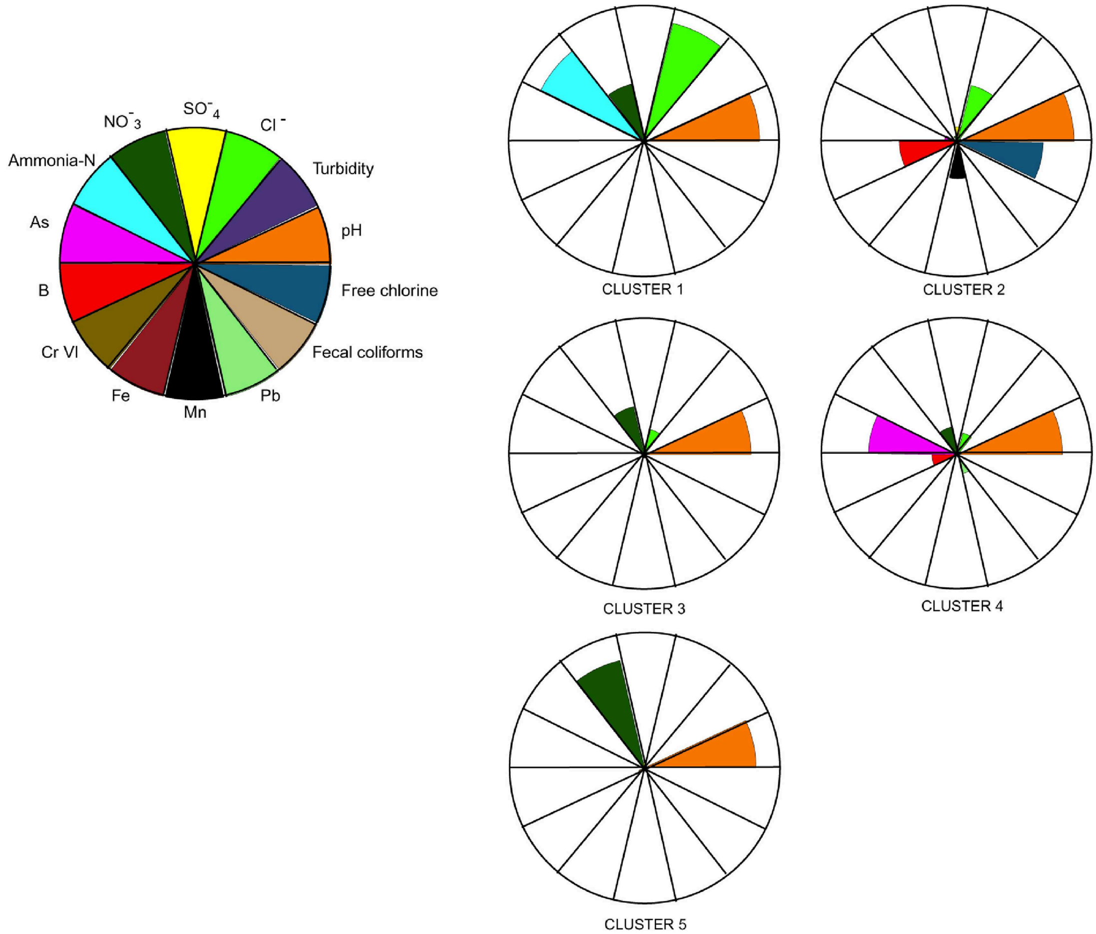

FIGURE 2 | Cluster models generated with groundwater quality information, figure shows number of data included to generate clusters. Number of data by cluster 231, 149, 347, 561, and 254 for cluster 1, 2, 3, 4, and 5, respectively.

and coincide with areas of major damage during the September 2017 earthquakes.

DISCUSSION

In an earthquake in Mexico City the lacustrine clays produce an amplification effect of the seismic waves, therefore it is important to describe the area based on its geophysical and geological characteristics. In this case we relate the earthquake impacts to the presence of fractures in contact areas of different materials, and explore the water quality data in order to assess if seismic zones may have an effect on water quality.

Considering seismic zones also related to the areas with relatively high sinking velocity, which may affect infiltration, that flooding events can occur, and that the well structure could be damaged, there is a need to evaluate all these phenomena and the potential influence on the water quality.

The clay layer with very low permeability protects to some extent the aquifer in the Lake Zone, which corresponds to the area marked as the seismic zones colored in orange in **Figure 4** iiid, iiic, iiib, iiia, but that it is also prone to fracture formation in the areas in contact with different materials such as Transition and Hill zones, fact that needs to be taken into account.

In a monitoring campaign of 41 wells between June and August of 2018, after the September 2017 earthquake there was no evidence of recent alteration; these based on a single monitoring campaign. The evidence found by analyzing data of 107 wells during 15 years indicated a temporal tendency for the concentration of certain compounds in specific areas of the city, mainly located in the Lake Zone iii in the Southern area of the city including *Xochimilco*, North of *Tlalpan*, *Milpa Alta*, and *Tláhuac*. These areas coincide with the most affected area since seismic waves entered the city in this particular earthquake in a southeast-northwest direction, therefore showing this was already a problematic area and we don't know if this was exacerbated after the earthquake. No evidence was found from the only sampling effort that took place close to the event.

The water quality of the wells located in the Western area of the city also corresponds to the zone where the aquitard presents the largest drawdown percentages (>60%), as reported in areas with clay thickness smaller than 25 m (Auvinet et al., 2017), a condition that may also influence water quality.

TABLE 3 | Groundwater quality trend during the period 2002–2017 in Mexico City.

Water quality parameter	Number of wells with statistically significant trend ($n = 107$, $p < 0.05$)	
	Increase	**Decrease**
Physical		
pH	4	9
Turbidity	4	6
Inorganic		
Chlorides	32	12
Sulfates	32	3
Nitrate	67	5
Ammonia	1	9
Metals		
Arsenic	57	0
Boron	23	32
Chrome VI	0	74
Iron	4	17
Lead	81	0
Manganese	61	4
Disinfection		
Free chlorine	1	0
Microbiological		
Fecal coliforms	0	0

Local, intermediate and regional flux type wells were used in order to assess if there was a difference in water quality according to flow regime. According to Tóth (1963) and Olea (2017) there would be an effect of the depth of the flux system, if deeper the water flux may be slower, and therefore could present a different quality. The local, intermediate and regional flows would allow us to get different information since water is flowing in the local flux from a recharge area with a high topography and discharging in the lower topographic area, an intermediate flow in which recharge and discharge areas do not occupy higher or lower places, respectively, and a regional flow where the recharge area is in the main watershed limit and the discharge zone is at the bottom of the basin. In order to understand if fractures affect wells with a different flux system, the wells analyzed were divided in these categories.

Indeed the cluster statistical analysis showed five patterns of water quality for the 107 extraction wells analyzed. In general terms, intermediate flow wells correspond to cluster 4, in which arsenic, lead and nitrates are relevant; local flow wells correspond to cluster 3, in which the most relevant parameters were nitrates and arsenic; and regional flow was represented by cluster 1, with the presence of ammonia and nitrates as relevant parameters. Clusters show, besides specific parameters types, wells with variable water quality. A more detailed study along a larger period of time is needed in order to get a better understanding of the water quality dynamics, including recent water quality data.

Of what is possible to say based on the available information, there is a trend of fracture formation in the contact areas of different materials and seismic zones (**Figures 4–6**), where wells are present and therefore this may correspond to overexploited areas with different stratigraphy and geologic characteristics, which in some specific areas is already affecting water quality. The more worrisome is that this trend will not stop and groundwater quality will continue to be contaminated and most likely the areas will increase.

At present the requirements for better environmental information are useful, not only for keeping track of water quality through monitoring programs, but also are useful for the implementation of actions relevant from the public health perspective and for the well being of the population. This is the case in water planning distribution, prioritizing investments for water management, facing environmental variations (climatic), responding to sanitary crises, and facing extreme dry events, flooding, and earthquakes. Adequate information is critical to face any problem related with water. Therefore, it is necessary to design and maintain a system that would be transparent, of reliable quality, and efficient, these latter currently a necessity anywhere worldwide (Horne, 2015; Plana et al., 2019).

Mexico City faces challenges to comply with constitutional mandates related to adequate quantity and quality of water for its inhabitants. There is a vast amount of information generated by the water authorities that has not been analyzed temporally and spatially, and that would aid in decision making for assuring minimal quality standards for the water distributed in the city.

It would be very useful to analyze databases of prolonged time periods, longer than 10 years, in order to understand tendencies of parameters such as fecal coliforms associated with free chlorine, as well as iron and manganese in certain areas of the city, and to monitor chemical contaminants strictly in industrial areas.

Water quality may be affected by extreme events such as earthquakes. Therefore, a baseline analysis of the regional water quality would be very useful to compare regular risks and potential contamination during extreme events such as earthquakes and climate extremes (drought and floods).

The main method of water disinfection in Mexico is chlorination. Our data show that it is evident that this process is not adequately performed, since the analysis shows that the majority of the wells do not comply with the minimum standard. In extreme events, this has been a problem, considering that the first obstacle evident following an event is the inadequate water quality due to lack of disinfection.

The existence and use of databases with hard data generated by an efficient water quality monitoring system would be imperative to support decision making related to water quality. Specifically, there is a need to examine the microbiological and chemical components in water, which can have impacts on acute-infectious and chronic-degenerative diseases. These databases would also contribute to our understanding of water quality issues related to seismic activity, as observed in Nepal, Iran, and Japan (Banjara and Paudel, 2017; Onda et al., 2018).

Therefore, it is necessary to consider technical, social, and financial feasibility for the implementation of a water quality monitoring system for Mexico City, as well as the Metropolitan Area. This means that it should integrate the water supply to the megacity, its intensely exploited aquifer, heterogeneous infiltration (Mazari-Hiriart et al., 2006), and high leakage into the pipeline (40%) and drainage system. All these issues should

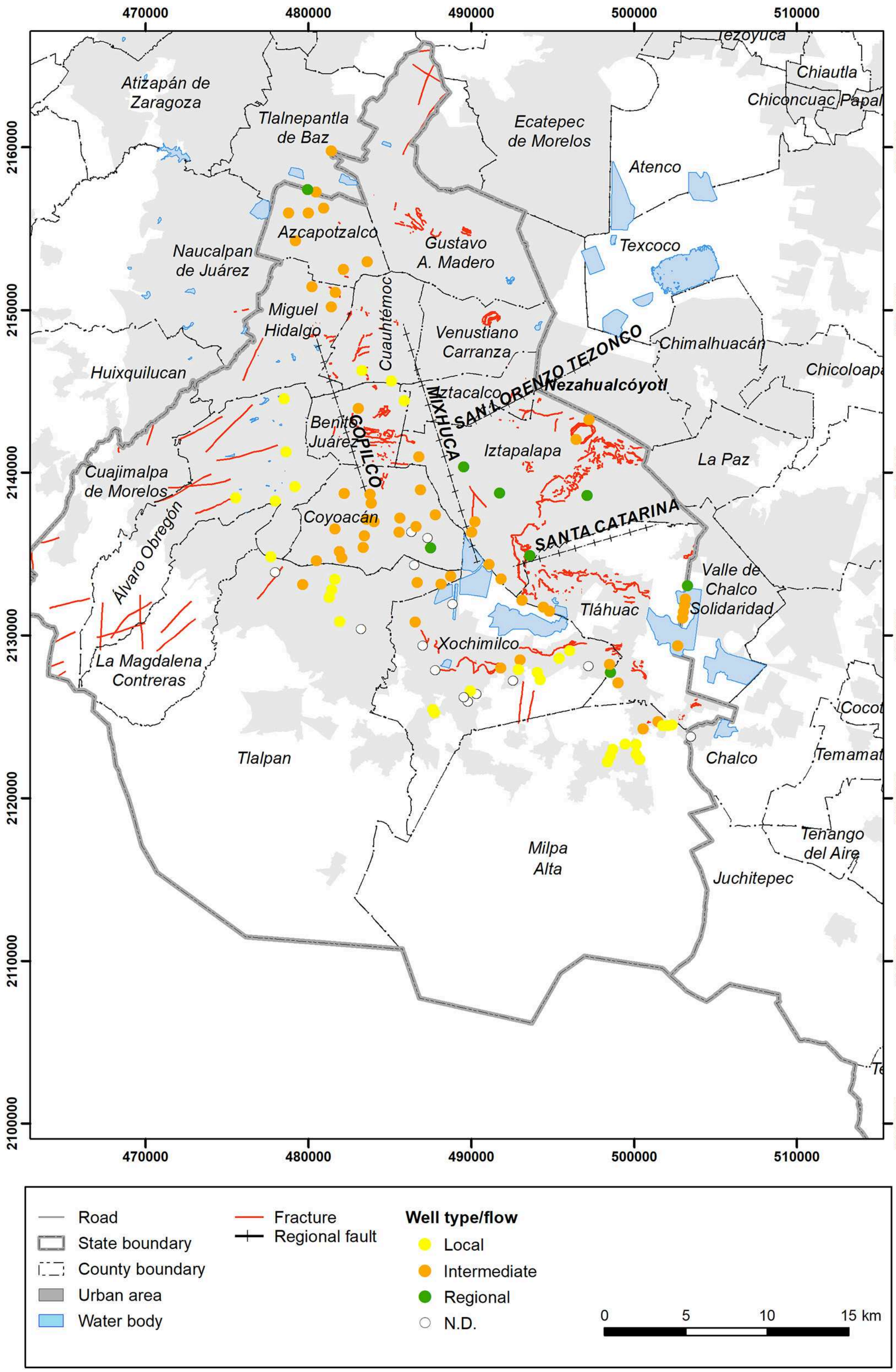

FIGURE 3 | Representation of wells with different flows, local (yellow), intermediate (orange), and regional (green).

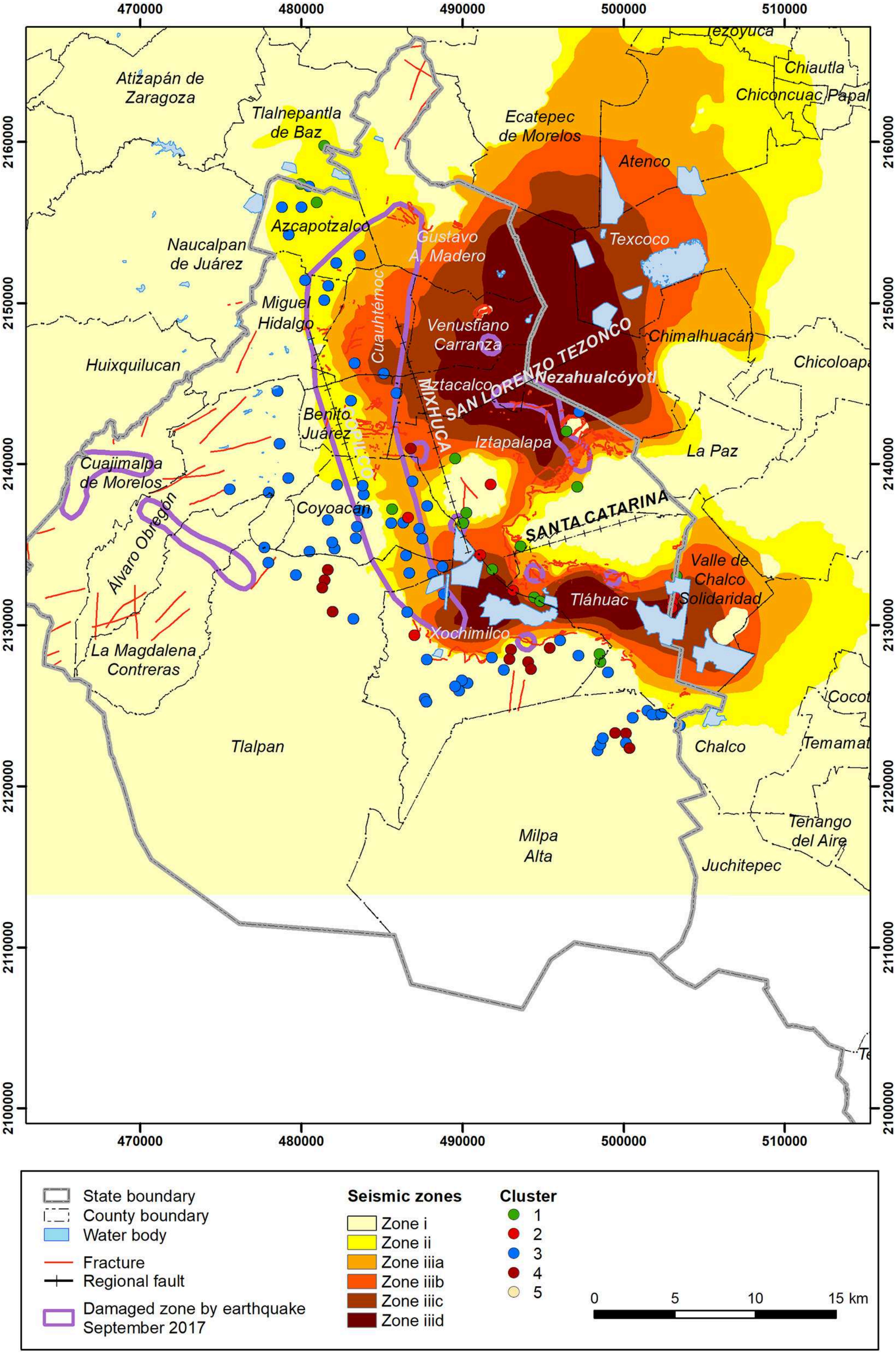

FIGURE 4 | Spatial representation of groundwater quality clusters, related to seismic zones, damaged zones in the 2017 earthquake (pink delimitation).

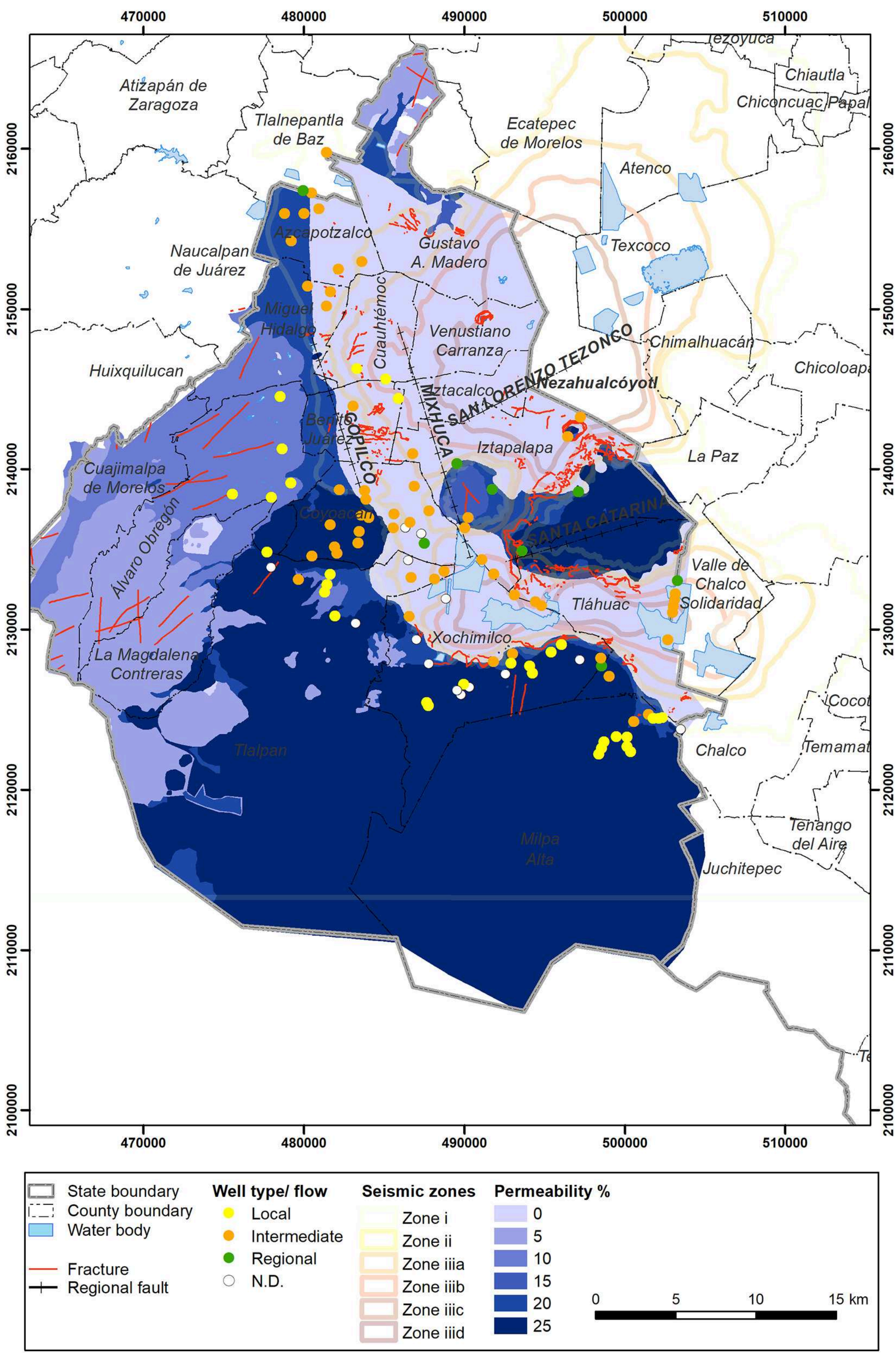

FIGURE 5 | Spatial representation of permeabilities and wells with different flows local (yellow), intermediate (orange), and regional (green).

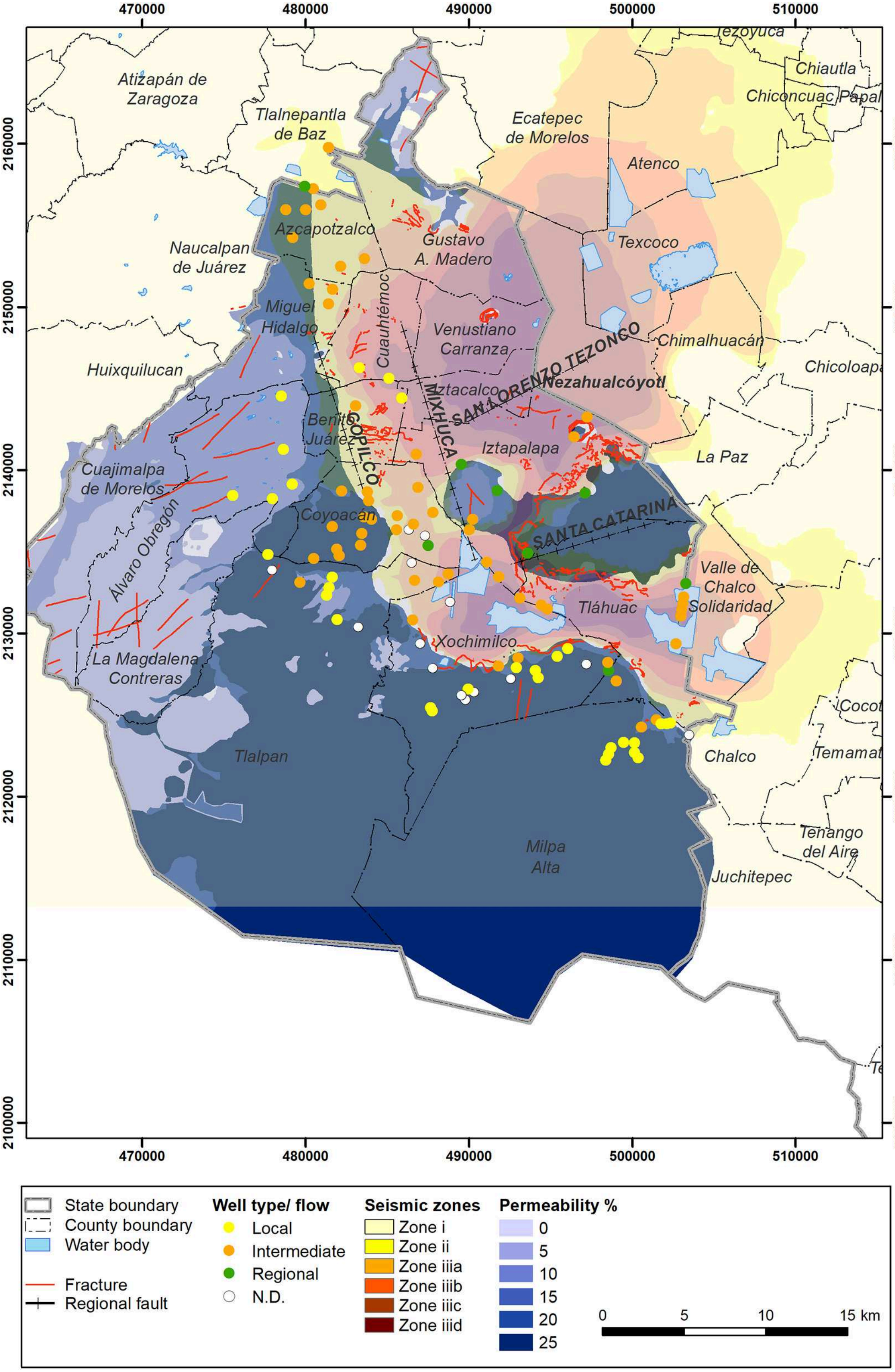

FIGURE 6 | Overlap of seismic zones with permeabilities and wells of different flows local (yellow), intermediate (orange), and regional (green).

be considered for Mexico City, which is one of the 20 most vulnerable cities to earthquakes worldwide, as well as being the economic center of Mexico.

Vulnerable areas of Mexico City, such as *Iztapalapa*, *Tláhuac*, *Xochimilco*, and *Coyoacán*, represent 36% of the city's population (INEGI, 2015). These areas have a particularly young population, being one of the more sensitive sectors of the population, a fact that the health and environmental authorities should take into account.

Specifically, for this change in paradigm of groundwater management, it is fundamental to have databases of solid data based on an efficient water quality monitoring system with defined indicators. The idea is that the databases should be the main source of information for the analyses and decision-making process for the city.

CONCLUSION

The data analysis from *SACMEX* (2002–2017) shows high heterogeneity in the water quality parameters. Due to the health risk, the concentrations of heavy metals (arsenic, mercury, boron, iron, manganese. and lead) stand out because they increase over time. This observation is of concern because if the aquifer is altered in an extreme event, this would be irreversible, with serious consequences for the water supply of several areas of Mexico City.

The water sampling that took place during 2018 allowed us to acquire a basic understanding of the groundwater conditions several months after the earthquake. The information obtained was consistent with the tendencies identified with the *SACMEX* database analysis.

Although it was not possible with such a small amount of data to relate groundwater quality parameters to the effects of the 2017 earthquake, it was possible to identify zones that were affected to a larger extent, specifically in the Southern, Northern, and Southwestern areas of the city, and these areas coincide with the increasing concentration of very important contaminants. Monitoring should continue to observe the evolution of specific parameters in order to reduce or control the potential risks related to the exposure of the city's inhabitants, especially in particular areas. We also recommend comparing this data to existing health reports in the more vulnerable parts of the city.

The trend observed for groundwater quality is extremely alarming in Mexico City, particularly for parameters such as arsenic and lead in the water that is being distributed throughout the water system. This trend is likely to continue and even expand to larger areas with low-income residents, generating greater social inequities in densely populated areas of the city. The environmental authority should strictly control contaminant sources in order to reduce the presence of these dangerous chemicals in Mexico City's intensely exploited water resources. Additionally, groundwater exploitation should be reduced, if possible, to stop the release of some of these contaminants from the geologic formations.

The activities of a new administration open opportunities for innovation in this water system, on which a large number of people depend as inhabitants of this complex megacity.

DATA AVAILABILITY STATEMENT

The datasets for this study will not be made publicly available because the databases are confidential, data generated by *Sistema de Aguas de la Ciudad de México* (SACMEX). We were allowed to analyze it and present the spatial results and conclusions.

AUTHOR CONTRIBUTIONS

MM-H, AE-G, and MT-P conceived the study. MT-P and AE-G performed the field and analytical work. AE-G supervised the laboratory tests. AZ-A, MT-P, and MM-H performed the statistical and spatial analyses. MM-H, AE-G, and MT-P wrote the manuscript. AZ-A elaborated all maps. All authors read and approved the final manuscript.

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Mental Models, Meta-Narratives, and Solution Pathways Associated With Socio-Hydrological Risk and Response in Mexico City

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Cities are far more than the people who reside within them, the activities that drive urban dynamism, and hard and soft infrastructure that create urban structure and form. Cities are also composed of stories–narratives–that emerge from the experiences, ideas, knowledge and agendas of urban residents, administrators, and individuals with stakes in the city's future. These narratives collectively not only reflect how the material landscape is perceived and socially and culturally appropriated, but also, by motivating and rationalizing human actions, contribute to shaping that material world, including the behavior and attitudes of humans within it. Here, we explore the narratives and associated solution pathways that have emerged and consolidated around the issue of water scarcity and flooding in the megalopolis of Mexico City. Effective and sustainable management of water resources has long been considered essential to the city's future, yet many scholars consider the city "stuck" in path-dependent development trajectories that seems unable to address pervasive social inequity, infrastructure fragility, and the city's precarious supplies. Through mental model data elicited from qualitative interviews and workshops with a cross section of urban stakeholders, we identify dominant narratives that articulate distinct causal premises and consequences associated with water related risk in the city. We juxtapose these narratives with the current and proposed solution pathways proposed by the interviewees. Our analysis demonstrates how, on the one hand, dominant narratives may quell innovation, and on the other, narratives collectively can foster the seeds of urban sustainability transformation.

Keywords: mental models, cognitive mapping, flood risk, water scarcity, urban resilience, governance

INTRODUCTION

Cities can be thought of as systems. They incorporate the soft and hard infrastructure that creates urban form. They contain a diversity of actors, and enable activities that take place in and around urban boundaries. Cities also consist of the immaterial and material flows of ideas, capital, and information that bind people to place; together these flows contribute to the dynamic identities that cities claim as their own (Pickett et al., 2003; Boone et al., 2014; Childers et al., 2015). Like other places of significance for human activity and well-being, cities are also places in which, and about which, people create narratives. Narratives are socially and ecologically situated stories or explanations about one's lived experience. Narratives refer to a sequential ordering of events that serve to communicate and share experience as well as to confirm identities–e.g., stories of cause and effect, and significance, stories about ourselves in a certain situation and about others (Elliot, 2005; Moezzi et al., 2017). Collectively, these narratives not only reflect how the material landscape is perceived and appropriated but also, by motivating and rationalizing human actions, contribute to shaping that material world, including humans in it (Manuel-Navarrete, 2015).

Sustainability scholars have argued such dominant narratives correspond to specific management strategies that can close off potential innovations and alternative solutions, potentially leading to unsustainable trajectories (Smith et al., 2005; Leach et al., 2010; O'Brien and Sygna, 2013; Fünfschilling and Truffer, 2014). The diversity of narratives that exist about any particular urban issue reveal "how geography, history, and politics have shaped the built environment, patterns of supply and demand, and the impacts of change on relatively vulnerable citizens…" (Darby, 2017, p. 120). However, the dynamics of power and influence among actors and institutional processes in cities can result in one or two narratives dominating the political discourse in a particular problem domain. These dominant narratives then become embedded as an institutional paradigm or "collective idea" regarding "the problem." Thus, the dominant narratives define what actions are considered legitimate for addressing that problem (Hall, 1993; Legro, 2000; Schmidt, 2010; Shanahan et al., 2017). While individuals, businesses, and political leadership come and go, many of the narratives and the ideas that they represent persist in the population (Legro, 2000). Individuals act in relation to their investment in specific narratives: they vote for representatives who resonate with or champion the narratives to which they relate. Individuals act to preserve their interests in relation to threats and opportunities embedded in such narratives, and in this way reinforce them (Ostrom and Janssen, 2002).

In this paper, we begin with the premise that understanding the dominant narratives about particular urban processes and outcomes should precede and accompany any effort to address persistent urban challenges. We argue that any effort to mobilize more sustainable trajectories of development should first account for the diversity of narratives within the city, which narratives are dominant and how they are shaping or blocking potential solutions to specific urban challenges, and how these narratives relate to subordinate narratives articulating different problem definitions and solution options.

In our case, we focus on the problem of water-related risk in Mexico City: flooding and water scarcity. These problems have existed since the city was founded in the fourteenth century (Tellman et al., 2018). Through the aggregation of individual and group narratives concerning the problem of water in the city, elicited through mental-model interviews and participatory workshops, we define a suite of "meta-narratives": collective associations of terms, represented as cognitive maps, that together create distinct stories about water with specific meanings concerning causal factors, associated problems, actors, and outcomes. We evaluate how urban actors residing in, or responsible for, specific areas of the city are differently associated with these meta-narratives, and explore how these differences may be contributing to unsustainable trajectories of water resource management in the city.

CONCEPTUAL FRAMING AND CASE STUDY

Narratives are hypothesized to be essential properties of what it means to be human (Elliot, 2005). Individuals and groups construct narratives to assimilate phenomena in their surroundings and their lived experience into mental schema and existing cognitive structures (Pokinghorne, 2013; Brown, 2017). Narratives correlate with mental models. Mental models are the cognitive structures that reflect how an individual perceives the environment. For example, an individual may have a mental model that associates forested area with greater rainfall; such a model supports a narrative that planting trees will bring rain, ultimately alleviating drought. The narrative may also incorporate the corollary that drought has been caused by deforestation. Such narratives are not only informed by one's individual, direct experience, but also by the experiences of neighbors, family and friends, social and cultural networks and belief systems, information read and heard, the particular history of the interaction between the group to which a person belongs and the environment, as well as a diversity of other influences (Jones et al., 2014; Shanahan et al., 2017).

Sustainability research has recently turned to knowledge on mental models to help evaluate why and how social and behavioral change does or does not occur, and thus how decision-making and management can be improved to address sustainability concerns (Biggs et al., 2011; Gray et al., 2014; Jones et al., 2014; Levy et al., 2018). Cognitive mapping analysis can help reveal, for example, the degree to which an individual's cognitive understanding (e.g., the content of their internal mental models) of social-environmental system interactions differs from an objective reality of such dynamics (Gray et al., 2018). Differences between "lay" mental models of a particular risk and "expert" mental models, as expressed in cognitive mapping exercises, can illustrate deficiencies in risk communication, and points for intervention (Morgan et al., 2002). Cognitive mapping is also being used in participatory natural resource management, as a means of understanding the baseline perspectives of individuals and groups entering into management negotiations, and to identify existing or potential sources of conflict (Biggs et al., 2011; Gray et al., 2014; Voinov et al., 2018).

In the case of water management and Mexico City, we argue that mental model analysis is critical for another reason. Mental models of individuals inform, and are informed by, the narratives of social groups as they act in a particular environment (Legro, 2000). Individuals draw on these narratives to understand and explain what happens in the world and their interactions with it and with others. The dynamic relationship of mental models and emergent, shared narratives, which we will refer to as "meta-narratives," about a problem domain legitimize and justify particular individual and collective action, and, when informing processes of governance, can be codified in institutions (Spoor et al., 2004; Pahl-Wostl et al., 2010). It is through the translation of cognitive models to meta-narratives and then into to action and policy, that meta-narratives, as intangible constructs, become materialized as part of the physical world (Eakin et al., 2017). In the context of urban areas, meta-narratives thus become embedded in urban infrastructure: they inform what decisions are made, when and where, and thus how the city expands, what is built, for whom and why (Eakin et al., 2017; Tellman et al., 2018).

Mental models are difficult to ascertain. Verbal narratives about specific real-world phenomena can be elicited in open-ended cognitive-model interviews (Carley and Palmquist, 1992; Cone and Winters, 2011) and this qualitative data can then be coded for more quantitative and comparative analysis (Jones et al., 2014). Alternatively, given that mental models are essentially *relational* (composed of related concepts and ideas), individuals and even social groups can directly create cognitive maps of constructs and their relationships (Carley and Palmquist, 1992; Kearney and Kaplan, 1997; Gray et al., 2014). These cognitive maps are then analyzed through methods such as network analysis and graph theory applications (Gray et al., 2012; Septer et al., 2012; Levy et al., 2018). The validity and reliability of these methods for capturing mental models is a point of discussion: we know, for example, that the location of any elicitation activity, the method of elicitation and the immediate social context and motivation of actors will likely influence the content and structure of elicited cognitive models (Jones et al., 2011, 2014; Lynam et al., 2012). Nevertheless, as the use of mental model methodology has increased in natural resource management research and sustainability science, there is growing confidence that the elicitation and visual and verbal depiction of cognitive models and their associated narratives can provide material for social learning, collaborative planning and conflict resolution (Biggs et al., 2011).

While water challenges are notorious in Mexico City, only a fraction of the city experiences acute exposure to water related risk on a regular basis. The focus of the case we present here is on the problem framing and meta-narratives associated with the experience of those most closely related with the problem. The sources of our data thus includes those in position of authority over water management and civil protection at the city level, and residents of neighborhoods most directly exposed to risk in three boroughs known for water challenges. Accordingly, we elicited the mental models of individuals and groups (technical experts, public officials, and residents from three city boroughs who frequently experience flooding and water scarcity) from qualitative interviews and participatory workshops to then construct meta-narratives associated with water challenges.

Mexico City has struggled with the twin problems of episodic flooding and chronic water scarcity since the city was founded in the fourteenth century (Tellman et al., 2018). The megacity of over 23 million people has expanded over a watershed, desiccating the natural springs, rivers and lakes. Today, ∼60% of the city's water comes from an over-exploited aquifer; the remainder of the city's supply is piped in from neighboring watersheds at increasingly high social, economic and political costs (Tortajada and Castelán, 2003; Delgado-Ramos, 2015). The location of the city in what was originally an endoreic (closed) basin supporting 5 shallow lakes has exposed it to flooding. The city has responded over time with the construction of elaborate drainage infrastructure. Yet, the challenges of constant and dramatic subsidence, population growth, land cover change, and infrastructure capacity have ensured that rainy season flooding of combined sewage and storm water has remained a significant threat to the population (Romero Lankao, 2010). Today, the city's water authority, SACMEX (Mexico City Water System), reports that 12% of the city's water supply is of a deficient quality, 26% of the city's inhabitants do not receive sufficient water and 15% lack daily water delivery [SACMEX (Sistemas de Agua de la Ciudad de México), 2018, p. 65].

There has been a wealth of research on Mexico City's water challenges over the city's history; most recently, scholars have highlighted how the water issues of the city are as much social and cultural challenges as they are technical and hydrological (Cohen and González Reynoso, 2005; Romero Lankao, 2010; Jiménez Cisneros et al., 2011). The city has tended to foster hard-infrastructure solutions, and relied on engineering expertise to address flooding and water supply concerns, yet increasingly these approaches are seen as unsustainable (Delgado-Ramos, 2015). More sustainable pathways for management will need to address the prevalent inequities in water access and distribution (Jiménez Cisneros et al., 2011), a culture in which water is used as political capital (De Alba and Hernández Gamboa, 2014), distrust of public officials (Castro, 2004) and public perceptions and misperceptions of water quality (Delgado-Ramos, 2015). As yet, however, alternatives to "big infrastructure" solutions for water resource management have not gained much traction in the decisions of city authorities.

METHODS AND ANALYTICAL APPROACH

We elicited 48 mental models of water related risk from individuals and groups at three organizational levels in the city: federal officials in agencies who are responsible explicitly for water related concerns pertaining to Mexico City, public officials at the whole-city level responsible for water and land (watershed) related concerns, and some residents and local-level political representatives and community activists and leaders of civil society groups from three urban boroughs that are frequently subjected to water scarcity and flooding (**Table 1**). We identified participants using a simple stakeholder analysis framework, listing all well-known organizations and prominent individuals with either a strong interest or influence on water and/or land use (in relation to the watershed) decision-making in the city. For local-level participants, we focused on the urban boroughs of Iztapalapa, Magdalena Contreras, Xochimilco.

All three boroughs are located in the southern half of the city, where the city's conservation zone—an area designated for watershed protection that is technically off limits for

TABLE 1 | Number of individual or group (in the case of residents) mental models elicited, by sector and organizational level.

Organizational level	Public sector	Individual civil society leaders and activists	Groups of residents*	Total mental models
Iztapalapa Borough	2	6	1	9
Xochilmilco Borough	9	1	3	13
Magdalena Contreras Borough	6	3	3	12
Mexico City Government	14	N/A	N/A	14

**The number in this column represents the number of workshops in each borough. Each workshop enabled the participation of three to twelve participants from vulnerable neighborhoods in each of the three boroughs, resulting in one aggregated mental model per workshop conducted.*

new settlement—meets the consolidated urban area (**Figure 1**). Iztapalapa is densely populated and economically marginal borough, housing over 1 million residents in one of the lowest part of the city, and has consistently been identified as one of the city's boroughs most exposed to flooding, subsidence and inadequate water delivery (Jiménez Cisneros et al., 2011). Xochimilco lies at the foot of the southern conservation area, where hillside communities have expanded and continue to practice agriculture. In its urban area, Xochimilco suffers from both flooding and water scarcity. The borough contains the last remnants of the wetland ecosystem that once characterized the basin, now maintained with treated waste water. Magdalena Contreras spans a steep slope from the heavily forested highlands above the city to the city's urban core; water scarcity is common in the highland areas, although the borough also contains the last free flowing river—the Magdalena River—in Mexico City.

We recruited participants in the three boroughs from specific neighborhoods that were known, either by public officials we consulted or from available statistical data, to suffer from inadequate water availability and/or where flooding during the rainy season (e.g., Jiménez Cisneros et al., 2011). Neighborhoods exposed to water scarcity typically lacked either a connection to potable water pipe infrastructure (and thus were dependent on water tankers for delivery) or were on the "*tandeo*" system: a system in which water is delivered only for set hours during a week. Such neighborhoods were more often than not characterized by low-income populations, often, but not always, living in settlements lacking formal urban zoning ("informal settlements"), most commonly located in the southern part of the city in the higher elevations (Jiménez Cisneros et al., 2011). In contrast to areas suffering water scarcity, flood-exposed areas were typically located in the lower elevations in some of the more densely populated areas, and thus were also more likely to be part of formal urban settlements.

We employed one of two distinct mental model elicitation strategies. For public officials and leaders of civil society organizations, we followed a mental model interview protocol (Cone and Winters, 2011). This entailed a two-stage interview in which in the first stage the interviewee describes the water situation with minimal prompting and intervention from the interviewer. The second stage of the interview entails probing for more specific perspectives on the two issues of interest to the project (flooding and scarcity). These interviews were then transcribed and coded for key terms. The relationships among the key terms elicited were then visually represented (by the research team) as a concept map depicting the causal linkages mentioned by the interviewee. This process also resulted in an associated relational matrix of terms for each interviewee.

A second approach was employed to elicit collective models, representing the ideas about a problem held by the groups of residents we consulted. In this approach, we contacted neighborhood leaders to recruit residents to participate in a workshop; the neighborhoods were identified *a priori* as being exposed to either water scarcity, flooding or both, according to official data from the city's water authority provided to the research team. Seven workshops were held: 3 in Magdalena Contreras, 1 in Iztapalapa, and 3 in Xochimilco. Each involving the participation of 3–12 participants resulting in a total of 22 participants in the 3 workshops in Magdalena Contreras, 12 in the workshop in Iztapalapa, and 16 in the 3 workshops in Xochimilco. Participants were typically a rough balance of men and women all over the age of 18. The workshop entailed a series of participatory mapping activities designed to help these vulnerable residents articulate, as a group, their understanding of water related issues in their neighborhood and borough. Residents participated in drawing "rich pictures" (Checkland and Poulter, 2006) of the water issues they confronted, prepared problem trees linking causal elements to outcomes, and ultimately participated in the creation of more abstract maps that depicted the terms and concepts they identified as associated with the problem, to the problems in their neighborhood and the actions they took in response to these problems. We expected each group to depict conceptualizations about water related risk that would be idiosyncratic to their particular geography and local circumstances; commonalities in the conceptualizations across the groups of vulnerable residents would thus be indicative of shared meta-narratives of water-related risk exposure among the participants.

The final result of both the individual and group approaches was the same: a relational matrix of terms, created by the research team, consisting of the terms that participants associated with water-related challenges in the city or in their own borough (depending on the system boundaries of the interviewee–e.g., city officials talked about water "in the city" while local level officials and residents discuss the issues largely within their own borough). These unweighted, and undirected matrices were then standardized through the creation of a "dictionary of terms"[1]. In

[1]The specific computational steps entailed in the analysis of the mental model is described in a related publication: Siqueiros-García et al. (2019).

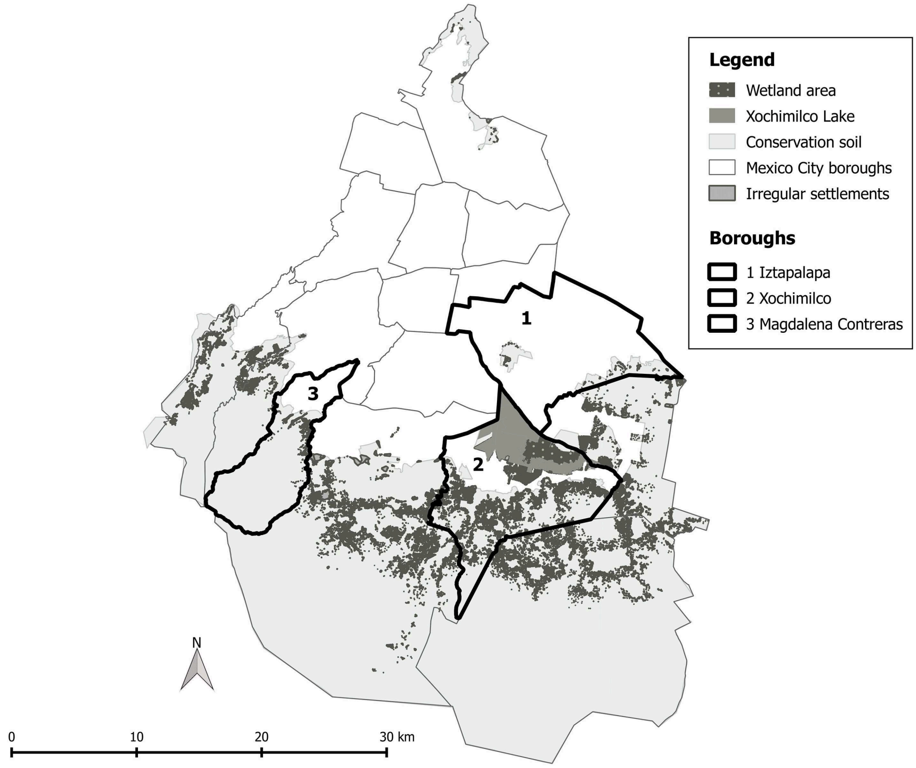

FIGURE 1 | Map of Mexico City, the three boroughs in which qualitative data was elicited, and the conservation zone. Map prepared by B. Hernández. Sources: data of irregular settlements provided by B. Tellman, sourced from Secretaria de Medio Ambiente de la Ciudad de México (2016); data on Conservation Soil & Xochimilco area provided by PAOT (2016), sourced from Atlas Geográfico del Suelo de Conservacicón del Distrito Federal (2012). PAOT, Mexico City.

this dictionary, one commonly used, generic term—for example, "water supply"—was defined by a series of terms with equivalent meaning—for example, "water supply from well water" or "water supply in the city's network"—that also were mentioned in interviews. While some nuances in meaning were likely lost in this process, we were careful to take the text of the interview into account when determining the appropriateness of using the standard term, or whether we needed to include an additional term in the dictionary to capture the specificity in the respondent's meaning.

We developed a computer program to automatically convert individual mental model inputs into the standardized language of the dictionary of terms, which then allowed us to create a global unweighted and undirected connectivity map of related terms for analysis—in other words, a "meta-model" (Siqueiros-García et al., 2019). This meta-model then served as the basis for identifying, through a process of community analysis using the algorithm and software Map Equation (Rosvall et al., 2009; Bohlin et al., 2014), the clusters of terms that were frequently associated in the aggregated data. These clusters or communities of terms were then interpreted as the prevalent, associated ideas about water-related risk, its causes, consequences and the actions taken in the city to address these issues. The most dominant clusters were identified as such by the number of terms that emerged as members of the cluster. In aggregate, the mental models of the individuals interviewed within each borough or across the city government, as predefined groups, would have an affiliation with these clusters of terms. We analyzed this affiliation using the Jaccard Index. The Jaccard Index is a measure of similarity/diversity between groups of observations or sets, identifying the proportion of elements that are shared. The higher the percentage, the more similar are two populations (communities or sets) (Jaccard, 1901; Niwattanakul et al., 2013). In our case, we expressed this similarity as a coefficient. For example, as described below, the mental models of the respondents at the level of city government shared 21% of the terms that appear in the cluster "Irregular housing," while none of the terms in the cluster "conservation of the *chinampa* ecosystem." Thus, we can conclude the governmental actors had more affiliation with the former narrative than the latter.

In order to associate narratives with discourse on actual and proposed solutions to the water situation in Mexico City, we drew from the same database of interview data used in the narrative analysis, coded using Dedoose Software (Sociocultural Research Consultants, LLC, 2018). Separate codes were created for water scarcity as a quantity issue, water scarcity as a quality issue, and flooding. Interviews were also coded for "proposed" or "actual" solutions. The solutions presented here are those from interview excerpts that co-occurred with water scarcity or flooding codes.

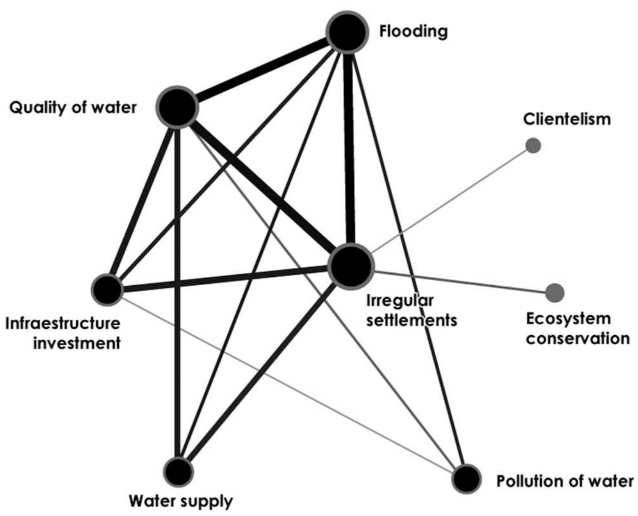

FIGURE 2 | Meta Narratives resulting from analysis of association of terms in respondents' mental models.

RESULTS

Meta-Narratives

The analysis of terms of the entire set of interviews produced 8 clusters of terms, supported by the qualitative data in the interviews, and gave rise to "meta-narratives" (**Figure 2**). Of these, three were clearly dominant, as signified by the node size in **Figure 2**. The linkages between the clusters are signals of their "proximity" in the universe of mental models that served as inputs in the analysis; the three most dominant clusters also exhibit such proximity. The first of these clusters, "Irregular Settlements," focused on irregular housing and the relationship of urbanization to the challenge of water scarcity in the city. This meta-narrative was strongly associated with the mental models of the respondents at the level of the city's administration (21%), as well as with the mental models of the government respondents in the borough of Xochimilco (19%), but also prominent in the discourse of interviewees (government & residents) in Magdalena Contreras (13%) and less with residents of Iztapalapa (10%) (**Figure 3**). Of the three case study boroughs, Xochimilco is still experiencing significant urban growth and contains a large segment of the conservation zone.

The concepts that were most frequently connected in this meta-narrative were urban growth, loss of agricultural areas, new infrastructure construction, urbanization of the conservation zone (watershed), and construction of housing in high risk areas. Other concepts included in this cluster of terms were land use change, land sales, deforestation and lack of urban planning. The narrative implication of this cluster is that the water challenges of the city are intimately linked to the expansion of the city's population, the physical urban footprint and land use change in high-risk, ecologically valuable areas.

The qualitative data illustrates that the prominence of irregular settlements in this cluster is largely associated with "blame": an expansion of housing in the city that is perceived to be unsanctioned, unregulated and out of formal control and management. As an example of such a narrative, one official of the city government explained that "*it hasn't been possible to contain or control the doubling of population in some areas, because there isn't any effective mechanisms to physically inhibit growth in relation to irregular settlements, particularly in Xochimilco.*" The meta-narrative depicts a process by which land in agriculture and forest (largely in the southern part of the city's watershed) is converted illicitly to housing, impeding hydrological processes (groundwater recharge), drying up springs, and creating undue pressure on the city's over-taxed infrastructure. As one interviewee commented "…I have irregular settlements [in my mandate], they don't ask permission from anyone…what happens? The *ejidatario* [peasant farmer] says "I'm going to give to my children" and begins to divide the land… and soon we have irregular settlements." Another commented "…they [land owners] continue to divide, sell and build, to the point which they are taking over ecological areas or areas of high risk…".

The populations who settle in these areas lack sufficient infrastructure, and are presumed to engage in illegal activities such as depositing sewage in waterways and gullies, or trying to connect themselves (illegally) to the formal drainage network, and thus causing sanitation and water supply problems for themselves and those downstream in the more consolidated urban areas. Interviewees described sewage accumulating in the unpaved streets of peri-urban settlements, as well as affecting public infrastructure in more consolidated areas. A public official in Xochimilco, for example, described the cross-contamination of groundwater wells for the city with unregulated sewage from the "hill settlements," forcing the city to perforate additional wells.

This meta-narrative has deep roots, into the early part of the twentieth century when water supply concerns began to become more acute, and scientists and urban planners called for conserving the watershed that fed the city's rivers and springs (Tellman et al., 2018). The southern part of the city is the geographic target of this meta-narrative; over 50% of the city's protected watershed (the conservation zone) is in the southern boroughs, and urbanization of this zone thus often receives disproportionate policy attention. There have been a variety of policy initiatives to control growth and discourage settlement; nevertheless, analyses of land change in the city demonstrate that these areas continue to show urban expansion within the protected areas at rates that typically exceed growth of formal consolidated areas (Aguilar, 1999; Gilbert and De Jong, 2015; Connolly and Wigle, 2017).

The second dominant cluster focused on the problem of flooding in the city, and was characterized by a focus on the inadequacy of urban infrastructure, technological and financial limitations in management. This meta-narrative was most associated with respondents from the borough of Iztapalapa and Xochimilco (affiliated with 18% of Iztapalapa residents and 15% of Xochimilco government of the mental models of the respondents, **Figure 3**), both areas that frequently flood and are subject to significant subsidence. The most central terms in this cluster referred to insufficient infrastructure, subsidence,

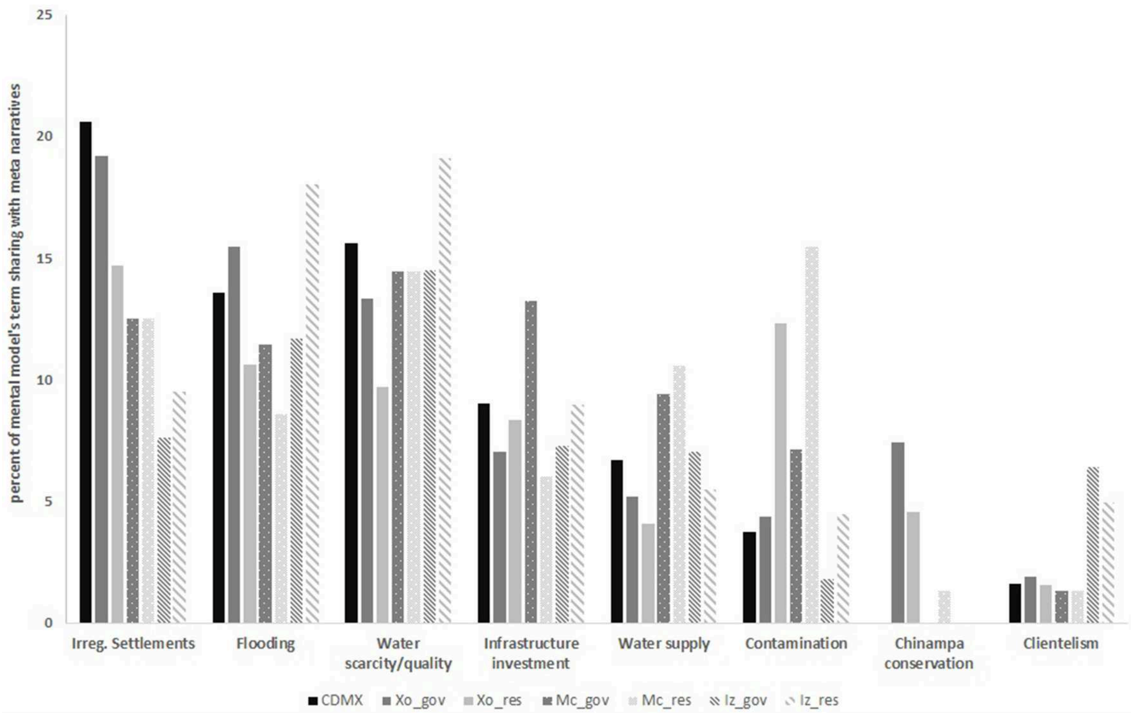

FIGURE 3 | Percent of respondents' mental models that share terms with meta-narratives. CDMX, Mexico City Authorities; Xo_gov, Xochimilco Borough Government; Xo_res, Xochimilco Residents (workshops); Mc_gov, Magdalena Contreras Borough Government; Mc_res, Magdalena Contreras residents (workshops); Iz_gov, Iztapalapa Borough Government; Iz_res, Iztapalapa residents (workshop).

sewage discharge, and lack of sewage connections, rainfall and water retention and pumping capacities. Problems in drainage maintenance—dredging, garbage in the drains, sedimentation—are also prominent elements in this cluster.

As a meta-narrative, these terms illustrate that flooding is a result of technological and infrastructure failures. As a city official commented "… flooding is about infrastructure; our infrastructure isn't sufficiently apt to channel and release the water we accumulate in the rainy season." The meta-narrative associated with this cluster is one in which the infrastructure system is depicted as underfunded, aged, inadequately maintained, and subject to leaks, blockages, and in constant need of repair. In the words of one respondent, "… the problem gets worse when the drainage system is obsolete or in bad condition, if we add to that the topic of culture and garbage management, then we have a situation that complicates infrastructure management and generates flooding where it really shouldn't flood."

A third dominant meta-narrative centered around water quality and scarcity, depicting a somber story of water being lost in leaks, overexploited aquifers, rising water demand and ill health effects. This cluster also relates to infrastructure failures: aging pipes and the inadequacy of the stop-gap measures to meet needs, such as water delivery through "*pipas*" (water tankers) and the necessity of residents' having to purchase water from private potable water suppliers. Here there is also an implicit and explicit critique of water management: water being "diverted" to more wealthy consumers, a lack of adequate infrastructure, anxiety about the privatization of water, and the lack of local water sources and storage capacity.

This meta-narrative is most associated with the mental models of interviewees from Iztapalapa (affiliated with 19% of resident interviewees) where water quality is often a source of deep health concerns: "Sometimes one isn't paying attention and the kids drink from the tap, and then the harm falls on them, they begin with nausea, then that their throat burns, that their stomach hurts… this is the danger we face as a family: our health." Water quality is also the dominant concern in Magdalena Contreras (affiliated with 14% of the mental models of the government & residents interviewees, **Figure 3**), but for different reasons: here the concern is related to the contamination of the last free-flowing river in Mexico City, the Magdalena River, with solid waste and sewage, which, in turn, affects flooding downstream and ecosystem services in the riparian areas.

Interestingly enough, given that water quality has essentially been "outsourced" to private potable water suppliers in Mexico City identification with this meta-narrative was associated with ~16% of respondents from the City Government (**Figure 3**). The interviews with city officials present a defensive tone regarding water quality, suggesting that if quality problems are perceived by the public it is either a result of within-household contamination (e.g., "…the water can arrive clean to the house, but if the cistern is dirty or the water tanks aren't clean, well, you've gone and spoiled everything"), or poor public understanding. For example, one official described a period of "smelly water" that came through the taps, but that apparently was not harmful to consumers. The official declared that the water was safe, but the public pushed back strongly, and forced the city to take palliative measures.

At a second tier of prominence, we identified three meta-narratives that reflected less widespread affiliation and a smaller overall associated number of terms, but still accounted for the perspectives of significant proportion of interviewees. While these meta-narratives were more associated with local level experience and phenomenon, they also shared many common terms with the more dominant narratives. These focused on, in order of prominence, infrastructure investment, water supply concerns, and water body contamination.

The meta-narrative of infrastructure investment reflected the politics of what parts of the city and who benefits from infrastructure improvements, as well as distrust over the city's intentions with infrastructure investments. The dominant terms of this meta-narrative were "institutional resources invested," "preventative measures," "pressure and claims on the borough government," "social mobilizations," and "efficiency in project execution." One borough official commented that when residents see infrastructure repairs taking place they can physically halt the works through protest. "They say, 'it's that they are going to take our water, they are going to steal our water!' although many times it isn't true, well, *always* it isn't true, because it is more expensive to move water to another borough than do the necessary public works within the same borough perimeter." But the residents have other perspectives, arguing that the city uses the excuse of lack of funding to justify lack of action to meet local water needs, and acts discretionally to allocate water and diverts water to meet the needs of more wealthy neighborhoods. And, under circumstances of significant "social pressure," public officials express that their hands are often forced. This meta-narrative relays the idea that there are underlying injustices in infrastructure decisions about flood risk and water supply, and that to get their voices heard and to claim rights, citizens may need to resort to more vocal and public protest.

The water supply meta-narrative was also shared across groups and levels of governance, and the terms reflected the specific challenges of managing the watershed that is perceived to be a source of Mexico City's future water sustainability. Here terms such as "water infiltration," "rainwater capture," "drying up of springs" and "check dams" are featured. In the words of one interviewee, "…at the rate that [vegetation] disappears, urbanization advances, there isn't anything that detains the water, and the water runs down… it's another element that is feeding the flooding and material impacts…". The meta-narrative reflects over a century of effort in Mexico City to control land use on the city's watershed, and the prominent place that watershed management has taken in public policy (although, given the continued urbanization of the watershed, with mixed success, see Tellman et al., 2018). This meta-narrative was given somewhat more prominence by the interviewees in Magdalena Contreras, where the Magdalena watershed is part of the identity of the borough, and by city officials, who have struggled over time to control settlement.

Finally, in relation to this tier of meta-narratives, was the concern for contamination of water bodies. This narrative was strongly influenced by the perspective of residents in Magdalena Contreras, who have been given some authority to monitor contamination of the Magdalena River from its source in the mountains above the urban seat of the borough. Lack of control over individual behavior—be it that of tourists to the protected area above the city, or households illegally evacuating sewage or solid waste into the river—features strongly in this narrative, where the problem of contamination is blamed on a lack of "culture," problems in garbage collection, and lack of regulation of human activities.

The last two clusters were far less connected to the other meta-narratives in terms of shared terms, and did not reflect a wide affiliation across the respondents in all three boroughs and at the city level. The meta-narrative of "*chinampa* conservation" unsurprisingly was almost exclusively affiliated with the borough of Xochimilco, where the Xochimilco wetland—a world heritage site, major attraction for urban tourism, and where the last remnants of the traditional agricultural system of *chinampa* farming still is practiced—is central to the borough's identity. Here the concerns are very specific to the social-ecological dynamics of the wetland: the problem of the canals that separate agricultural beds (*chinampas*) being filled in, the problem of invasive species such as water hyacinth and tilapia, problems of contamination from agricultural activities and the need for community planning.

The concern over "clientelism" and corruption defined the last meta-narrative, with only six associated terms relating to how water is distributed, how complaints from citizens are received, the use of construction material in exchange for votes and conflicts over water. This meta-narrative was most associated with the densely populated and highly politically mobilized participants from Iztapalapa.

Solutions

Embedded within each of the meta-narratives described above are terms suggestive of solution pathways. In the interviews with actors in the city, we asked both about what *is* being currently done to address the problems that they identified, as well as what they thought *should* be done. An individual's mental model of a problem domain often contains ideas about solutions that go beyond his or her formal responsibilities, official mandate for action, scope of experience or scope of agency. In this section, we describe the scope and nature of currently implemented solutions described by three different groups—public actors at the city level, public actors at the local level, and residents—and relate these to the identification of these groups of actors to particular problem narratives. We then describe the *proposed* solutions by these groups—which tend to address a much broader range of concerns and causal factors—and evaluate how these proposals may indicate novel points of intervention should alternative problem narratives become more prominent in urban discourse.

Current Solutions: Water Scarcity, Flooding, and Water Quality

Water authorities at the city level and borough level are obligated to provide a minimal allocation of water to every urban resident, regardless of legal status. Sending out water tankers to satisfy unmet demand is, as the meta-narratives above reflect, a political and contentious issue. Nevertheless, it is the primary "solution" to the immediate problem of water demand and scarcity at the disposal of water authorities. In some cases, also used to disincentivize growth. Xochimilco officials described limiting access to water in tankers to only those households on a registry; this policy was intended to make water access more difficult for newcomers to irregular settlements. Residents, unsurprisingly, focus on those solutions to scarcity they have at their disposal: construction of cisterns for storing water, purchasing water, and rainwater capture when they have the financial resources to do so, as well as water recycling and reuse, organizing their schedules to be available at home when water might be delivered, sharing water with neighbors and mobilizing with petitions, street protests and other actions to alert the city when they feel their needs are not being met.

Infrastructure investment dominates the solution discourse for flooding. In response to disastrous flooding over the last decade, the city and federal government has constructed huge drainage canals for the city (called "TEO II"), increased the number of pumping stations, and created new water retention lagoons. This infrastructure focus is also reflected at the borough level, where dredging, solid waste collection, construction of retention lagoons and infrastructure maintenance dominates the interviewee's commentary. Residents' solutions are also infrastructure-based, involving adding an additional story to their homes, constructing permanent or sand barricades at their thresholds, and manipulating the drainage in the street to divert sewage flooding. They also manage floods through collective action, such as turning on neighborhood pumps provided by the borough government, and clearing trash from streets and out of the drains. Proposed solutions for flooding, across all groups, emphasize further investment in and repair/maintenance of drainage, water capture, and pumping infrastructure and programs to educate citizens about or enable proper waste disposal.

Infrastructure was also a dominant theme in government interventions to address quality concerns, including fixing leaks in the distribution infrastructure to prevent cross-contamination from sewage, encouraging septic systems for the hillside populations, and in some cases, investing in local treatment plants for locally controlled wells. Many of the "solutions" to quality concerns, however, are undertaken by residents, who resort to purchasing water that they hope has been purified for drinking, boiling water, and installing filters to remove physical and other contaminants. Wealthy residents in the city typically can afford better filters, and are more likely to be able to get the delegation to respond if water is not of the quality they expect from the public service.

Proposed Solutions

What is perhaps more revealing are the solutions that are proposed by the interviewees, but are currently not being implemented. Here we see evidence that interviewees are connecting their meta-narratives to a solution space, and seeking to address the underlying conditions they believe are giving rise to the problems they experience. At the level of public administrators, for example, respondents suggested decentralized and smaller scale solutions such as green roofs to slow runoff and inhibit flooding, and local-level rainwater harvesting to address scarcity. They brought up the need for more small dams and ponds to collect rainfall and enhance infiltration on the watershed. And, in relation to the dominant meta-narrative that links informal settlements to water risk, they discussed the need to change real estate practices to encourage housing where infrastructure networks already exist, and the promotion of more ecologically-oriented construction practices in fragile areas. In general, they recognized that the current policy of prohibiting settlement on the watershed was largely unsuccessful and that novel solutions would be required.

In terms of proposed solutions to water quality issues, many city officials believed there needed to be an increased culture of care among citizens, and that citizens required education about the quality of their water. Gray water reuse also emerged as a possible solution, requiring investment in waste water treatment. Many respondents discussed a need for collaborative governance across sector agencies and with residents to find viable alternatives to current land management and water use behavior.

The residents also expressed considerable interest in demand-side conservation measures, ideally with support from public programs. These measures would include household water conservation, leak repairs, and household-level rainwater capture and cistern construction—particularly to improve water access in informal settlements. They expressed interest in containing runoff and enhancing infiltration through public works. And they concurred with public officials that better public housing was needed to alleviate irregular housing construction in the conservation areas of the city. But most starkly, they expressed a need for a different and more responsive water management system. Residents wanted to see more investment by the public sector in water quality in the public water storage tanks and distribution system, in addition to better information and an improved "culture of water" among citizens. They want financial support for water filters and decentralized, ecological solutions for waste such as bio-digestors. But more than anything, they wanted new political leadership, more transparent investment decision-making and efforts to address the injustices they perceive in water distribution and access.

DISCUSSION

The analysis of mental models and meta-narratives is not common as a means of informing urban planning and governance. Nevertheless, the persistence of sustainability challenges in urban contexts can be attributed at least in part to path dependencies that result from dominant meta-narratives about a specific problem domain. Ideas about the city and its problems become embodied in habits, policy, planning instruments and decisions in ways that create and sustain path dependencies (Eakin et al., 2017). For example, Bausch et al. (2015) demonstrated how in the peri-urban context of Phoenix, Arizona, the meta-narrative of the inevitable decline of agriculture—and the water and land policies and development priorities built on this meta-narrative–marginalized alternative ideas depicting a more synergistic future of agricultural and urban sustainability. Similarly, Borie et al. (2019) revealed the existence of a diversity of narratives on urban resilience in Manila, Cape Town and Nairobi, which together suggested alternative ways of realizing urban policy objectives. Narratives shape what knowledge in the city is put forward and what is silenced (Muñoz-Erickson, 2014). For this reason, some sustainability scholars argue that in new policy directions must be founded in a shift in the narratives about a problem, in order to "open up" alternative solutions that would otherwise be discarded (Leach et al., 2010; Pelling, 2011; Wise et al., 2014).

Our analysis of water meta-narratives in Mexico City identifies not only a confluence of perspectives on what the problems are, but also on the determinants of these problems. The interviewees in Mexico City highlighted endogenous processes as the primary drivers of risk, rather than exogenous natural phenomena or broader national economic conditions. Interestingly, given the dominance of climate change in global discourse, and the increasing attention to "urban resilience" in the face of environmental extremes (Romero Lankao, 2010; Lankao and Qin, 2011; Childers et al., 2015; Béné et al., 2017; Eakin et al., 2017), the concepts of rainfall, climate change and other exogenous environmental stressors are not part the water meta-narratives. Instead, the interviewees describe how the city itself generates the challenges it faces through its patterns of urbanization, the relationship of citizens to the city administration, and the ability of the city to respond appropriately to the burgeoning demand for housing, for sewage infrastructure and potable water. While the popular media—particularly the international media (e.g., Watts, 2015; Kimmelman and Haner, 2017)—have highlighted Mexico City's challenges in light of changing global climate conditions, the residents and officials managing the city offer a distinct view. They are well aware that their challenges have been a long time in the making (see Tellman et al., 2018) and view the megacity's water issues as a product of individual and collective actions—albeit the actions of *others* in the city, rather than themselves.

Embedded within the meta-narratives are also stories of differential responsibilities, and differential perspectives among local residents and public officials. Flooding, for example, is described by the residents consulted as a result of the city's lack the capacity to maintain infrastructure and inadequate management plans for extreme events. Public officials deflect this responsibility by blaming informal settlers and residents for dumping garbage in drains, nevertheless, all agree about the need for better infrastructure management. In the case of the water scarcity meta-narrative, "blame" is more implicit. The city is blamed for inefficacies in water distribution and injustices in water distribution, while the population at large in "blamed" for increased demand (see also Eakin et al., 2016). Residents perceive the city as responsible for poor water quality, while the city attributes the problem to mismanagement and lack of education among households, while acknowledging the infrastructural challenges they have in managing water contamination. In relation to the meta-narrative of irregular urban growth, illegal and irregular settlements are blamed for the water crisis. This meta-narrative thus blames the "other"—those that, by definition (being irregular), are beyond the control or influence of any "legal" resident or public official (see also Lerner et al., 2018).

The analysis of meta-narratives also help identify where there are incongruencies in how issues are perceived and understood, and what the available empirical evidence suggests in terms of causality, problem explanations and solutions (Morgan et al., 2002). For example, the rapid expansion of settlements onto the southern watershed and conservation zone is often attributed to a neoliberal shift in Mexico City's public housing policies (Guillermo Aguilar and López, 2009; Wigle, 2010; Guillermo Aguilar and López Guerrero, 2013), a shift that increased the scarcity of affordable housing in the city and left economically marginal populations with no alternatives. Land use in the urban periphery is also suspected to be manipulated by vote-buying behavior (Connolly and Wigle, 2017). Others have criticized the incentives that the city has provided to private sector housing developers at the expense of investment in public housing (de Mattos, 2007; Delgadillo Polanco, 2012). This literature thus would suggest that far from being the responsibility of irregular settlers and settlements ungoverned by the city, the water supply concerns and associated watershed development is in fact, at its roots, a result of central government policy concerning accessible and affordable housing for the urban poor (Lerner et al., 2018). The recognition that the solution to the city's water issues may well reside more in public housing development than in water infrastructure *per se* is evident in the respondents' proposed solutions, and represents a challenge to the dominant meta-narrative of irregular settlements.

Collectively, the meta-narratives of water related risk articulate a shared frustration: a perception that managers may be facing human and institutional limits, and that the capacity of infrastructural system itself has long been surpassed, and that management decisions themselves are politically motivated and often contested. Water management is seen as much an issue of governance and social relations as it is of failed infrastructure, and, conversely, the infrastructure of the city is also embedded in social and political relations (see also Eakin et al., 2017). Here again the respondents had some ideas of solutions that would go beyond the traditional efforts in "hard" infrastructure improvements. In addition to more on decentralized and "greener" options such as rainwater capture and runoff management, the interviewees revealed nascent ideas of increased public participation, transparency and collaboration at different levels and across levels of governance as a way forward in improving water outcomes in the city.

CONCLUSION

Our analysis demonstrates how, on the one hand, dominant meta-narratives may quell innovation, and on the other, meta-narratives collectively can foster the seeds of urban sustainability transformation. While the physical infrastructure of cities and its management is a strong focus for intervention in the face of emerging and chronic threats, less attention has been paid to the meta-narratives that are constructed over time, shape public and private discourse, and ultimately influence how solutions are conceived of and implemented. In this analysis, we provide insight into the spectrum of meta-narratives on issues of water and flooding in Mexico City. The dominance of some meta-narratives over others—and particularly those that are held more closely by actors with significant influence, such as those in the public sector—provides some insight not only into how problems are social constructed but also how the lines of action implied by these meta-narratives can lead to either "dead ends" or unsustainable path dependencies. We see this in the externalization of blame on irregular and "ungoverned" settlements, and the focus of the city's managers on hard infrastructure investment, regardless of unease in the adequacy of such measures to address evolving urban water challenges.

On the other hand, residents, public officials and others interviewed in the city all appear to have a strong sense of the endogenous and social nature of water-related risk: the threats posed to the city's water system and residents are part and parcel of citizen's relationships with the government and each other, as well as decisions made about water infrastructure, land use, garbage and housing. Thus collectively these narratives point to clear opportunities for intervention: public housing, citizen participation in water conservation and ecological restoration, decentralized water storage and management, and the need to divorce water supply interventions and flood risk management from the party politics. Meta-narratives matter; collectively they form a persistent form of "ghost" infrastructure, shaping urban form, social relations and solution pathways. By making these transparent and visible, and mobilizing the solutions they imply, we expect new opportunities for urban sustainability may emerge.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author, conditional on maintaining the confidentiality of interviewees.

ETHICS STATEMENT

This study was carried out in accordance with the policies and approval of the Internal Review Board (IRB) of Arizona State University. The study was determined exempt: The IRB determined that the protocol is considered exempt pursuant to Federal Regulations 45CFR46 (2) addressing tests, surveys, interviews, or observation, on 10/28/2014.

AUTHOR CONTRIBUTIONS

HE and LB-T conceptualized the study. JS-G and LB-T organized the design of the mental model analysis. JS-G, BH-A, and RS organized the database. JS-G and BH-A performed the mental model analysis. RS and HE performed the qualitative analysis. HE wrote the draft manuscript with the support of RS and JS-G. All authors contributed to manuscript revision, read, and approved the submitted version.

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Recovering of the Monterrey Metropolitan Area, Mexico, After Hurricane Alex (2010): The Role of the Nuevo Leon State Reconstruction Council

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The Monterrey Metropolitan Area (MMA), strategically located in Northeastern Mexico, has a population of over 4.5 million people. The metropolis is the second largest economic center in the country, only after Mexico City, and maintains a key role in the Mexico-US trade corridor. Thus, the issue of urban resilience to extreme weather events is a matter of national security and not only a local concern. In July 2010, Hurricane Alex hit the Monterrey Metropolitan Area (MMA). It is estimated that 15 human lives were lost. The hurricane generated severe damages to the metropolis's infrastructure and economy. In the aftermath of Hurricane Alex, the Nuevo Leon State Reconstruction Council (CERNL, in Spanish) was established, with the participation of government agencies and actors from the local community (universities, non-governmental organizations, and large firms). This paper analyses the role played by the CERNL in the reconstruction of the MMA. In 2013, the CERNL ended its mission. Most basic services and infrastructure were re-established, some of them within a few days and weeks after Alex hit the MMA. The relative good work of the Council, in spite of a fragmented and dysfunctional institutional framework, has to do with a local enabling environment that facilitated its establishment and the carrying out of activities. However, this case study also shows the difficulties associated with the design and implementation of coherent, sound strategies in this governance framework. Furthermore, the metropolis has been losing the policy capabilities built through the Council. This is a very risky current context that could have serious social, economic and environmental damages to Monterrey. The lessons presented in this contribution may be of interest to other cities in Mexico and elsewhere.

Keywords: urban resilience, floods, Monterrey, Mexico, infrastructure, reconstruction council

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INTRODUCTION

The theme of building resilience to the occurrence of hurricanes has been gaining a great deal of attention by international organizations, national and local governments, as well as from the academic community. Concerning the former, the World Bank (2013), the United Nations (UN, 2011; UNISDR, 2017), the OECD (2013a), and the World Economic Forum (WEF) (2019) have produced very influential reports that have helped to better understand the complexities of the issues at hand and the urgency for policy intervention. The resilience of urban systems is a particular good example of this interest. As its name implies, the city is seen as part of a wider urban regional system, as has long been argued (Bourne and Simmons, 1978; Friedman, 2002). Central to the notion of resilience is the recovery of, mainly, basic services and infrastructure of regional or national strategic relevance (Meerow et al., 2016; Pant et al., 2018). *Building back better* (Hallegatte et al., 2018) is an expression that encompasses the complex processes behind post-disaster reconstruction, which is not limited to the recovering of the prior provision of services but to improved ones—often through renovated or totally new infrastructure (Miller et al., 2018).

Although it could be improved, Mexico has made good progress toward the management of hazards like flooding. The National Disaster Fund (FONDEN) was established in 1996 to provide financial support to states and municipalities hit by natural disasters (OECD, 2013b). The National Reconstruction Fund (FONAREC) was created in 2010 to aid the reconstruction works as a result of hurricanes Alex and Manuel that affected the country that year (OECD, 2013b). There have also been good advances in the design and implementation of early warning systems (EWS) (Magaña et al., 2014).

In July 2010 Hurricane Alex hit the Monterrey Metropolitan Area. It is estimated that 15 human lives were lost. The hurricane generated severe damages to the metropolis's infrastructure and economy. In the aftermath of hurricane Alex, the Nuevo Leon State Reconstruction Council was established, with the participation of agencies from the three levels of Government (federal, state, and local), and actors from the local community (universities, non-governmental organizations, and large corporations). The establishment and performance of the Council sends a powerful message in the sense that recovery from a major hurricane can be led by the local and business community.

In 2013, the CERNL ended its mission. After spending around US$2.1 billion, most basic services and infrastructure were re-established, some of them within a few days and weeks after Alex hit the MMA. The relative good work of the Council, in spite of a fragmented and dysfunctional institutional framework that involves multiple jurisdictions working at the metropolitan scale (federal, state, and municipal), had to do with a local enabling environment that facilitated its establishment and the carrying out of its activities; the participation of universities and the business community were of great importance, in the light of their credibility built over decades.

Given the economic relevance of the MMA to Mexico, the attention on its vulnerability to flash floods should be a question of national interest and not only a local or regional concern. From a national perspective, however, and notwithstanding the progress that has certainly been achieved, there is a long way to go toward an integrated comprehensive management model for hazards like flooding. Schmidt and Hatch Kuri (2012) argue that the official discourse in regard to water must change to place the management of the resource as strategic and of national security. This requirement goes against a fragmented, dysfunctional and reactive—rather than preventive governance. In its 2011 Report of the Global Evaluation of Disaster Risk Reduction, prepared for the United Nations, Mexico recognized the slow progress regarding the prevention and mitigation of hydro meteorological events, in spite of their strong incidence and severe impacts. The Report estimated that the ratio of reactive to preventive expenditures was 33 to 1 (UN, 2011).

It is in this context that the work of the CERNL is remarkable, even considering its shortcomings and limitations. This paper addresses four major and interrelated questions: (1) What were the major impacts of Hurricane Alex; (2) what has the Alex event revealed about Monterrey's vulnerability and resilience with respect to the risk of flash floods and the existing framework for flood management? (3) what was the role played by the CERN in the reconstruction of the metropolis? and (4) what were the major lessons of the reconstruction?—more particularly, 9 years after Alex, to what extent has Monterrey reduced its vulnerability and increased its resilience to future flash flood events?

More specifically, and after this brief introduction, this contribution is structured into seven parts. The second part contains a basic methodological outlook. The third presents a brief flooding history of the MMA, to provide context to Alex. The fourth centers on the phenomenon Alex, its impacts and the existing water governance for flood management. The work of CERNL is discussed in the fifth part. Part six deals with major policy lessons and recommendations. Part seven presents the conclusions.

METHODOLOGICAL OUTLOOK

This section provides a basic methodological outlook of the methodology used to construct this article, which focuses on the impacts of Hurricane Alex in the Monterrey Metropolitan Area and the reconstruction coordinated by the State of Nuevo León Reconstruction Council. This story is a relatively recent one that has not been discussed in an in-depth way. The references in English are limited and those in Spanish are not abundant.

Although it is not claimed that a comprehensive in-depth analysis is done here, this paper certainly presents not only the process of building resilience to weather hazards related to hurricanes—to provide context to the Alex phenomenon—but also a close up to the role played by the CERN in the reconstruction of the metropolis. In order to do this, the paper offers an essential description of this process of resilience building, from a multidimensional approach. This multidimensionality involves geographical, hydrological, economic, and historical issues. There is special interest in showing how knowledge has been added in this process over several decades, particularly since 1988 when hurricane Gilbert hit the MMA. The achievements, limitations, and shortcomings of the reconstruction are presented within this comprehensive framework.

The methodology followed is structured around the four research questions. It was necessary to study academic references, as well as published and unpublished internal government reports. In addition to this literature review this research also benefited from reflective discussions with relevant respondents.

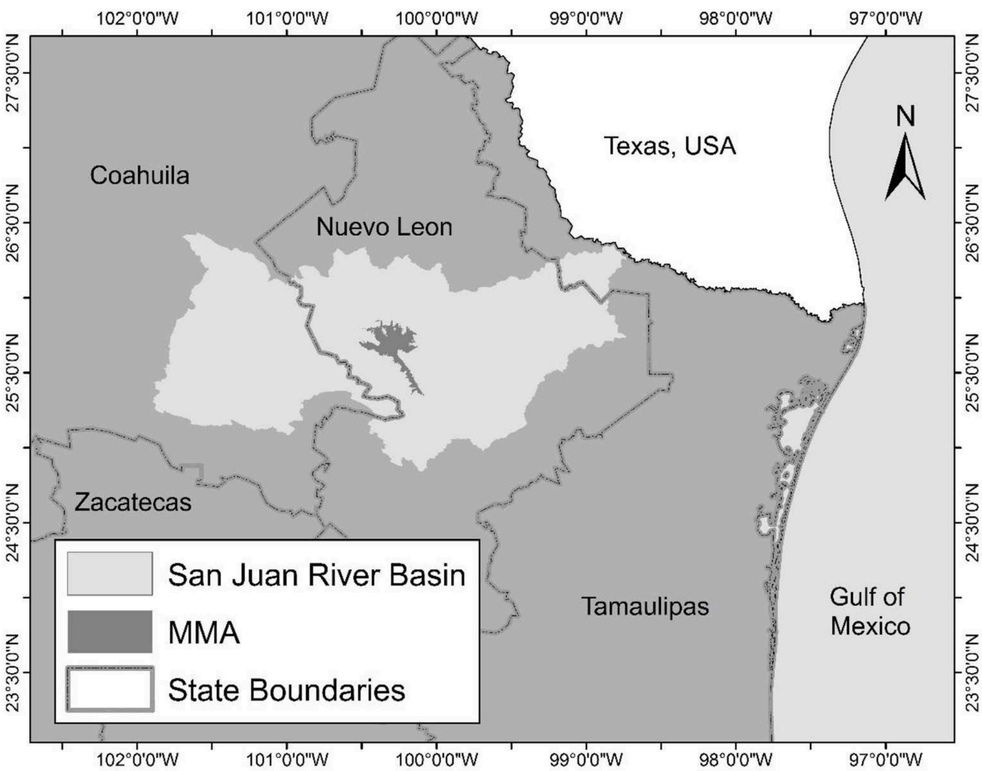

FIGURE 1 | Location of the Monterrey Metropolitan Area.

The official final report of the CERNL, with which its mission was finished, was of enormous value. Other documents that were consulted are the following: Nuevo Leon State Development Plan (Gobierno Constitucional del Estado de Nuevo León, 2010a); The Risk Atlas of Nuevo Leon (Gobierno Constitucional del Estado de Nuevo León, 2010b); The Final Official Report of the Water Public Utility about Hurricane Alex (SADM, 2010a) and Minutes of SADM about the reconstruction works undertaken by this institution.

There was also the opportunity to have talks with different people with first-hand knowledge of the reconstruction. This proved to be of great value to aid in the understanding of this complex process. Key informants included, among others: current Nuevo Leon state Secretary for Sustainable Development; two former state governors; current and former Director-Generals of SADM (and their top technical and managerial collaborators); former Director of the MMA's Stormwater Management System; current Director of the Monterrey Metropolitan Water Fund and the former Director of the Regional Office of the National Water Commission.

THE MONTERREY METROPOLITAN AREA AND ITS FLOODING HISTORY

The City in Context

The Monterrey Metropolitan Area (MMA) is formed by 12 municipalities including Monterrey, the capital of Nuevo León, a dynamic and prosperous state in Northeastern Mexico within the San Juan River Basin (**Figure 1**). The metropolis concentrates the bulk of the population and economic activities of the state. The MMA is a major metropolis of around 4.5 million people, and one of the three economic axes of Mexico. Large national corporations have their headquarters here. The foreign direct investment that comes to the country goes to the state of Nuevo Leon, its second destination, only after Mexico City. Most of these flows are directed to the MMA. The metropolis has prospered in spite of being in a semi-arid region, with little rain—unless, of course, a hurricane comes. In addition to this limiting geographical, climatic setting, there is also a complex water management framework (OECD, 2013c; Aguilar-Barajas et al., 2015; Torregrosa et al., 2015). The Santa Catarina River, the MMA's principal watercourse, crosses the whole urban area west to east (**Figure 2**). This river was channeled in the 1950s, with the intention to reduce the adverse impacts of flooding in the city (Torres and Santoscoy, 1985).

Summary of Recent Flooding History in the MMA

The city has always been prone to flash flood hazards. **Table 1** presents a brief chronology of these events. The 1909 flooding remains the worst. The toll in human lives is estimated at 5,000 people (Graham, 1911). The heavy rains of 1938 also left a mark. In more recent times, it is Hurricane Gilbert, that constitutes a before and after in the flooding history of the city. The Santa Catarina River broke its banks; infrastructure built on the margins and the river bed were destroyed. The peak

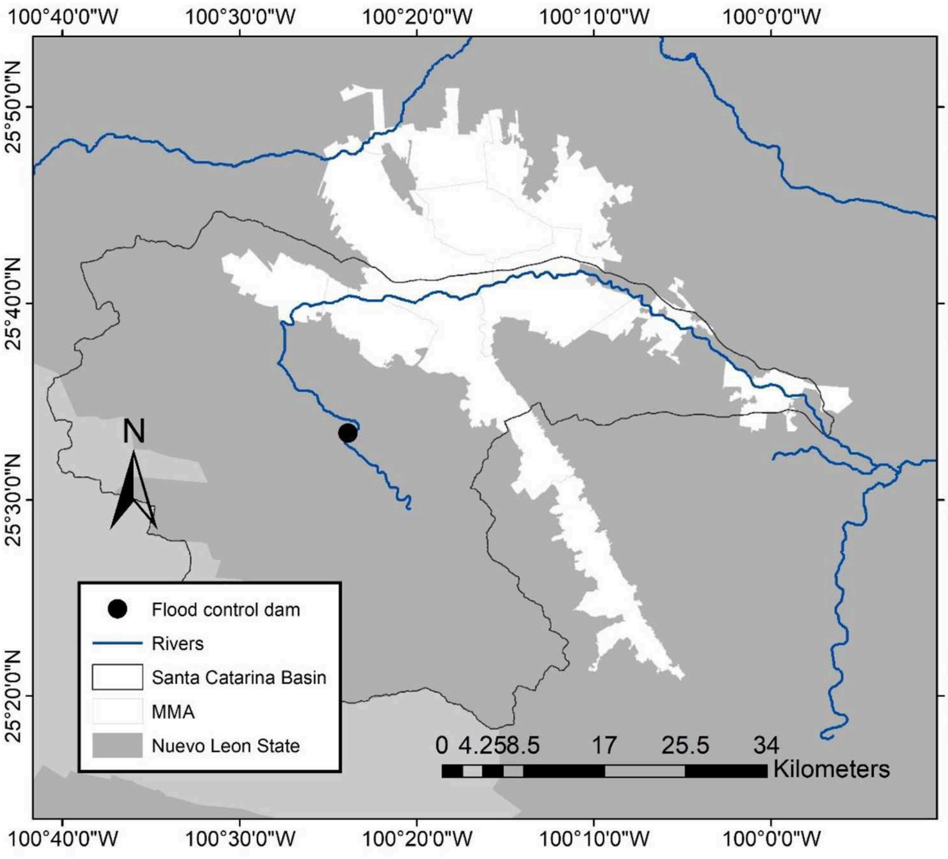

FIGURE 2 | The Santa Catarina river and the Monterrey Metropolitan Area.

flow in the Santa Catarina River was the highest on record (around 4,400 m^3/s CONAGUA, 2018 (**Figure 3**). The number of human losses vary from over 220 to 280 (Chávez Gutiérrez, 1995; Salazar, 2008; CERNL, 2013). Damages to the metropolitan mobility infrastructure were severe (Bitrán, 2001; Benavides and Lozano, 2013; OECD, 2013b). The magnitude of the damages was compounded by irregular settlements along the margins and even on the river bed, showing the deficient enforcement of land use regulation (de León Gómez, 2009), and the limited or almost non-existing warnings. The early warning system (EWS) was yet to come.

Hurricane Gilbert caused all the damages mentioned above, but also paved the way for more resilient preventive measures to face future floods. Civil protection systems were strengthened and flood control infrastructure was constructed. This is in the case of the Rompepico dam, built during the years 2002–2004. This dam was built in the upper part of the Rio Santa Catarina basin, 22 km upstream of the metropolis to regulate flows in the river. Years later an urban storm drainage system was also undertaken (in the period 2002–2009). The Rompepicos dam was first tested, successfully, during the occurrence of Hurricane Emily in July of 2005. The EWS were already in place (Cenapred, 2006). Damages were small and no human lives were lost. This was not going to be the case of Hurricane Alex, which would hit Monterrey 5 years later. In both cases, however, the role of this soft and hard infrastructure was crucial.

As a background to what is the central theme of this paper, it is worth mentioning the establishment of the State Reconstruction Council to deal with the reconstruction after Gilbert (Benavides and Lozano, 2013). This council was formed 2 days after the hurricane hit. In comparison with what was going to be the case of Hurricane Alex, this board was fairly small. It was presided over by the state governor. As in the case of Alex, however, the reconstruction was led by a prominent figure of the private sector. The council had immediate access to a civil contingency fund of then 1,000 million pesos (US $ 440 million), created as a result of the earthquake that hit Mexico City in 1985. This fund was created precisely to attend a contingency derived from a natural disaster. In September 2013 came Hurricane Ingrid; the damages were not very significant. Ingrid did, however, bring much needed water to fill up the reservoirs that supply water to the MMA.

THE IMPACTS OF HURRICANE ALEX (2010) AND WATER GOVERNANCE IN THE MMA

Hurricane Alex and Its Impacts

Alex is considered among the strongest hurricanes that have affected Mexico in the last 50 years. In Nuevo León, this hurricane caused the loss of at least 15 people and considerable economic

TABLE 1 | Flooding history of the Monterrey Metropolitan Area, 1909–2013.

Year and event	Impacts
1909	The worst flooding in the history of the city. It is estimated 5,000 people died.
1938 (28 of August)	Torrential rains uncommunicated parts of the city.
1967 (20 September)	Hurricane Beulah. This hurricane filled the río Santa Catarina to its maximum capacity, water remained within its banks.
1986 (4 September)	It is estimated 20 people die in this flooding.
1988 (16-17 September)	**Hurricane Gilbert*** hit the MMA. Over 200 people lost their lives. As a result, major infrastructure works were carried out. Estimated precipitation of 175 mm. Peak flow of 4,400 m^3/s.
1999 (14 June)	Heavy rains cause severe damages. Eighteen people lost their lives.
2005 (19–21 July)	Hurricane Emily did bring about heavy rains. Though there were no human losses, damages did occur.
2007 (21–23 August)	Strong rains produced by Hurricane Dean.
2008 (20–25 July)	Intense rains brought about by Hurricane Dolly
2010 June 29–July 2	**Hurricane Alex*** hit Nuevo León State and the MMA. It is estimated 15 lives were lost, in addition to considerable damages in the infrastructure of the city. Estimated precipitation of 275 mm. Peak flow of 2,700 m^3/s.
2013 (September 13–14)	Hurricane Ingrid did not cause significant damages; no lives were lost: The heavy rains filled the reservoirs that supply water to the MMA.

**Emphasis added in the light of their significance to the MMA. They are usually considered as reference.*
Own elaboration based upon Torres and Santoscoy (1985), CERNL (2013), Aguilar-Barajas et al. (2015), and Sisto et al. (2016).

assets (Sisto and Ramírez-Orozco, 2015). In Nuevo León, and particularly in the MMA, Alex did bring about torrential rains that amounted to up to 446 mm in 24 h and above 800 mm in 48 h. It is estimated that the maximum discharge on the Santa Catarina River was about 2,700 m^3/s (Ramírez, 2011). According to CONAGUA (2018), the Santa Catarina River reached its second highest recorded flow (**Figure 3**). This was the direct result of the flood control dam, built upstream from the city as part of post-Gilbert resilience building efforts in the MMA. **Figure 4** exhibits a view of the river during the event. **Figures 5–7** illustrate some of the damages in the city.

The damages of Alex included urban infrastructure (electrical network, water and drainage, as well as roads and bridges), housing and vehicles (**Table 2**). The two main arteries of the metropolis—*Constitución* and *Morones Prieto* were seriously affected (**Figures 8–11**). This not only caused severe mobility problems for the MMA, but it also damaged the links of the city with national markets and the US (via Texas). The CERNL estimated the reconstruction works at around MX17 billion pesos (US$ 1.3 billion). Estimates of the OECD suggest a figure of over US$2.1 billion (OECD, 2013b). Since these are the estimates for the reconstruction that took place, it is very likely that the real damages had been higher. Fortunately, the flood control dam plus the storm drainage infrastructure, as well as the EWS were key to reducing the adverse impacts of Alex. This time the city was not taken by surprise.

The Existing Framework for Flood Management in the MMA Before Alex

Hurricane Alex revealed the coexistence of both a resilience base and serious vulnerabilities in respect to flood management in the MMA. Concerning the former, before this event the metropolis already had in place the flood control dam, storm drainage infrastructure, as well as the EWS. There was also a proven financial capacity of prosperous metropolis, as well as a long-standing business and academic involvement in urban policy design. Although Alex revealed some shortcomings, it is also fair to say the metropolis displayed technical capabilities in the recovering process. The case of the metropolitan water utility—and the quick recovery of water and sanitation services—is a good example. It is worth underlying that business leadership and credibility were key in the establishment and performance of the CERNL.

Notwithstanding this context of preparedness, by the time Alex hit there was also a vulnerable metropolis. Metropolitan governance was not functioning well (EGAP, 2010), which was illustrated by the insufficient coordination between and within the three levels of government—federal, state, and local (Aguilar Barajas et al., 2016). The legal framework was either unclear or with superseded responsibilities of these levels. Comprehensive urban planning and risk management were rarely mentioned in the state development plan of the time (Gobierno Constitucional del Estado de Nuevo León, 2010a). Furthermore, it is striking that the draft of the first Risk Atlas (Gobierno Constitucional del Estado de Nuevo León, 2010b) was still under review well after the hurricane had hit the state and the metropolis. Not surprisingly, as it happens in Mexican cities, irregular settlements exposed to flooding were also very common, notwithstanding the fact that the regulatory framework prohibited this practice (Leal Diaz, 2012). Solid waste management was separated from water and sanitation management. The leisure and sporting structures and activities located on the river bed could have contributed to reduce the hydraulic capacity of the river, which was already insufficient to handle the flow. The enforcement of land use planning directives faced strong political opposition.

In summary, the balance of resilience and vulnerability conditions prior to Alex indicate the existence of a local enabling environment that was able to mobilize collective actions and the establishment of the CERNL.

HURRICANE ALEX AND THE NUEVO LEÓN STATE RECONSTRUCTION COUNCIL (CERNL) (2010–2013)

The Council's Structure and Operation

The arrival of Hurricane Alex in July 2010 has been highly significant for the state of Nuevo León and the Monterrey Metropolitan Area, especially due to the way in which reconstruction works were addressed. The same month that hurricane Alex occurred, the state government established the State Council for the Reconstruction of Nuevo León (CERNL), to guide and coordinate all reconstruction works. The Council was formed with representatives from all three levels of government

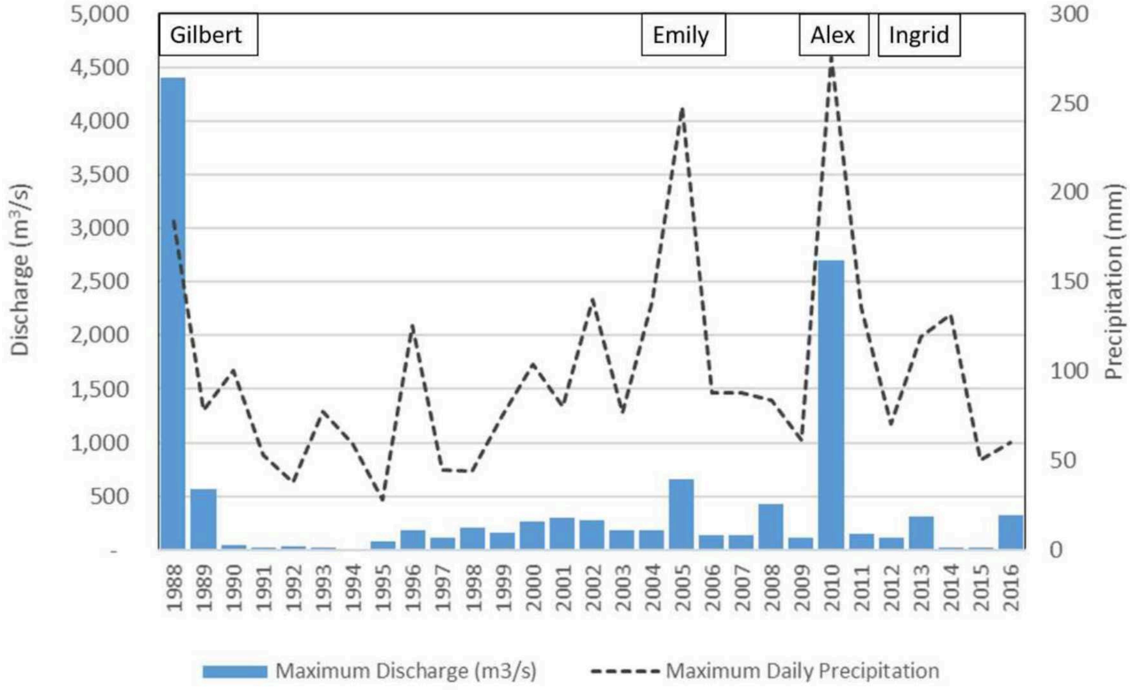

FIGURE 3 | Peak flow Santa Catarina River and maximum daily precipitation (MMA), 1988–2016.

FIGURE 4 | The Santa Catarina River during Hurricane Alex, July 2010. Courtesy from the National Water Commission.

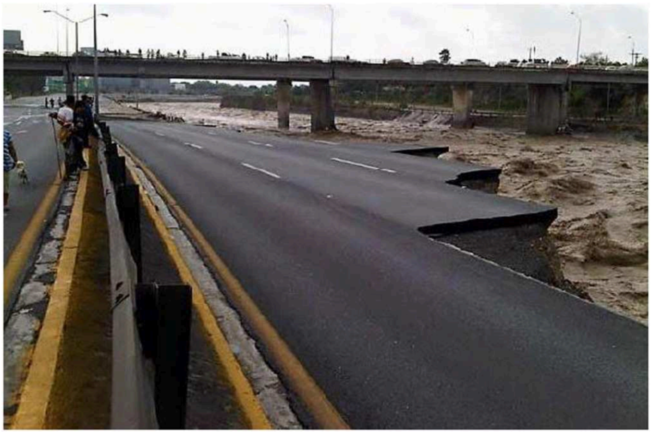

FIGURE 5 | Damages to urban metropolitan mobility infrastructure.

and civil society actors, predominantly from prominent members of the business community and the principals of the major local universities. The operation of the Council was structured into ten committees (**Table 3**). The coordination of the committees was held by prominent figures of the business community (CEOs of large Mexican corporations based in Monterrey) and the academic world (principals of the major local universities).

Although the overall functioning of the CERNL went relatively well, the operation of the Council was complex and not trouble free. Coordinating this large number of committees was difficult, a situation that was exacerbated by the rotation of those responsible for federal and state agencies due to normal changes in government positions (Torregrosa et al., 2015). Soon after the establishment of the CERNL, between half and two thirds of government officials left their positions. Although these positions were filled by other people, it is likely that these changes had affected the undertaking of works.

For example, in April 2011 the structure of the Council saw changes. In the third planning meeting, which took place on the 11th of this month, it was decided to conclude and/or restructure

FIGURE 6 | Damages to urban metropolitan mobility infrastructure.

FIGURE 7 | Damages to housing.

TABLE 2 | Impacts and damages of Hurricane Alex (2010), Monterrey and Nuevo León, Mexico.

- Fifteen people lost their lives
- 12 thousand people rescued and evacuated
- 68 thousand households required emergency help
- 148 thousand homes without power
- 1.7 million residents without piped water services
- 7.8 million square meters of pavement washed away
- 154 culverts obliterated
- 100 bridges damaged or ruined
- 54 km of piped water lines wiped out
- 45 km of sewerage lines destroyed
- 1,502 schools affected at various levels
- 211 health clinics damaged

CERNL (2013) and Sisto and Ramírez-Orozco (2015).

the works of several committees. Educational Infrastructure, Aid for Vulnerable Households and Attention to Citizens belonged

FIGURE 8 | Impacts to Constitucion Avenue. Courtesy from El Norte.

FIGURE 9 | Partial destruction of Constitucion Avenue in central Monterrey. Courtesy from El Norte.

to the first group. The committees of Meteorological Risks and Hydraulic Works, Housing and Urban Planning were integrated into the Citizens Council for Urban Development. By doing this, the very important functions originally assigned to these committees lost relevance. This was also the case for the Committee for Economic Reactivation which was incorporated into the program *Nuevo León: A model for Development*.

First Tasks and Responses From the Nuevo León State Reconstruction Council

Very early on, the Council understood the seriousness of the *problematique* behind the reconstruction tasks. In its second working meeting, on the 16th of December, 2010, the CERNL reached the following agreements, which are cited textually below and were taken from the official website of the Council:

- To manage in an efficient and transparent way the resources from FONDEN, and those from FONAREC;
- To seek an ordered urban development pattern;

FIGURE 10 | Damages to Morones Prieto Avenue. Courtesy from El Norte.

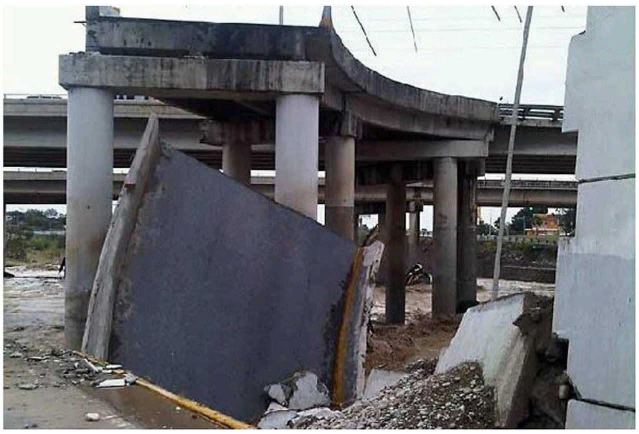

FIGURE 11 | Severe damage to bridge over Constitucion-Lopez Mateos Avenue. Courtesy from El Norte.

TABLE 3 | Committees of the Nuevo León State Reconstruction Council, after Hurricane Alex, 2010.

Committee
• Design and management of a reconstruction master plan and information system
• Financing and transparency
• Meteorological risks and hydraulic works
• Logistics, roadways and mobility.
• Educational infrastructure.
• Housing and urban planning
• Aid for vulnerable households and attention to citizens
• Economic recovery
• Health
• Communication

Own elaboration based upon (CERNL, 2013).

- To monitor, closely, the commitments, requirements, and necessary supports for the execution of priority reconstruction projects, including, of course, the two major avenues *Constitucion—Morones Prieto*, which are at the heart of the metropolis's mobility and its links with national and US markets;
- More particularly, the National Water Commission identified that the main problems to be solved had to do with three issues: water infrastructure within the river bed; vegetation within the river bed; and irregular settlements. These problems were well-known before Alex hit the metropolis.

To achieve these agreements, however, required major institutional coordination and a flexible management of FONDEN's and FONAREC's financial resources. In the Mexican context, however, to do this means to go against a highly fragmented and dysfunctional water and metropolitan governance architecture (OECD, 2013c; Torregrosa et al., 2015; Aguilar Barajas et al., 2016). Not surprisingly, the Council had to face and solve several coordination problems (CERNL, 2013). More particularly, cooperation among the three levels of government—although it did take place, perhaps in a far better way than is usual in Mexico—proved to be difficult. The access to funds from FONDEN and FONAREC is a case in point.

Notwithstanding this context, inter-institutional collaboration was essential to undertake key interrelated projects (CERNL, 2013). For instance, the maintenance of the flood control dam, upstream of the Santa Catarina River, by SADM and the state secretariat of urban development and public works, required rapid access to FONDEN's funds to repair the connecting road, for which the Federal Ministry of Communications and Transport (SCT) was responsible. This task, however, was in conflict with the establishment of irregular human settlements on or near risky river bed areas, whose responsibility was shared by the National Water Commission, the Nuevo León sustainable development secretariat, and the metropolitan municipalities. Reinforcing river banks and the rectification of the Santa Catarina River also fell within this multi-institutional framework (Ramírez, 2011; Sisto and Ramírez-Orozco, 2015).

CONAGUA also requested the federal Secretariat of Environment and Natural Resources (SEMARNAT, in Spanish), in the light of the emergency and urgency, not to comply with the Environmental Impact Assessment—required for the undertaking of hydrological and hydraulic studies needed in the rectification of the Santa Catarina River. The Commission also asked for the reallocation of the existing infrastructure within the river bed, which obstructed the reconstruction works. This infrastructure belonged to the Federal Electricity Commission, the state water authority and even private firms. In the case of water, there were pipelines dating back to the beginning of the 1900s.

The above account is very illustrative in the sense that it shows the kind of problems and challenges predating Alex, but that became very visible during the reconstruction works. As shown, the projects and actions to be undertaken were very diverse and interrelated. Some were of a financial nature but others required changes in the normative framework. In many cases, the challenge was to improve the inter and intra institutional communication channels. The CERNL was well aware of this and, accordingly, designed a matrix to interrelate problems, requirements and commitments of all institutions involved. This matrix enabled them to see very clearly all these links.

Reconstruction Works

Achievements

Given the restrictive water and metropolitan governance framework in Mexico, the reconstruction works went fairly well. As it will be shown, most basic services were reestablished relatively shortly. As mentioned, the existing culture of public-private collaboration was key in both the establishment and operation of the Council. In spite of the shortcomings and limitations of the CERNL to guide and carry out the reconstruction works—some of which were of a more structural and external nature—the city was able to recover rather rapidly. The degree of collaboration around the reconstruction works is not common in Mexico. There was already the prior experience of the reconstruction after Hurricane Gilbert, whose coordination, as expressed earlier, needed the collaboration of the private sector, in addition of course to government efforts at the federal, state and local spheres. Over the decades, the city has been accumulating knowledge and technical capabilities to increase resilience to this kind of events.

The CRNL was established almost immediately−3 weeks after the incoming of Alex. The Council had eight planning sessions in its 3 years of existence, plus numerous working meetings of the specific committees. A great deal of documentation was generated about the undertaking of projects and particular actions. In addition to the final memoir that was prepared (CERNL, 2013), studying the issues discussed in each session provides rich elements to understand the real achievements, limitations and shortcomings of the reconstruction. During these 3 years, progress reports were produced to cover not only physical but also economic, financial and auditing issues.

The coordination works of the CERNL led to a quick recovery, as illustrated in the next four examples. Approximately 85% of the metropolis's population had access to pipeline water only 3 days after the disaster. This service reached the entire population within 15 days. At the end of the month the city was able to drink water from the tap, as before (SADM, 2010a,b). To achieve this required truly hard work by the water and sewer agency to repair the damaged infrastructure and to ensure the population remained informed about the progress of the reconstruction. This authority reports on the work of 2,200 workers and the use of 300 vehicles on a continual, 24 h basis. Rapid recovery was also shown by the fact that schools started classes in August, on time, notwithstanding their infrastructure was partially seriously damaged (CERNL, 2013). Furthermore, the intervention works in the river itself are worth noting: 27 km of the Rio Santa Catarina riverbed were rectified, as well. The fourth example is given by the reconstruction of the *Constitución* and *Morones Prieto* avenues, which are, as mentioned before, the heart of the MMA's mobility. This case is addressed next.

Throughout the state, transport infrastructure was one of the sectors most damaged by Alex. For example, the reconstruction of the avenues *Constitución* (on the north bank of the Santa Catarina River) and *Morones Prieto* (on the south bank), as well as several bridges—was a central task for the CERNL. These avenues, which follow the course of the river, are key for the metropolitan mobility (and economy), and also maintain a national relevance. The Secretariat of Communications and Transport (SCT, in Spanish) understood very well this regional and national significance. For the SCT, the proposed work for these avenues was thought not only to improve intra-metropolitan mobility, but also the communication of the transport network of Monterrey with the rest of Mexico and the US (especially with Texas)[1]. Therefore, the reconstruction work after Alex was not a local concern only, but of national interest. This is consistent with the longstanding recognition of Monterrey as a major North American trade metropolis and at the heart of what has been referred to as the Tex-Mex trade axis.

Another major issue worth highlighting, and which applies to the reconstruction work as a whole, is that the new strategic infrastructure built represented a major improvement in regard to the existing one before Alex; therefore, the city is in far much better conditions to face future floods (Sisto and Ramírez-Orozco, 2015). It is possible that this new infrastructure has had a beneficial role in the almost insignificant damages brought about by Hurricane Ingrid in September 2013. This new event, however, as addressed below, also showed some of the limitations of the reconstruction. Overall, the Monterrey case shows what in the literature is referred to as *building back better*.

In July 2013, 3 years after Alex, the CERNL formally ended its mission[2]. A final report included the complete undertaking of 5,523 actions, which represent 99.5% of all those proposed initially (CERNL, 2013). The total reconstruction expenses were estimated at almost 17 billion pesos (approximately US$1.3 billion) (**Table 4**). These expenses amounted to ∼1.8% of the 2010 state Gross Domestic Product (OECD, 2013b). Out of this total, over 10,000 million pesos were contributed by the federal government (62%); almost 6,400 million pesos came from the state government (38%)[3]. The state, however, handled most funds—almost 12,100 million pesos—regardless of the financial source. Of this total, 95% were allocated to three areas: Roads, 48%; urban infrastructure, 39%; and water, 8.4%. Out of the funds operated by the federal government—almost 4,800 million pesos−96% went to the water sector[4]. It is worth noting that the social sector only received around 4% of the total expenditures (education, 2.9%; housing, 0.9%; and sanitation, 0.3%). The environment represented only 0.5%.

Limitations and Shortcomings

There were also limitations and shortcomings in regard to the reconstruction work. In fact, at the moment of presenting the final report of the CERNL there several tasks were still pending

[1]The recognition of the significance of these two avenues was presented during the working session of the CERNL, 2 years after Alex, which took place on the 5th of July, 2012. This information was obtained from the Council web site.

[2]See press communique No. 26, of 18 July 2013. The following figures come from this document. In this meeting was presented the Memoir 2010–2013 with which the Council concluded formally its work.

[3]Although out of this total, MX1400 million pesos were provided by the FONAREC, which means that the share of the state government is lower.

[4]The source of thee data is: Secretaría de Finanzas y Tesorería General del Estado, Fondo de Desastres Naturales, Presentation of 18 July, 2013, internal document, available then on the webpage of the Council.

TABLE 4 | Reconstruction expenditures, sources of finance and operation of funds, 2013 (millions of pesos).

Sectors	Federal source	State source	Total	Percentage of subtotal
Subtotal operated by the State of Nuevo León				
Roads	2,895	2,895	5,790	48.0
Urban	1,883	2,824	4,708	39.0
Water	512	512	1,024	8.4
Education	278	83	361	2.9
Housing	73	30	103	0.9
Environment	33	33	66	0.5
Health	20	20	40	0.3
Subtotal	5,694	6,397	12,092	100
Subtotal operated by the Federal Government				
Roads	178			
Water	4,606			
Subtotal	4,784			
Total	10,478 (62%)	6,397 (40 %)	16,875 (100%)	

Own ellaboration based upon "Presentación de la Secretaría de Finanzas y Tesorería Estatal de Nuevo León, Natural Disaster Fund. 18 July, 2013". 8th Planning Meeting.

completion. The incoming of Ingrid confirms the latter. Some of the works done in the reconstruction of Constitución and Mororones Prieto were not done entirely well. In several parts of these two arteries no storm drainage was introduced. The rains of Ingrid highlighted this problem and caused problems to transit and mobility. In the view of authorities there were no funds for this infrastructure (Aguilar-Barajas, 2013). Furthermore, in the context of the urgency to undertake the reconstruction work, some norms were not observed (Leal Diaz, 2012).

Although in its final report the CERNL mentioned that federal and state funds were assigned on time and in the agreed forms, it does not seem this was entirely the case. This is so true that one of the main recommendations of the report underlined the need to restructure the functioning of FONDEN and FONAREC (and their operating rules) as well as changes in the Public Works Law. As a matter of fact, 2 years after Alex, some of the damages were still unattended. The incoming of Hurricane Ingrid in September 2013, demonstrated the existence of deficient work in the main arteries *Constitution* and *Morones Prieto*. The press from those days illustrates this situation. Another example that things were not always well was the intention of the state government to substantially reduce its share in the total reconstruction budget, with hopes that the federal government would take a larger share. Once this was not accepted, there was also the intention to cover part of the state's share with funds from the 2011 federal budget proposal that did not pass either.

Without changing it entirely, the CERNL addressed relatively well the water governance framework existing before Alex. Even within this framework it was possible to secure inter and intra institutional collaboration at the three levels of government. It was mentioned earlier that metropolitan and flooding management in the MMA before Alex had very restrictive conditions. At the end of the Council work, the question was, "what is going to happen to this institutional capacity built for handling the reconstruction?" With the ending of the CERNL's mission, and in spite of the fact that the Council left a highly-detailed memoir of what to do in the future, in practice it seems that all this knowledge capital has been fading away. In part, due to the work of the Council, the state created the Nuevo León Council for Strategic Planning, charged with the responsibility to elaborate the State Development Plan. It is striking, though, that in these initiatives the issues of risk and flood management are given little attention.

It is also fair to say that while the CERNL contributed to the city's reconstruction after the occurrence of Alex, it lacked the structure to address underlying issues and structural matters associated with urbanization, like irregular human settlements along and on the river bed and the presence of climatic events. The complexity of these issues and their understanding go beyond actions designed in times of emergency.

DISCUSSION

In large urban areas with high relevance to their national economies, such as the Monterrey Metropolitan Area, managing weather hazards, like flooding, should be seen as an issue of national interest. In this regard, robust water governance must be at the center of development policy design and implementation. As found by the OECD for the international arena, to a large extent water crises have to do with deficient governance frameworks (OECD, 2011). Therefore, thinking in terms of sustainability challenges for urban futures, which is the topic of this special issue of *Frontiers in Environmental Science*, the Monterrey story shows that investing in comprehensive, robust urban planning represents a good strategy to face climate change and variability.

The relatively effective reconstruction of the metropolis was possible thanks to the coordinated and collaborative work of a committed institution like the CERNL. In spite of the inherent difficulties the Council had to face—mostly due to the dispersion of the metropolitan and water governance—basic services were reestablished in a fairly rapid manner. This includes water, electricity, transport, and schools' infrastructures. After the summer holidays, students could return to school as if nothing had happened. Credibility in leadership was at the center of these achievements. It is fair to say that while the CERNL contributed to the city's reconstruction after the occurrence of Alex, it lacked the structure to address underlying issues and structural matters associated with urbanization and the occurrence of extreme climatic events. The complexity of these issues and their understanding go beyond actions designed in times of emergency.

The recognition of this complexity is clearly seen when one looks at the recommendations contained in the final report of the CERN, oriented to respond more effectively to the risks imposed by future hurricanes. Knowledge produced within the Council was presented in a systematic and ordered fashion in its final report. The main takeaways in terms of recommendations for increasing resilience to floods consisted in: building an additional regulating dam in the upper Santa Catarina River Basin to complement the existing Rompe Picos Dam system (arguably, two or more additional dams would be of use); relocating people living in areas at risk of flooding and impeding their return (i.e., to enforce existing federal land use laws); reforming and simplifying existing regulations on the operations of FONDEN as well as procedures for public works contracts (i.e., to cut red tape); reforestation of the upper basin of the Santa Catarina River to limit runoff downstream and into the city.

The MMA Water Fund (FAMM in Spanish), created in 2013 for that specific purpose, gathered stakeholders from government, the private sector, academia, and civil society in general. The Fund has been working systematically on this issue. In 2016, it purchased 1,200 hectares of land for reforestation in the upper basin. In 2018, FAMM was in the process of acquiring an additional 1,000 hectares. The message behind these initiatives is that society can organize itself around a common purpose. The connection of FAMM and the construction of capacities in the urban water sector is highly relevant.

CONCLUSIONS AND RECOMMENDATIONS

The Monterrey Metropolitan Area is one of the economic hubs of Mexico and prone to flash flood hazards, which means the attention to this phenomenon is a matter of national interest. Over the decades the metropolis has been increasing its resilience to the presence of hurricanes, through the joint deployment of hard and soft infrastructure. Among the former the flood control *Rompepicos Dam* and the storm drainage program, undertaken in the 2000s in the aftermath of Hurricane Gilbert (1988), are cases in point. Concerning soft infrastructure, the (nationwide) establishment of early warning systems is a good example. The creation of FONDEN and FONAREC also aided in the institutional architecture to face flood hazards.

When Hurricane Alex hit in early July 2010, the city was more prepared due to projects carried out by the state government with the support of the federal government and the local community, despite the fact that the Santa Catarina River reached its second highest recorded flow. The fatalities caused by Alex were estimated at 15. The damages to the state of Nuevo León and the metropolis were, however, considerable. Furthermore, Alex revealed deficiencies in the existing framework for flood management.

In order to face the reconstruction of the state and the metropolis, the State Council for the Reconstruction of Nuevo León was established almost immediately. The Council did a fairly good job in getting things back to normal in a relatively short period of time. As highlighted in this case study, the service of piped water was reestablished for 85% of the population within the 3 days following the hurricane. Schools could start their new academic year in August, without much difficulty. Moreover, the reconstruction allowed for the replacement of strategic (but old) infrastructure, like the arteries *Constitución* and *Morones Prieto*, and several bridges, with much improved or new ones. This more robust infrastructure was tested in 2013 when Hurricane Ingrid hit the metropolis.

This relatively successful reconstruction shows the multi-faceted, collaborative work of the Council, which was the result of an enabling local environment. The Council was able to group and guide the efforts of the three levels of government and those from the civil society. The role of the private sector was essential in the coordination of the more than 5,000 actions documented in the final report. This public-private cooperation has a long-standing tradition in the state and the city and is rather rare in Mexico. Furthermore, this success is even more striking given the fragmented and dysfunctional water and metropolitan governance existing in the country. This is one of the major lessons of this case study.

Of course, there were limitations and shortcomings in the reconstruction process. The above restrictive framework meant time had to be invested in creating the necessary collaborative networks. Access to the funds of FONDEN and FONAREC could have been faster. Attention to the social agenda was limited. Handling land use regulations was beyond the sphere of influence. With the urgency, some of the works along *Consitución* and *Morones Prieto* arteries were not done well.

Several policy recommendations derive from this case study. For a hurricane prone region like the MMA, the incorporation of coherent urban planning should be a permanent, central part of local and national development policy. As shown, the losses associated with Alex had to do more with insufficient urban planning than with the phenomenon itself. More particularly, the incorporation of hydrological criteria and sound land use planning into urban development plans—and its corresponding legislation—are urgent matters.

Overall, the case of Alex indicates the need to professionalize the management of weather hazards. The Council gained and accumulated valuable knowledge that could be of use in the creation of a more permanent institution, whose work banks upon more proactive approaches and less on emergency-based responses. This new entity would need to have the capacities to draft a long-term plan for the metropolis. This proposal is a must in times when, paradoxically, the awareness and influence of the Council has been fading. Since July 2013, when the Council ended its mission, the interest and actions toward a comprehensive, preventive model has been diminishing. The lesson here is that the social construction of all this knowledge to increase urban resilience might be lost. Going back to the "business as usual" philosophy (Shaw, 2005), and waiting until the next hurricane comes, is not a sound strategy, especially under the current challenges imposed by climate change. In this more coherent approach, the focus on robust urban planning is a must.

More specifically, there is also the need to develop and use robust methodologies for valuing the impacts and adverse effects of future hurricanes. In turn, this requires the formation of human resources highly specialized in these matters. Although it did not get the level of other projects in the city and the country, the faults detected in the reconstruction of *Constitución* and *Morones Prieto* avenues revealed by hurricane

Ingrid in 2013, show the fundamental importance of the initial design of infrastructure projects, which includes the professionalization of both the monitoring of projects and the budgeting process. This professionalization should also include the technical analysis of hydro meteorological risks and the proper communication of weather hazards like flooding. All these requirements suggest the need to strengthen the university curricula concerning disaster risk management. The media should also be included in this better equipped understanding of these issues.

In the end, it may be fair to hope that the lessons and experiences drawn from the case of Monterrey may also be of interest to other cities in Mexico and Latin American (Torregrosa et al., 2015). This case study shows that for metropolis like Monterrey, tackling the impacts of a hurricane like Alex, requires the collective production of knowledge and well-informed decisions about risk. The costs and benefits of risk taking in the light of development policy in general and flooding in particular have been the theme of serious research in the international sphere (WMO, 2009; UNESCO, 2012; World Bank, 2013). A useful warning for Monterrey, derived from the review of international literature (Frantzeskaki and Kabisch, 2016; Muñoz-Erickson et al., 2017), is that knowledge systems are dynamic—they do not last forever. The fading institutional capabilities and learning gained by the CERN, should be taken as reminder of the crucial necessity of sustaining and improving these capabilities. Doing this would be an indispensable input for a more preventive strategy. The next hurricane could well be around the corner.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

AUTHOR CONTRIBUTIONS

IA-B: general coordination, economic impacts section, figures, photograph selection and editing, and editorial work. AR: hydrologic and hydraulic concepts, figures, photograph selection and editing, and editorial work.

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An Analysis of Current Sustainability of Mexican Cities and Their Exposure to Climate Change

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The increasing demand for goods and services in cities around the world due to a rapidly growing urban population is pushing the socioecological systems that support them to their limits. The complexity of urban socioeconomic and environmental systems and their interactions generate a challenging multidimensional decision problem. In response, governments around the world are currently generating a variety of measurements that aim to portrait the main factors that are related to the level of sustainability that a city shows. While the objective of these efforts is to help in the process of urban policy making, these measures are often hard to interpret and do not lend to discover underlying characteristics that may be common among a group of cities. Moreover, these measures are typically focused on describing the current state and omit future challenges such as climate change, which may significantly affect any evaluation of urban sustainability. Recently, the Institute of Ecology and Climate Change (INECC) of Mexico produced a dataset of 36 sustainability related variables for over 100 cities that has the objective of helping federal and state level governments defining sustainable urban strategies. Here we use multivariate statistical techniques to (1) decrease the dimensionality of the dataset and find indices that could be more useful to decision makers; (2) find commonalities among cities include in the dataset in order to help in designing urban strategies for cities with similar characteristics; (3) cities are ranked in terms of their sustainability and characteristics and; (4) the sustainability ranking is compared to estimates of how much the current climate in each of these cities is expected to change during this century, which would add further challenges to maintain or improve urban sustainability.

Keywords: climate change, multivariate analysis, cluster analysis, vulnerability, urban sustainability assessment

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INTRODUCTION

Urbanization is one of the most significant trends of this century. Cities occupy about one percent of the Earth's land but account 60–80 percent of energy consumption and over 70 percent of carbon emissions; more than half of humanity lives in urban settlements (Munich Re Group, 2004; Akbari et al., 2009; Dobbs et al., 2011). Climate change impacts would be particularly large in cities due to their enormous levels of exposure and the convergence of socioeconomic and environmental problems and risks: cities account for ~80% of GDP generated worldwide and, by 2050, 70% of the world population (Stern, 2008; Estrada et al., 2017). At the same time, cities have a crucial role in facing climate change. This implies the need of a better understanding of urbanization processes, interactions, and feedbacks with other systems under different timeframes and scales.

By 2030, 60 percent of the world's population is expected to live in cities and around 90 percent of this urban expansion will take place in the developing countries (UN Habitat, 2015). Therefore, leading urban expansion in optimal directions by sustainability goals could foster reducing inequalities within cities and between regions (Sobrino et al., 2015).

Since its popularization in 1972, sustainability remains a broadly defined concept that has been applied to mean everything from environmental protection and social cohesion to economic growth and neighborhood design (Kropp and Lein, 2013). Interpretation of this concept has always caused debate, including the extent to which sustainability could be both a goal and a process, and how the economic, social, and environmental dimensions could be reconciled (Simon, 1989).

More holistic interpretations of sustainability are emerging that focus on urbanization and cities as key components of this process (Simon et al., 2018). There is a need to place this concept into a more functional decision-making context where changes in development plans can be evaluated in a more consistent way with present and future societal needs.

The dataset used in this paper, comes from the Platform of Knowledge about Sustainable Cities (PKSC) of the National Institute of Ecology and Climate Change (INECC) of Mexico. This institutional effort constitutes a self-evaluation tool for local authorities. The PKSC dataset was conceived as a assembly of urban data from a growing number of Mexican cities (135 at present) that is planned to be regularly updated to offer a dynamic description of sustainability for selected cities. It considers ten main dimensions that are related the goal of attaining urban sustainability. This dataset has the objective of facilitating the formulation of urban development policies, which would be prioritized and evaluated, taking into consideration the needs of society.

Urban data analysis must consider that cities are not closed systems; they exert environmental, social, and economic pressure on larger geographic areas. New metrics are needed to identify desirable and undesirable development patterns, synergies, as well as underserved urban aspects. These metrics could help designing better urbanization policies at local, national, and international level. The use of multivariate techniques to analyze to the broad dataset provided by the platform, with the addition of climate change scenarios for each location, is a step toward transforming the PKSC into a useful tool for policy-making.

This paper is structured as follows. Section Data and methods describes the datasets and methods used, and briefly discusses the benefits of multivariate analysis to analyze multidimensional datasets such as those commonly used to evaluate urban sustainability. Multivariate sustainability indices are proposed, and their interpretation is discussed in section Multivariate sustainability indices, cities similarities, and rankings. Cities are analyzed using biplots of indices and cities are ranked according to multidimensional scores. Cluster analysis is used to find groups of cities that are most similar according to the proposed sustainability indices. Section Climate change and urban sustainability challenges discusses the expected changes in climate for the different cities using distance measures based on 19 bioclimatic indices between current climate and expected changes in climate during this century. Cities are grouped according to their current sustainability scores and the level of challenges that changes in climate will impose them. Section Summary of main findings and conclusions summarizes the main findings, proposes future extensions to the present analysis and concludes.

DATA AND METHODS

Datasets Description and Sources

The dataset of variables related to sustainability in Mexican cities was obtained from the PKSC platform of INECC[1] The PKSC has the main objective of providing multidimensional information to stakeholders, decision-makers, and society at large about urban challenges, green growth, mitigation, and adaptation instruments to climate change. For this study, we consider the variables that are described in **Table 1**. Form a total of 36 variables that are available from PKSC (**Table A1**), 22 were selected for this study. The selection of these variables was done in collaboration with INECC and it responds mainly to data quality and availability as well as to the represent ability of multiple dimensions of urban sustainability as conceptualized in PKSC, and avoiding excessive overlap of variables measuring very similar characteristics. These variables cover key socio-environmental aspects such as: water, energy, atmospheric pollution, motorization, urban greenspaces, population, GDP, waste generation, land use and management. **Table A2** in the **Appendix** lists all the cities included in the analyses and their ID number.

To evaluate the potential changes in climate that the cities could face during this century, we use the projections from four General Circulation Models (CCSM4, HadGEM2-AO, IPSL-CM5A-LR, MIROC-ESM-CHEM) included in the Coupled Model Intercomparison Project phase 5 (CMIP5). We followed commonly used general guidelines for climate change scenarios for impact assessment, which include selecting at least two climate models and contrasting emissions scenarios (IPCC-TGICA, 2007; Conde et al., 2011; Estrada, 2018). The climate variables used are monthly mean, maximum, minimum temperatures, and accumulated precipitation. To explore the uncertainty caused by different development pathways, we include the RCP2.6, RCP4.5, RCP6.0, and RCP8.5 emissions scenarios. However, most of results are presented mainly for the RCP8.5 and RCP2.6 scenarios as they depict the most dissimilar trajectories and cover the full emissions uncertainty considered by the IPCC. The RCP8.5 represents a high-warming scenario with no international mitigation and the RCP2.6 an stringent climate policy scenario consistent with the Paris Climate Agreement goals. All scenarios were obtained from the WorldClim 1.4 downscaled database (Hijmans et al., 2005). Two future temporal horizons are considered: mid-term and long-term scenarios, referred to as 2050 (the average of 2041–2060) and 2070 (the average of 2061–2080), respectively. We concentrate in the mid-term scenario results since the consistency between the PKSC data and the climate projections decreases with time as large socioeconomic and ecological

[1] https://www.gob.mx/inecc/acciones-y-programas/crecimiento-verde.

TABLE 1 | List of variables selected from PKSC for this study and their description.

ID	Name	Description
AG01	Per capita water consumption	Ratio of the quantity of water that is consumed per capita with respect to the amount required to satisfy basic needs. Considers the climate conditions of each city.
AG04	Percentage of hoses with access to piped water	Percentage of houses with access to piped water indoors or within its grounds.
AG06	Percentage of houses with sewage systems	Percentage of houses with access to the city's sewage system or to a septic tank.
AG08	Residual water treatment capacity	Installed capacity to treat residual water divided by the number of dwellers and the amount of water per capita provided by the water network.
AI12	Emission of atmospheric pollutants per capita	Total amount of criteria pollutants produced per year divided by the population count (kg/dweller/year)
BS01	Green areas per capita	Surface of green areas (agriculture, grassland, forest, jungle, xerophytic scrub, secondary vegetation, and other types of vegetation) divided by the population count.
BS03	Ecological restoration	Amount of reforested area.
BS06	Percentage of green areas with respect to the total area of the city	Total surface of green areas divided by the total land surface.
ED01	Energy-efficient buildings per 50,000 dwellers	Amount of buildings that have the LEED certification per 50,000 dwellers.
ED02	Proportion of houses that use solar power	Number of houses that use solar panels or water heathers divided by the total number of houses.
EN01	Proportion of houses with access to electricity	Number of houses with access to electrical power divided by the total number of houses.
EN07	Percent of households that use charcoal or wood stoves	Number of houses that use charcoal or wood stoves divided by the total number of houses.
EN11	Energy-intensity of the city	Total annual energy consumption of divided by gross product.
IN11	Proportion of companies with ISO14001 certification	Number of companies with ISO14001 certification per 1,000 companies in the state.
MO04	Rate of motorization	Amount of motor vehicles per 1,000 dwellers
MO10	Per capita greenhouse gas emissions from transport	Greenhouse gas emissions from transport, per capita (ton/dweller/year).
GMP	Gross municipal product	Gross municipal product.
POP	Urban population count	Urban population count.
RE02	Generation of urban solid waste	Total amount of urban solid waste collected divided by the total population count.
US05	Urban household density	Number of households divided by the total surface of the city.
US06	Ratio of urban built-up areas and population growth rates	Rate of growth of urban built-up areas divided by the rate of growth of population.
US09	Urban and territorial planning level	Total number of normative urban or territorial planning actions divided by the number of municipalities within the city.

changes are expected to occur during the century which are not reflected by the current PKSC dataset. However, the combination of the PKSC analysis and the long-term climate scenarios provides some insights that may be valuable for decision-makers. Thus, the 2070 results are included in the **Appendix** and are only briefly discussed in the text.

The statistical techniques used to analyze the information contained in the PKSC dataset are described briefly in the remainder of this section and **Figure A1** provides a flowchart describing how these techniques were applied. Principal Component Analysis (PCA) is commonly used to reduce the dimensionality in a set of interrelated variables, while retaining most of the variability present in the original dataset (Jolliffe, 2002). Moreover, this technique has the potential to provide insights about the interrelations of variables and their spatial and temporal patterns, as well as to suggest new interpretations of the original data (Jolliffe, 2002; Wilks, 2011). Note that the interpretability of the results of PCA does not come from the mathematical procedure, but from the experience and ingenuity of the analyst and thus have a subjective component (Jolliffe, 2002). PCA makes use of the variance-covariance structure of the data to produce linear combinations $Y_i = \sum_{j=1}^{n} a_{ij}x_j$ that are orthogonal to the original dataset X. The first principal component (PC1) is the linear combination $Y_i = \sum_{j=1}^{n} a_{ij}x_j$ that maximizes $var\left(a_1{}'X\right) = a_1{}'\Sigma a_1$ subject to the constraint $a_1{}'a_1 = 1$ and where Σ is the variance-covariance matrix of the dataset X. The maximization of quadratic forms on the unit sphere is achieved when a_1 is equal to the eigenvector associated to the largest eigen value (called by convention the first eigenvector) of the variance-covariance matrix of X. The remaining principal components (PC) are the linear combinations of $a_1{}'X$ that maximize $var\left(a_j{}'X\right)$ subject to the constraints $a_j{}'a_j = 1$ and $cov\left(a_j{}'X, a_k{}'X\right) = 0$ for all $j \neq k$. The factor loadings L are the product of the eigenvector entries and the squared root of the eigenvalue that corresponds to that particular eigenvector. Loadings represent the correlations between the PC and the original variables and help determining which variables are more closely associated to a particular PC. Scores $Y_i = \sum_{j=1}^{n} a_{ij}x_j$ are the projection of the original variables in the new principal component coordinate system. Principal component rotation can help further separating the main variability modes in the dataset and to simplify the interpretation of the PC. For the analysis presented in this paper, varimax rotation normalized is applied, although several other rotation methods are possible, including orthogonal, and oblique (Jolliffe, 2002). In the case of rotated

PCA, the scores are calculated as $F = BZ$ where F is the matrix of scores, Z is the matrix of standardized values of X and $B = L\left(L^{'}L\right)^{-1}$ is the matrix of loadings (Harman, 1976; Jolliffe, 2002). An important step is to select the number of eigenvectors to be rotated, as selecting too few (underrotation) could distort or lead to mixed modes and selecting too many (overrotation) could contaminate the analysis leading to excessive separation of modes (O'Lenic and Livezey, 1988). As suggested by O'Lenic and Livezey (1988), here we analyze the existence of "shelves" which would suggest the mixing of signals and, depending on the amount of explained variance, they could indicate that the remaining PC may represent noise. In the case of no clear "shelves," we combine this truncation criteria with the Kaiser rule which suggests that the PCs with associated eigenvalues smaller than 1 should be discarded (Johnson and Wichern, 2007). The total amount of explained variance of the set of selected PCs is the same before and after rotation. However, after rotation, the explained variance is redistributed among the PCs, and their relative contribution will likely be different.

Cluster analysis is a multivariate exploratory data technique to classify similar cases or variables into meaningful structures based on the values of a data matrix *X*. The aim of this unsupervised learning technique is to find the "natural" grouping of variables or cases contained in a dataset (Johnson and Wichern, 2007). The agglomeration method used for the analysis in this paper is hierarchical clustering, which starts by considering that every observation in the dataset is an individual cluster. This technique requires selecting some similarity (or distance) measure and an amalgamation rule. Several distance measures have been proposed (e.g., Euclidean, Manhattan, Chebychev) as well as amalgamation (linkage) rules (e.g., single linkage, complete linkage, Ward's method) and different selections of linkage and distance can lead to different groupings (Johnson and Wichern, 2007; Hartigan, 2015). The results presented here are based on Ward's method and Euclidean distances.

Bioclimatic Indices

We derived 19 bioclimatic variables (Hijmans et al., 2005) from monthly values of temperature and precipitation for current climate (1960–1990) and each of the future climate change scenarios (four GCM and two RCPs). These variables have been used extensively to predict potential impacts of climate change on ecosystems and species at worldwide (Anderson et al., 2011; Guisan et al., 2017). These indices are listed and described in **Table A3**. The data were interpolated to a pixel resolution of $\sim$5 $\times$ 5 km pixel size for Mexico.

Euclidean Distances as A Description of Climatic Departure

To establish the degree of exposure of urban cities to climate change scenarios is the first step to a comprehensive evaluation of city vulnerability. This provides decision-makes information to help design adequate public policies to adaptation and mitigation in the mid and long-term. The current climate space (i.e., combinations of temperature and precipitation) are usually used to define land use and regulation plans for each city. Here we represent climatic departure by means of Euclidean distances which provide a measure of dissimilarity between current and future climatic conditions for a given of geographical location. The Euclidean distance for n-dimensions is calculated as $d\left(p,q\right) = \sqrt{\sum_{i=1}^{n}\left(p_i - q_i\right)^2}$. This metric also helps to assess how much climatic exposure is projected for each location and temporal horizon, across different models, and emission scenarios. **Figure A2** shows that most Mexican cities are projected to exhibit very different climate spaces since the mid-term and that exposure is expected to vary considerably across space.

Multivariate Sustainability Indices, Cities Similarities, and Rankings

As a first step, PCA analysis was conducted on the PKSC dataset to extract indices that retain a significant portion of the information of the original dataset and to could help identifying the main factors related to sustainability in Mexican cities. The scree plot of the eigenvalues (**Figure A3**) shows that the explained variance decreases smoothly for each additional PC and no shelves are present before the magnitude of the eigenvalues drops below 1, which occurs after PC9. For this reason, the first 9 PC were retained, and the remaining PC were discarded. The set of 9 PC account for about 76% of the variance in the original dataset.

Varimax normalized rotation was applied to the retained PCs and the resulting factor loadings are shown in **Table A4** and a list of names and interpretations of the rotated PCs is provided in **Table A5**. PC1 accounts for about 14% of the total variance of the PKSC dataset and the loading coefficients indicate that the variables that are more strongly correlated with it are POP, GMP, and AG01. Given that these coefficients are all positive, PC1 can be interpreted as an index of city size and development in which high score values correspond to cities with large population, higher economic development and higher per capita water consumption. The association between city size and development, and higher per capita water consumption has been discussed previously in the literature. Economic development and urbanization tend to lead to higher per capita water consumption due to the increase in use showers, washing machines and other residential appliances (McDonald et al., 2014; Paterson et al., 2015). There are some evidence that this association may not hold for cities in highly developed countries (Mahjabin et al., 2018), but the present analysis suggests that for Mexico, city size and development are still associated with higher levels of water consumption. In itself, PC1 suggests that the current scheme of urban development in Mexico can have strong implications for local and regional water resources that are prone to lead to hotspots of high water consumption and scarcity (World Bank, 2018).

The values of the elements of the loading vector indicate that the most important variables in PC2 are the rate of motorization (MO04), the per capita greenhouse gas emissions from transport (MO10) and, to a lesser extent, urban solid waste generation (RE02). PC2 explains about 12% of the total variance of the original dataset and can be interpreted as an index of the relative size of the motor vehicle fleet and its emission efficiency. High PC2 score values are associated to cities in which the motor vehicle fleet and its greenhouse gas emissions are large. This suggests that in such cities transport is dominantly private, urban density is likely low and the use of non-motorized transport is limited, which would lead to higher levels of energy consumption per person/kilometer and higher per capita sector emissions (Gwilliam, 2013; World Bank, 2014).

PC4 is the third most important component in terms of explained variance (about 10%), and the variables that are more closely related to it are the percentage of green areas with respect to the total area of the city (BS06), the proportion of companies with ISO14001 certification (IN11) and the amount of green areas per capita (BS01). PC4 can be interpreted as an index of conservation of green spaces and improved environmental standards. High score values in PC4 are associated with cities with greener and more environmentally committed cities. PC5 and PC6 explain a similar amount of variance (8%) and are related to household characteristics within cities. PC5 is related to the type of energy households have access to. Positive values in this index correspond to access to electrical and solar power, while negative values to more traditional sources of energy such as charcoal and wood for cooking. Access to improved water and sanitation is represented by PC6 which is strongly correlated to the percentage of households with piped water (AG04) and the percentage of households with access to the city's sewage system or to a septic tank (AG06).

The entries of the third loading vector show that PC3 is strongly related to the ratio of the growth rates of urban built-up area and population (BS03) and the amount of reforested area (US06), respectively. The factor loading coefficients for these variables have opposite signs, implying that positive score values in PC3 correspond to cities with high rates of increase in built-up area per capita and small reforestation efforts. PC3 can be interpreted as an urban sprawl index, in which high values indicate expansion of the urban spot while low values denote deliberate efforts to recover green spaces. The remaining three components (PC7, PC8, and PC9) account individually for about 6% of the explained variance and each of them is highly correlated to only one variable. These three PCs are related to different aspects of city management: PC7 is related to air quality represented by the annual per capita emissions of criteria pollutants (negative values in this index denote cities with poorer air quality); PC8 to the city's level of urban and territorial planning (higher values, more regulations); PC9 to the installed capacity to treat residual water (low values correspond to better capacity). Below we present some examples of the usefulness of developing indices by means of rotated principal component analysis to explore the performance of cities in a bidimensional and multidimensional context.

Figure 1 shows a scatter plot of PC1 and PC2 which summarizes about 25% of the explained variance of the original data. The distribution of cities within the four quadrants of the figure depict different development paths in city growth and

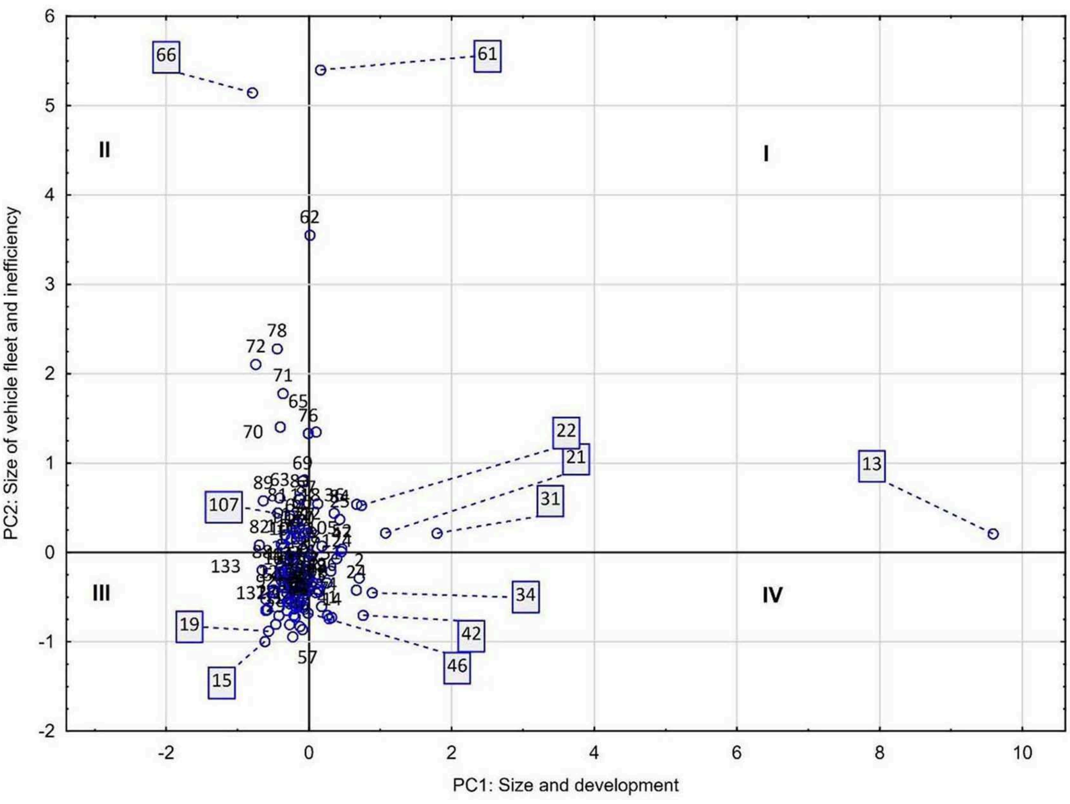

FIGURE 1 | Scatter plot city size and development index (PC1) and size of vehicle fleet and inefficiency index (PC2). A list of names and ID numbers of Mexican cities is provided in **Table A2**.

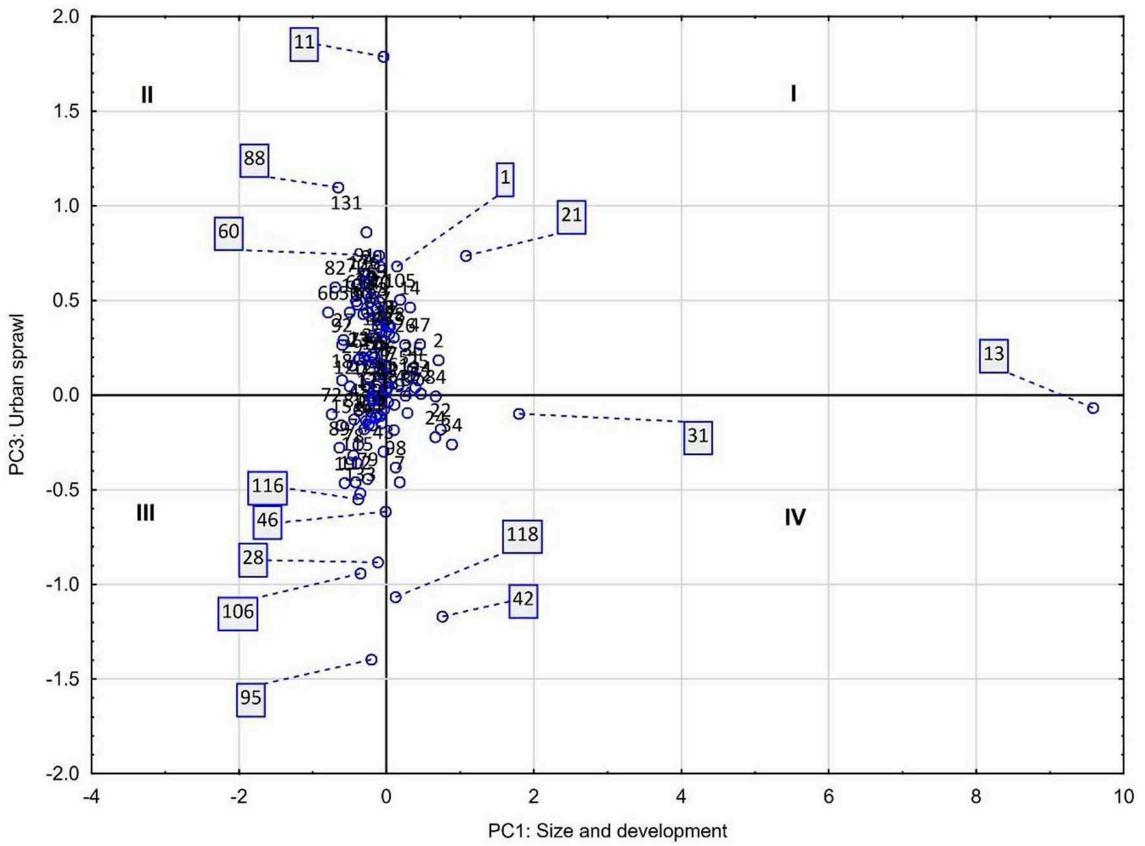

FIGURE 2 | Scatter plot of city size and development index (PC1) and urban sprawl index (PC3). Cozumel is an outlying value in PC3 and it was excluded from the figure to improve clarity. A list of names and ID numbers of Mexican cities is provided in **Table A2**.

transport that have implications about the future sustainability of cities. Quadrant I includes cities with high levels of population and GMP and a transport sector with a large vehicle fleet (dominantly private) and high GHG emissions. The largest cities in México, namely Valle de México (Mexico City metropolitan area), Monterrey and Guadalajara, show a relatively smaller per capita vehicle fleet size and more efficient in comparison to less developed cities in the same quadrant. According to a study from the Mexican Institute for Competitivity (IMCO)[2], Valle de México and Monterrey have much lower CO_2 emissions per vehicle than the average of Mexican cities; Valle de México and Guadalajara and Monterrey rank 1st, 3rd, and 10th, respectively, as the cities with the best public transport system in the country. Large cities that want to improve their sustainability in terms of transport and emissions reduction would have to implement policies to move toward quadrant IV, in which is also characterized by high levels of development but with smaller motorization rates and GHG emissions per capita. It is important to keep in mind that cities in both quadrants I and IV are still characterized by high levels of water consumption per capita that may lead to water scarcity and compromise their sustainability goals. Quadrant III represents the case of smaller, less developed cities and with smaller, less GHG-intensive transport sector. This quadrant suggests a much larger use of public and non-motorized options of transport. Cities in quadrant II represent a more concerning case of urban development path in which the levels of emissions and vehicle fleet are much larger than those that would correspond to city size and development. This is the case of cities such as Guanajuato, Cabo San Lucas, Cárdenas, Zitácuaro and Uruapan. This type of development would be characterized by a less developed public transport system and a less efficient, probably older, private fleet. Outlying values in this figure could constitute useful case studies to provide lessons about how to improve urban transport for the urbanization planning. A relatively rapid transition toward the adoption of clean energy and improving the public transportation systems will be useful to mitigate greenhouse emissions in the short and medium term as the urban expansion continues to increase.

City growth can lead to different urbanization intensities and ecological restoration decisions. The cities included in this analysis illustrate how cities with similar sizes and development can show very different rates of urbanization and recovery of greenspaces. Both quadrants I and IV in **Figure 2** correspond to large, developed cities but that have smaller rates of urban sprawl and larger reforested areas (quadrant IV) or where the

[2]https://imco.org.mx/banner_es/indice-movilidad-urbana-2018-barrios-mejor-conectados-ciudades-mas-equitativas/

urbanized area has grown faster than population (quadrant I). Monterrey and Guadalajara provide contrasting examples when comparing these two indices: while they show similar size and development scores, Monterrey has a much smaller urban footprint. Other cities in quadrant IV, such as Tampico and Playa del Carmen, are moderately large and developed cities but where the rate of urbanization is smaller than population growth, exerting less pressure over greenspaces. Quadrant II is characterized by smaller, less developed cities but that show high rates of urban sprawl, and low efforts of ecological restoration. The most extreme case is San Cristobal de las Casas, which shows the highest score value in PC3 (i.e., the combination of the high urbanization rate with respect to population growth and low levels of reforestation) of all the cities in the dataset. In contrast, San Miguel de Allende is the city with the lowest urban footprint. The adoption of conservation and reforestation actions would have an impact on human well-being and help to avoid more habitat fragmentation as these cities continue growing.

The relationship between the level of urban sprawl (PC3) in cities in Mexico and their level of urban and territorial planning (PC8) is explored in **Figure 3**. In contrast to the previous figures, there is a highly statistically significant relationship between PC3 and PC8, but with the opposite sign that could be expected. For these cities, a higher level of urban and territorial planning implies a higher level of urban sprawl. This result is interesting because it may suggest that normative urban or territorial planning actions are enacted as remedial (i.e., after urban sprawling is a problem) and not as preventive measures.

Our analysis also suggests that charcoal and wood for cooking is still a common practice of a large proportion of households in many Mexican cities (PC5). Moreover, for the data at hand, city size, and development show a positive but not statistically significant relationship with transitioning to electricity and cleaner energies. The environmental impacts of charcoal production such as deforestation, forest degradation, and greenhouse gas emission are well-established (Chidumayo and Gumbo, 2013). Air quality (PC7) is also a negative factor affecting several cities in Mexico and our analysis suggests that it is not directly related to city size or degree of economic development. However, a regression analysis (excluding Cozumel) does indicate a statistically significant positive relationship between air pollution (PC7) and urban sprawl (PC3). The regression equation is $PC7 = -0.04 + 0.18PC3$, where the slope coefficient is significant at the 10% level. The implementation of strategies to recover and/or expand greenspace areas, for example by means of urban protected areas, can help to simultaneously improve air quality, reduce greenhouse gas emissions through carbon sequestration, reduce

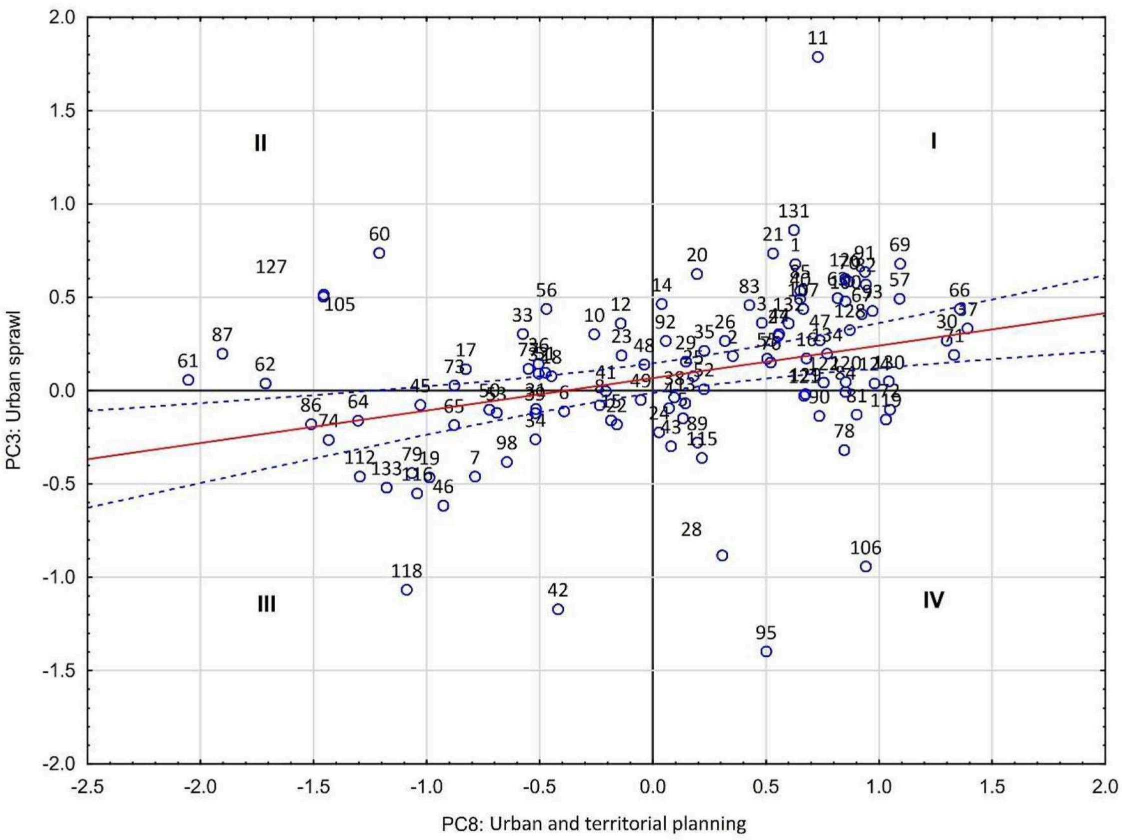

FIGURE 3 | Scatter plot of urban sprawl index (PC3) and urban and territorial planning index (PC8). The regression line is: PC3 = 0.07 + 0.33PC8; the slope coefficient is significant at the 5% level. Cozumel and San Cristobal de las Casas are outlying values in PC3 and PC8, respectively, and were excluded from this analysis and figure. A list of names and ID numbers of Mexican cities is provided in **Table A2**.

impacts of heat island effects, and protect local biodiversity (Armson et al., 2012; Trzyna, 2014; Abhijith et al., 2017).

Cluster analysis can be used to classify similar cities and to get insights into what makes them similar. **Figure 4** shows the cluster groups obtained for larger, more developed cities, based on the PC2–PC9 indices. At a linkage distance of 10, three groups of cities are formed which can be broadly described as (from left to right): (1) coastal/oil cities which includes cities with ports and tourism (e.g., Veracruz, Acapulco, Puerto Vallarta, Playa del Carmen), and oil industry (e.g., Poza Rica, Minatitlán, Coatzacoalcos); (2) El Bajío region which correspond to metropolitan areas in Jalisco, Aguascalientes, Guanajuato, Michoacán, Querétaro, San Luis Potosí y Zacatecas which have high economic growth and living standards, as well as very high levels of industrialization. Some of the cities included in this group are Guadalajara, Aguascalientes and Zamora; (3) Cities with large manufacturing and services industries such as Valle de México, Monterrey, Tampico, Toluca and Tijuana. These groups suggest that economic activity and some geographical features are two of the main determinants of the environmental and sustainability characteristics of Mexican cities.

A simple composite index is proposed to summarize the information contained in all of the indices presented in this section, and to help rank cities according to their performance in the different dimensions. As discussed in the previous paragraphs, the nine rotated principal components that were selected represent particular sets of characteristics of cities, and positive/negative values in these indices can be associated to challenges or advantages certain cities have in terms of potential sustainability. For example, negative (positive) values in PC7 are associated to higher (lower) levels of criteria pollutants, which pose a challenge to sustainability; positive (negative) values in PC6 are associated more (less) widespread access to improved water and sanitation, which improves quality of life and contributes to urban sustainability. **Table A6** provides a list of all PCs and their assumed effects on sustainability depending on their sign in the corresponding score values. Based on these rules, each PC was transformed into a dichotomous variable that takes the value of 1 if for a particular city its score contributes to urban sustainability and zero otherwise. The composite sustainability index is the average value of the transformed PCs. For the calculations presented here, PC1 was used to separate large and most developed cities from those that are smaller and less developed. To illustrate the calculation procedure, consider the case of a particular city for which only one the conditions expressed in **Table A6** is satisfied. Then the score of the city in

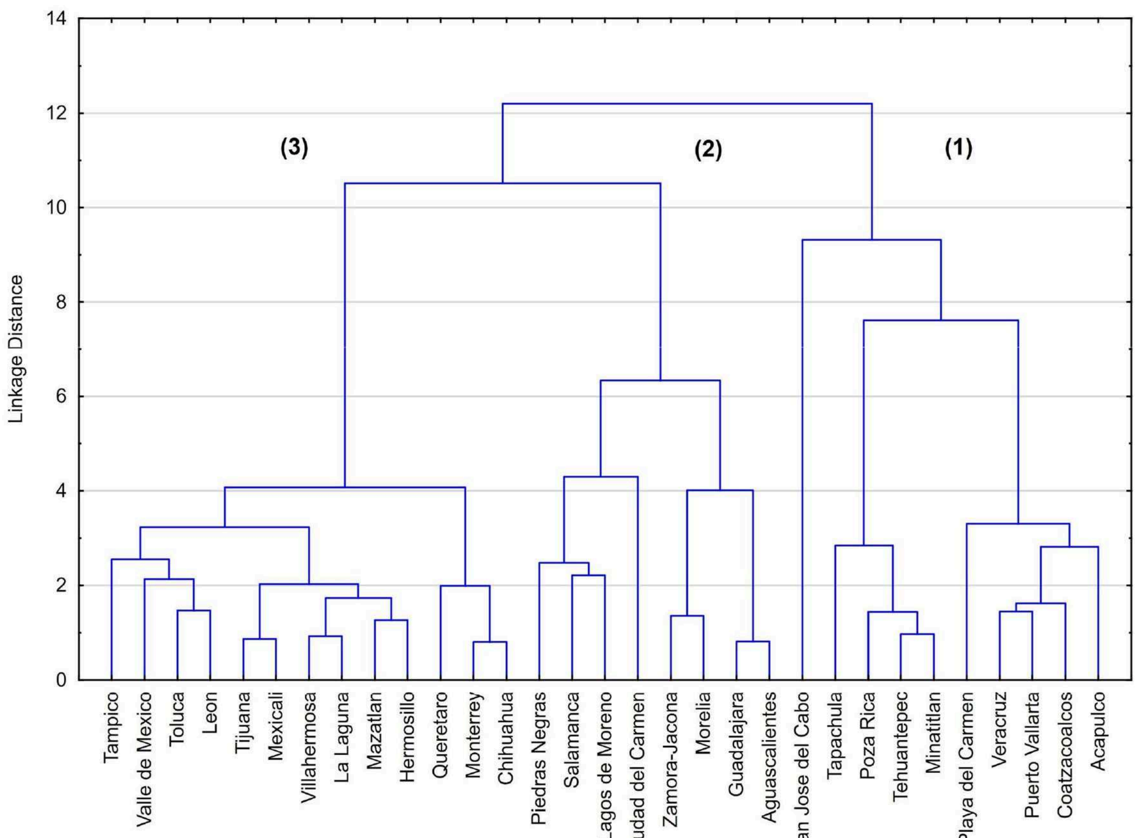

FIGURE 4 | Cluster analysis for the largest, more developed cities (PC1>0), based on the PC2–PC9 indices. Ward's amalgamation method and Euclidean distances were used.

the composite sustainability index would be 1 divided by the total number of PCs included in the composite index.

Toluca, Monterrey and Ciudad del Carmen share the highest position in the composite index, while cities such as Valle de México, San Luis Potosí-Soledad and Piedras Negras follow in the second position (**Table 2**; **Table A7**). Cities that are commonly considered as sustainable such as Guadalajara and Aguascalientes are ranked as medium in this composite index. It is important to underline that this type of analysis is empirical and highly dependent on the sustainability proxy variables that are used. At the bottom part of this table oil-cities such as Minantitlán, Poza Rica and Coatzacoalcos are found, and the less sustainable city in this ranking is Acapulco. These results are consistent with other studies based on different measures of urban sustainability. **Table 3** presents the rankings based on the composite index for the group of smaller, less developed cities (see **Table A8** for score values). The cities with the highest ranking are Cuauhtemoc and Tepatitlán de Morelos, followed by cities such as La Paz, Uruapan and Cozumel, which rank second place in this list. Oaxaca, Pachuca and Cuautla have the lowest ranking.

CLIMATE CHANGE AND URBAN SUSTAINABILITY CHALLENGES

Climatic Departures and Sustainability Ranking of Cities

We explore the relationship between degree of climate change exposure for 2050 of Mexican cities (i.e., Euclidean distances) and our derived sustainability ranking from PC scores. Also, we explore individually how PC scores vary across climate departures for each emission scenario. We did not find a general spatial or geographical pattern across cities (**Figure 5**). However, as mentioned in the previous section, cities form clusters according to the sustainability scores in a way that is related to their dominant economic activities and some geographical features such as proximity to the coast.

We ranked Mexican cities according to their projected climate change exposure for 2050. Quartiles were used to classify those cities with high exposure from those with low exposure (**Table 4**). However, we noted that all Mexican cities are projected to be

TABLE 2 | Ranking of larger, more developed cities according to their score in the composite index.

City	Rank	City	Rank
Toluca	1	Playa del Carmen	3
Monterrey	1	Hermosillo	3
Ciudad del Carmen	1	Aguascalientes	4
Mexicali	2	León	4
La Laguna	2	Guadalajara	4
Piedras Negras	2	Puerto Vallarta	4
Chihuahua	2	Zamora-Jacona	4
Valle de México	2	Tampico	4
San Luis Potosí-Soledad de Graciano Sánchez	2	Veracruz	4
Villahermosa	2	Lagos de Moreno	4
Salamanca	2	Mazatlán	4
Tijuana	3	Tehuantepec	5
Morelia	3	Puebla-Tlaxcala	5
Querétaro	3	Poza Rica	5
San José del Cabo	3	Coatzacoalcos	5
Cabo San Lucas	3	Minatitlán	6
Tapachula de Córdova y Ordóñez	3	Acapulco	7

Colors from green to red denote higher to lower ranking in the composite index score.

TABLE 3 | Ranking of smaller, less developed cities according to their score in the composite index.

City	Rank	City	Rank
Cuauhtémoc	1	San Miguel de Allende	4
Tepatitlán de Morelos	1	Linares	4
Uruapan	2	Matehuala	4
Chetumal	2	Los Mochis	4
La Paz	2	Heroica Caborca	4
Sabinas	2	Heroica Nogales	4
Cozumel	2	Puerto Peñasco	4
Ciudad Valles	2	San Luis Río Colorado	4
Saltillo	3	Juárez	5
Colima-Villa de Álvarez	3	Moroleón-Uriangato	5
San Francisco del Rincón	3	Tulancingo	5
La Piedad-Pénjamo	3	Tula	5
Tepic	3	Cuernavaca	5
Ríoverde-Ciudad Fernández	3	Tehuacán	5
Campeche	3	Cancún	5
Manzanillo	3	Matamoros	5
Zitácuaro	3	Nuevo Laredo	5
Túxpam de Rodríguez Cano	3	Tlaxcala-Apizaco	5
Fresnillo	3	Xalapa	5
Ciudad Acuña	3	Zacatecas-Guadalupe	5
Delicias	3	Irapuato	5
Hidalgo del Parral	3	Chilpancingo de los Bravo	5
Nuevo Casas Grandes	3	San Juan Bautista Tuxtepec	5
Victoria de Durango	3	Acatzingo de Hidalgo	5
Apatzingán de la Constitución	3	Huamantla	5
Culiacán Rosales	3	San Cristóbal de las Casas	5
Agua Prieta	3	Atlixco	5
Navojoa	3	San Juan del Río	5
Ciudad Victoria	3	Ciudad Mante	5
Monclova-Frontera	4	Tuxtla Gutiérrez	6
Ocotlán	4	Orizaba	6
Guaymas	4	Córdoba	6
Reynosa-Río Bravo	4	Mérida	6
Celaya	4	Comitán de Domínguez	6
Ensenada	4	Iguala de la Independencia	6
Guanajuato	4	Pachuca	7
Ciudad Lázaro Cárdenas	4	Cuautla	7
Ciudad Obregón	4	Oaxaca	7
Cárdenas	4		

Colors from green to red denote higher to lower ranking in the composite index score.

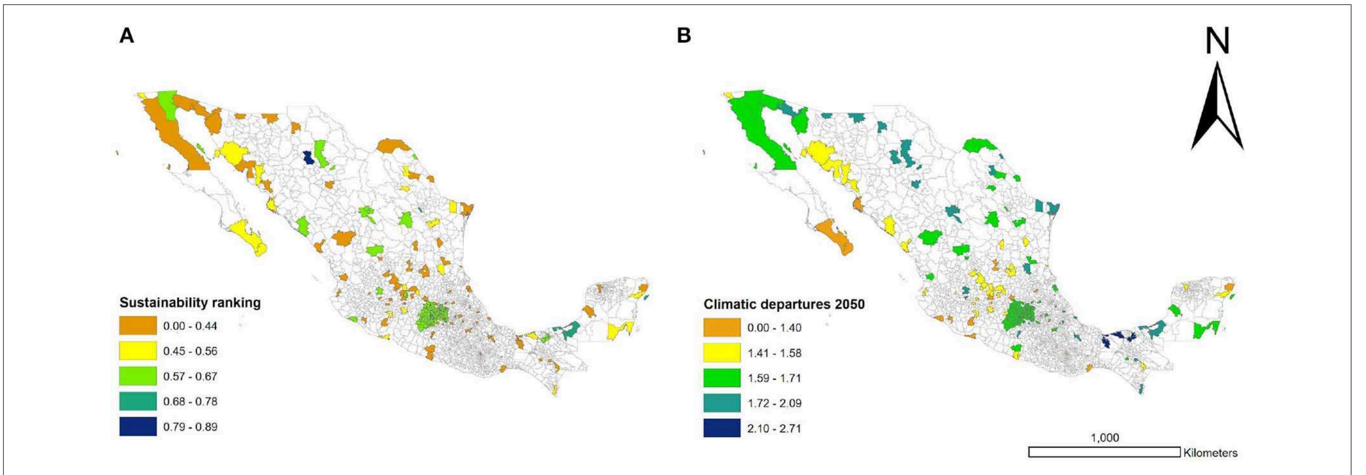

FIGURE 5 | Geographical distribution of sustainability ranking values **(A)** and climatic departures using Euclidean distances averaged for all climate change scenarios (GCM and RCPs) for 2050 **(B)**.

TABLE 4 | Ranking of Mexican cities according to its projected exposure to climate change in 2050.

City	ED (high exposure)	City	ED (low exposure)
Minatitlán	2.71	La Paz	1.17
Coatzacoalcos	2.56	San José del Cabo	1.25
Cárdenas	2.38	Ciudad Lázaro Cárdenas	1.35
Villahermosa	2.33	Colima-Villa de Álvarez	1.37
Tapachula de Córdova y Ordoñez	2.09	Apatzingán de la Constitución	1.38
San Juan Bautista Tuxtepec	2.04	Manzanillo	1.38
Córdoba	2.00	Los Mochis	1.39
Orizaba	1.88	Tehuantepec	1.40
Veracruz	1.86	Mérida	1.43
Nuevo Casas Grandes	1.83	San Francisco del Rincón	1.44
Hidalgo del Parral	1.83	Zamora-Jacona	1.45
Iguala de la Independencia	1.83	Culiacán Rosales	1.45
Ciudad del Carmen	1.82	La Piedad-Pénjamo	1.45
San Cristóbal de las Casas	1.80	Acapulco	1.47
Xalapa	1.80	Mazatlán	1.47
Ocotlán	1.78	Oaxaca	1.48
Cuauhtémoc	1.77	Navojoa	1.48
Piedras Negras	1.77	Salamanca	1.48
La Laguna	1.77	Irapuato	1.48
Chihuahua	1.77	Querétaro	1.49
Tepatitlán de Morelos	1.77	Ciudad Obregón	1.49
Sabinas	1.75	León	1.49
Agua Prieta	1.74	San Miguel de Allende	1.50
Puerto Peñasco	1.74	Aguascalientes	1.50
Ciudad Valles	1.74	Guaymas	1.51
Cuernavaca	1.74	Guadalajara	1.51
Reynosa-Rio Bravo	1.74		

Euclidean distances were averaged for all GCMs and RCPs (RCP2.6, RCP4.5, RCP6, and RCP8.5). ED, Euclidean distances.
Colors from green to red denote lower to higher Euclidean distance values.

exposed to substantial novelty in climate conditions across all GCM and RCPs (**Figure 6**). This is particularly true under the RCP8.5 that can be interpreted as an inaction scenario (see **Tables A9, A10** for 2050 and 2070). For instance, Coatzacoalcos and Minatitlán exhibit relatively low sustainable ranking values and likely will be exposed to non-analog climates in the near future (**Figure 6**). Oaxaca and Cuauhtémoc are cities with low and high ranking in sustainability, respectively, but both cities are projected to be exposed to moderate climate departures in comparison with other cities (**Figure 6**).

Cluster analysis allows to further explore how cities can be classified based on their future climate exposure and current scores in the composite sustainability index. **Figure 7** shows that at a linkage distance of 2, five groups of cities are formed. By characterizing these groups by their average values in the projected climate exposure and the composite sustainability index, cluster analysis suggests which groups of cities may be more at risk. While all groups are expected to face challenges under climate change conditions (RCP8.5), they do differ in levels of climatic exposure and presumably in their capability to absorb the impacts and manage them. Considering the mid-term climate scenario (2050), the group with the highest average score in the composite sustainability index (0.68), labeled (d) in **Figure 7**, is expected to experience the second largest change in climate (2.02). Cities such as Valle de Mexico, Monterrey and Toluca are included in this group (see **Table A11**). Groups (e) and (c) that include Guadalajara, Aguascalientes, Querétaro and León, would face moderate changes in climate and have relatively high scores on the composite sustainability index. Climate change is expected to be a particularly important challenge for two groups of cities, labeled in **Figure 7** as (b) and (a). Cluster (b) has the highest average climatic departure (2.29) and the second lowest sustainability score (0.36), while cluster (a) has the third largest climatic departure (1.92) and the lowest sustainability score (0.24). Cities in these groups include Acapulco, Oaxaca and Poza Rica are likely to become risk hotspots under climate change conditions. The long-term horizon (2070) under

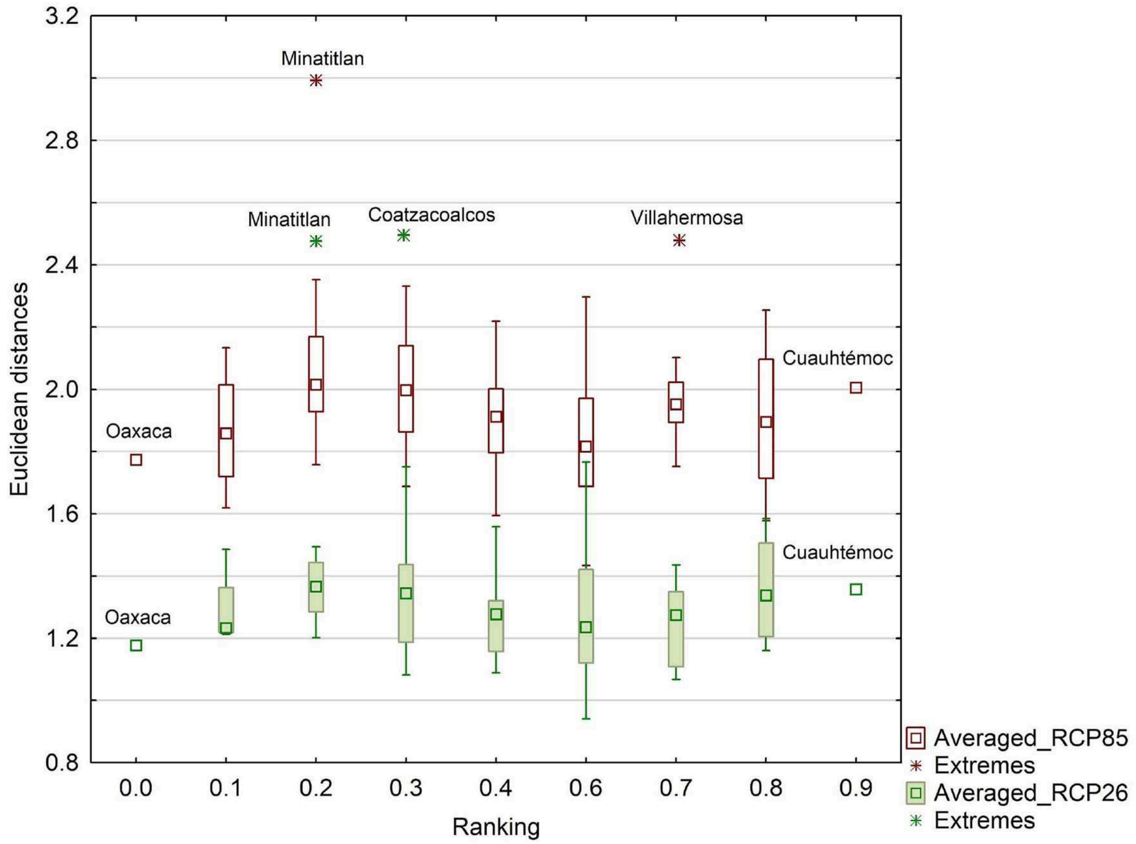

FIGURE 6 | Boxplots of the average Euclidean distances from four Global Circulation Models for RCP 2.6 and RCP 8.5. The Euclidean distances capture the exposure of each city to novel climates.

the RCP8.5 implies much larger exposure for most Mexican cities (**Table A10**). Keeping all other things constant, climatic departures in 2070 by themselves would produces considerable changes in how cities cluster (**Table A12**), and under such conditions four cities (Cárdenas, Coatzacoalcos, Minatitlán, and Villahermosa) would face disproportionate climate exposure. However, the realism and usefulness of the analysis of such long-term horizons would greatly improve if projections for variables such as those included in the PKSC were available. The absence of socioeconomic and ecological scenarios with adequate spatial resolution for the assessment of the consequences of climate change at local scales constitutes a common limitation, and appropriate downscaling/projection methods are still lacking (IPCC, 2014; Samir and Lutz, 2014).

Note that even if strong international mitigation actions like the Paris Climate Accord (RCP2.6; **Figure 6**) can significantly reduce the departures from current climate, the residual risks are still large. Moreover, cities may experience particularly large impacts from climate change due to the convergence of environmental and socioeconomic factors. A recent global study showed that local climate change due to the urban heat island (UHI) effect could significantly amplify the economic losses from global climate change (Estrada et al., 2017). City-level actions to improve local environmental conditions, such as reducing the UHI, constitute an important risk reduction instrument for city governments, and have been shown to have net economic benefits, even if co-benefits are ignored (EPA US, 2008; Estrada et al., 2017). Accordingly, an explicit incorporation of climate change in the urban planning and development agenda should be a priority for local authorities in these Mexican cities.

Climate Change and Sustainability Challenges

Investigating the associations between some of the individual PC scores and climatic departures for 2050 using the Euclidean distances reveals some interesting patterns. Socio-environmental problems tend to scale with city size, as more population and income per capita usually imply more demand for goods and services which translates to more pressure and depletion of natural resources and ecosystems (Grimm et al., 2008). Water is a prime example of climate change challenges in urban areas (World Bank, 2018) and, as it was discussed in the previous section, urban development in Mexico seems to be intrinsically related to higher per capita water consumption. Climate change will pose additional challenges to satisfy the ever-growing consumption requirements of urban population (e.g., food, water, energy, infrastructure) and this is expected

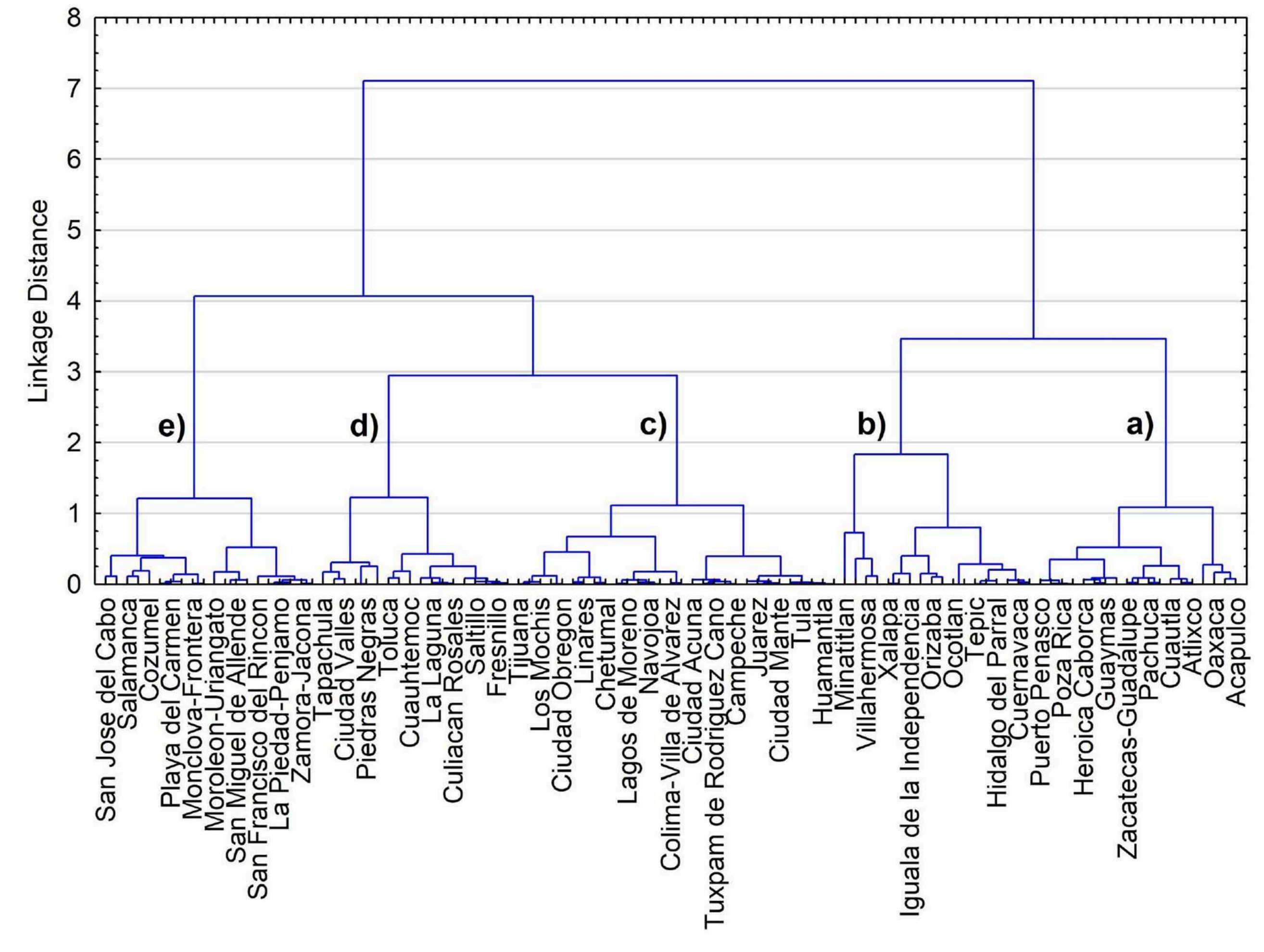

FIGURE 7 | Cluster analysis of cities based on their score in the composite sustainability index and in their climatic departures in 2050 under the RCP8.5 scenario. Ward's amalgamation method and Euclidean distances were used.

to result in environmental impacts extending beyond current urban areas (Jiang et al., 2013). **Figure 8A** shows a scatter plot of PC1, which scores cities according their size, development degree and level of per capita water consumption, and the climatic departures from current normals. The most urbanized cities in Mexico, namely Valle de México, Monterrey and Guadalajara, are projected to experience significant changes in climate. Impacts from global climate change in such urbanized cities can expected to be considerably amplified by the local changes in climate due to the UHI effect (Estrada et al., 2017). The creation of more greenspaces and implementation of white, green roofs and cool pavement could help to reduce the joint impacts of local and global climate change (EPA US, 2008; Estrada et al., 2017; Imran et al., 2018). Cities such as Minatitlán, and Coatzacoalcos which have a very low score in the composite vulnerability are expected to experience the largest changes in climate. Moreover, the areas where these cities are located already face significant challenges due environmental pollution form the oil industry which have affected ecosystems' health (Mendoza-Carranza et al., 2016; Ruiz-Fernández et al., 2016).

A scatter plot of between the urban sprawl index (PC3) and climatic departures under the RCP8.5 (**Figure 8B**) complements this discussion. Guadalajara and some cities such as Querétaro, Aguascalientes and Guanajuato, which have become increasingly important in terms of their population count and their contribution to the national product, have rates of urbanization larger than population growth. Although for these cities the projected changes in climate are moderate, such fast urbanization processes can lead to rapid and large changes in local climate (Estrada et al., 2009; Li and Bou-Zeid, 2013) and widespread impacts ranging from loss of productive farmland, changes in energy demand, alterations of the hydrologic cycle, biodiversity loss, and habitat fragmentation (Foley et al., 2005; Grimm et al., 2008; Seto et al., 2011). On the opposite side, some cities like San Miguel de Allende, Playa del Carmen, Tampico and markedly Cozumel show large efforts for ecological restoration and climatic departures for these cities are expected to be moderate. These examples illustrate the wide variety of current conditions and future changes that characterize urban areas in Mexico, and point to the need of coupling platforms such as PKSC with multivariate

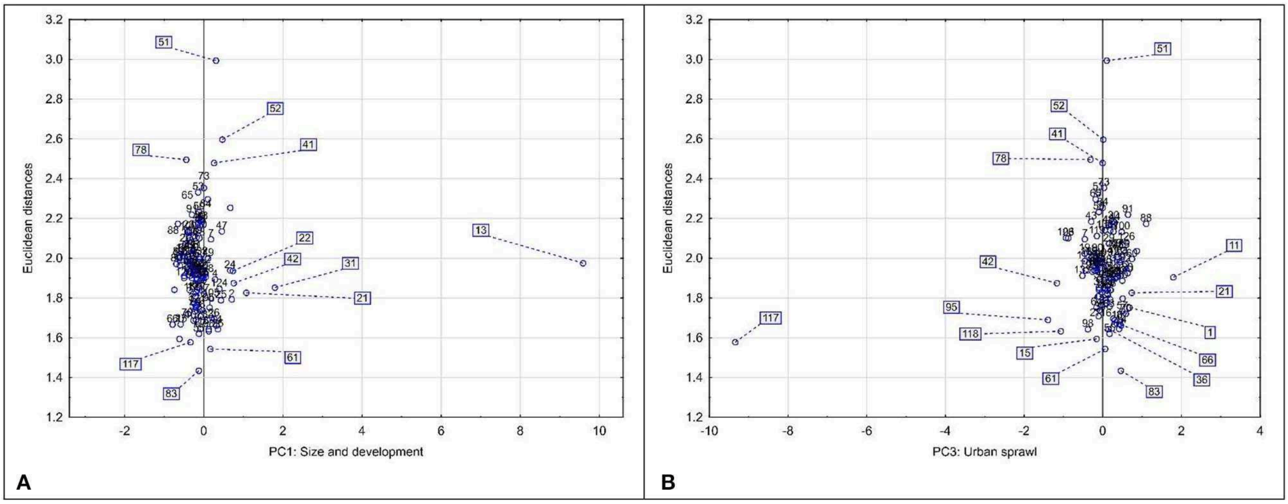

FIGURE 8 | Scatter plots of urban sustainability indices and climatic departures. **(A,B)** show scatter plots of climatic departures from current normals and the city size and development index (PC1), and the urban sprawl index, respectively. A list of names and ID numbers of Mexican cities is provided in **Table A2**.

exploratory techniques to find commonalities among cities to help decision-makers in designing urban strategies.

SUMMARY OF MAIN FINDINGS AND CONCLUSIONS

We analyzed a multidimensional dataset related to urban sustainability that was produced by the Mexican government to help federal, state, and local level governments defining sustainable pathways for urban development. By means of rotated principal component analysis, 9 indices were defined which in total account for about 76% of the explained variance of the original dataset. These indices are related to city size and level of economic development, size and GHG-efficiency of the vehicle fleet, urban sprawl, conservation of greenspaces and good environmental practices, access to improved water, type of energy households have access to, air quality, urban and territorial planning, and the installed capacity to treat residual water.

The analysis reveals features that are relevant for understanding some patterns of growth of cities in Mexico which can be useful for helping urban policy design. The strong association between city size and development and higher per capita water consumption suggests that the current scheme of urban development in Mexico is likely to have strong implications for present and, in particular, future urban sustainability. This index explains the largest share of variance in the PKSC dataset (about 14%) and suggests that important efforts in Mexican cities should be devoted to breaking the linkage between city growth and water consumption, as has been done in other cities around the world (McDonald et al., 2014; Paterson et al., 2015). The structure and GHG-efficiency of the transport sector are diverse among cities and constitute the second most important index for describing urban areas in Mexico. Large, more developed cities in Mexico tend to rely more on privately own motor-vehicles than on public transport, which generally leads to higher levels of energy consumption per person/kilometer and higher per capita sector emissions. Valle de México, Monterrey and Guadalajara, show a relatively smaller per capita vehicle fleet size and more efficient in comparison to less developed cities as well as much lower CO_2 emissions per vehicle than the average of Mexican cities. The formation of conglomerations of urban centers and of megacities is increasingly common, and it poses important urban policy challenges as local social and environmental problems —such as emissions, pollution and transport— become more regionally intertwined and decision-making more complex as it requires better coordination to be effective. Results suggest that improving public transport would contribute to reducing motor-vehicle fleet size and emissions. More efficient ways of transport have been shown to provide important health co-benefits due to improvements in air quality (Kelly and Fussell, 2015; Kwan and Hashim, 2016).

City growth can lead to different urbanization intensities and ecological restoration decisions. The cities with similar sizes and development can show very different rates of urbanization and recovery of greenspaces. Interestingly, results show that in the case of Mexican cities, urban sprawl and urban and territorial planning are negatively related, suggesting that normative actions are remedial and not preventive measures. A statistically significant relationship (10% significance level) was found between urban sprawl and atmospheric pollution, but not with city size, and development. This finding strongly suggests that promoting legislation for effective urban and territorial planning should be a clear policy goal for improving sustainability in Mexican cities.

Using cluster analysis, cities were classified according to their scores in the rotated principal components (PC2-PC9). PC1 was used to separate the sample of cities in two subsamples: (1) large, more developed cities and; (2) small, less developed cities. Three main groups were identified that can be broadly described as: (1) coastal/oil cities; (2) metropolitan areas in El Bajío region;

(3) large manufacturing and services industries. These groups suggest that economic activity and some geographical features are two of the main determinants of the environmental and sustainability characteristics of Mexican cities. Moreover, further analysis of the common features of these groups of cities can help designing policies to tackle shared socioeconomic and environmental challenges to improve urban sustainability.

A simple composite index was proposed to help rank cities according to their performance in the different dimensions included in PKSC. Comparing all cities, Toluca, Monterrey and Ciudad del Carmen share the highest position in the composite index, while Oaxaca, Pachuca and Cuautla have the lowest ranking.

The exposure of Mexican cities to future climate change scenarios will be relatively severe according to metric based on Euclidean distances. This metric allows to combine temperature and precipitation variables in a single index. The exposure is projected to be more severe in business-as-usual emission scenarios (RCP 8.5). We find high variability between GCMs which suggests that a more comprehensive evaluation incorporating more models will be necessary to have a more complete picture of climate change exposure across Mexican cities. By means of cluster analysis we define five groups of cities according to their climatic exposure and their scores in the composite sustainability index. Cities such as Acapulco, Oaxaca and Poza Rica are likely to become risk hotspots under climate change conditions. Moreover, ambitious international mitigation actions such as those proposed in the Paris Climate Accord can significantly reduce future changes in climate, but the residual risks are still large and call for strong local adaptation strategies. Our analysis based on the composite sustainability index and climatic departures can help policy makers to identify cities that would be most affected by climate change and that are currently less prepared for them. This information can help guiding risk and vulnerability reduction actions based on improving current socioecological indicators and on designing adaptation strategies, as well as for prioritizing most vulnerable cities. Moreover, our analysis points out that urban sustainability assessments and effective urban policy making cannot ignore climate change anymore as it is an increasingly important factor that can limit urban viability, particularly if its interactions with other socio-ecological risks that converge in cities are considered.

The PKSC data shows that there is already a significant deficit of green spaces and ecological policies for the business sector across many Mexican cities. How urban policies will shape the development of Mexican cities in the next decade will have a predominant and persistent influence on their viability. Degradation of the environment due to urbanization will be likely amplified in the next few decades due to climate change. As we show, climatic departures are projected to be rather severe and residual risks are likely large even the most stringent international mitigation scenarios if no local adaptation strategies are adopted. It is well-established that urban green surfaces and water bodies are effective strategies to mitigate impacts of the urban heat island effects, to promote climate change adaptation (Martínez-Arroyo and Jáuregui, 2000; Wong and Yu, 2005; Sun and Chen, 2012) as well as to help to people relate to nature (Fuller and Gaston, 2009), which has been recently suggested to improve substantially health well-being (White et al., 2019). To avoid the potential socioeconomic and environmental negative impacts of the joint effects of the UHI and global warming, municipal authorities should prioritize implementing ecological restoration strategies across urban areas.

Future work should focus on two aspects that would help advancing the evaluation of urban sustainability under climate change conditions. First, further research and transdisciplinary discussion needs to continue about how to define urban sustainability, what set of dimensions and variables provide meaningful proxy measures for it, and about how to produce consistent measures across geography (Kropp and Lein, 2013). Vulnerability is sometimes considered an emergent property of socio-ecological systems with vulnerability patterns emerging from the interaction of the biophysical, social, and political domains at multiple scales (De Sherbinin et al., 2007; Oppenheimer et al., 2014; Weber et al., 2015). Future extensions of this work will focus on developing local socioeconomic and environmental scenarios for Mexican cities and integrating into the analysis how the evolution of social relations, political discourses, and demographic trends can affect the proposed sustainability indices and modify the relationships between cities. Research about the potential impacts of local and global warming on urban areas would benefit from adopting a risk management perspective. Introducing dynamic metrics such as those that aim to establish the timing and velocity of exceeding risk thresholds across cities would constitute a useful tool for decision-makers and would enrich government efforts such as the PKSC (Loarie et al., 2009; Hawkins and Sutton, 2012; Mora et al., 2013). For instance, time of emergence (Hawkins and Sutton, 2012) is a metric used to estimate the year at which a novel climate combination (i.e., non-analog climates) would occur for the first time at each site (Williams and Jackson, 2007). Similarly, estimating the velocity of climate change (Loarie et al., 2009) would be useful to establish the speed of changing conditions across geography. These metrics have been used in assessments of climate change exposure on biodiversity (La Sorte et al., 2019) and to apply them for urban policy and planning would be a sensible extension.

DATA AVAILABILITY STATEMENT

The datasets analyzed in this article are not publicly available. Requests to access the datasets should be directed to contacto@inecc.gob.mx; feporrua@atmosfera.unam.mx.

AUTHOR CONTRIBUTIONS

FE, JV, and OC-B processed and analized the data. FE, JV, and AM-A developed the idea and wrote the paper.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2020.00025/full#supplementary-material

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Pathways for Sustainable Urban Waste Management and Reduced Environmental Health Risks in India: Winners, Losers, and Alternatives to Waste to Energy in Delhi

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This paper examines the shift toward centralized waste-to-energy (WTE) as a singular solution to Delhi's solid waste crisis and describes a transdisciplinary research process that sought to understand how and why this dominant waste management pathway emerged. It also sought to engage with and facilitate debate on the potential for alternative waste management pathways, which may better address combined environmental and social justice concerns. We explain the emergence of a transforming narrative that reframed waste from a risk to a resource, reflecting and reinforcing the dominant trajectory of socio-technical-ecological change in urban development, and reconfiguring waste related infrastructure to involve public private participation and WTE technology. Drawing on empirical studies, involving local residents, wastepickers associations, NGOs, and government officials, we discuss implications of WTE projects in Delhi. We argue that the current WTE focused approach, without modification, may simply displace health hazards across time, space and social groups and exacerbate social justice concerns. The dominant narrative on waste management priorities appear to make certain health risks protected and recognized whilst others are made invisible. We make the case for possible alternative waste management scenarios, institutional and regulatory arrangements that may better address environmental health and social justice concerns. These are summarized under eight principles for reframing urban waste management policy challenges in the context of sustainable urban development. These principles include a reframing of waste management through a sustainability lens that links currently divergent initiatives on environmental health and social justice. It involves an appreciation of complex socio-material flows of waste, the need to move beyond perspectives of waste management as an environmental policy issue alone, appreciation in policy development that the informal sector will remain a key player despite attempts to formalize waste management and the need to provide incentives for diverse waste management strategies that move beyond the private.

Keywords: solid waste management, social justice, Delhi, sustainable cities, environmental health, transdisciplinary action research, waste to energy (WTE), pathways to sustainability

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INTRODUCTION

India faces an urban waste management crisis driven by a combination of increasing municipal solid waste (MSW) generation (the result of a growing population, rapid urbanization and changing consumption patterns associated with economic growth), an inadequate waste management infrastructure and routine lack of compliance with waste management rules. It is estimated that more than 90% of waste in India is dumped in public spaces instead of being sent to properly engineered landfill sites (Kumar et al., 2017). This leads to a host of well-documented environmental and public health impacts and increasing pressure on municipal governments to implement solutions. Recently, waste-to-energy (WTE) technologies have become India's preferred mainstream solution to this waste management crisis, but several WTE projects implemented in Delhi have met with widespread opposition and controversies over environmental impacts and social justice concerns.

Waste-to-energy technologies have been applied extensively in European contexts as part of attempts to find more sustainable ways to deal with urban waste (Dube et al., 2014). However, the operation of such plants depends on a supply of segregated waste that can provide a suitable input to the energy recovery process so it cannot be assumed that any given WTE technology will be workable in a particular context (Joshi and Ahmed, 2016). Indeed, some have argued that incineration based WTE plants in India will be unsuccessful because the calorific value[1] of Indian waste is very low (Sharholy et al., 2008; Talyan et al., 2008). By advocating a recovery-centric approach to municipal solid waste management Narayana (2009) argues that WTE cannot be successful without active citizen participation and careful attention to the proper implementation of regulations. In the context of WTE in Delhi, recent projects have been reported to have been hurriedly implemented without due consideration of the socio-economic and environmental implications (Shah, 2011) or concern for the impact of such projects on the informal livelihoods of wastepickers (Bharati et al., 2012; Schindler et al., 2012).

This paper documents a transdisciplinary action research process in which a group of academic researchers from the UK and India collaborated with local community groups and NGOs to explore how and why WTE came to play such an important role in the government response to the waste crisis, understand the implications of such a response and attempt to promote more socially and environmentally just alternatives. We reflect on this process and its outcomes to consider lessons for the establishment of sustainable urban waste management trajectories which can address environmental and health challenges whilst also addressing social justice concerns.

The action research process was designed according to the STEPS[2] Pathways Approach (Leach et al., 2007, 2010b) which emphasizes the need to understand how competing possibilities for socio-technical and social-ecological system change evolve, interact and shape development trajectories. Drawing on science and technology studies and development studies, it considers how these trajectories of change are shaped by power and politics and co-evolve with the broader, political economic context. The STEPS Center is concerned with the potential to enhance environmental integrity and social justice through sustainable development trajectories that appreciate a diversity of knowledges and innovation options.

The Pathways approach works on the premise that there are multiple, contested "sustainabilities" to be defined and deliberated for particular issues and groups (Leach et al., 2010b). It builds on the concept of framing, defined by Goffman (1974) as a cognitive process by which people make sense of events and experiences, bringing different ideas and interpretations to a problem within a given frame, to the exclusion of others. Leach et al. (2010a) observed that "all framing involves not just choices about which elements to highlight, but also subjective and value judgements." For any given problem, there may be multiple contested framings, all leading to different types of envisaged solutions. These framings are associated with narratives, or stories which define a problem, its consequences and potential solutions in a particular context. The STEPS approach recognizes that "contextually powerful institutions assert particular narratives and framings, so that it is these that become interlocked with strategies of intervention and ensuing pathways of system change, marginalizing alternative narratives in the process." Leach et al. (2010a).

The methodology involves exploration of a diverse range of narratives. Narrative analysis can be used to develop an understanding of the underlying system and problem framings of the stakeholders from which they emerge. In addition, examination of the interplay between narratives can reveal how power is enacted in negotiating potential socio-technical solutions to sustainability challenges, and how narratives come to be reinforced through policy interventions. The pathways approach for action-oriented research seeks to open up dialogue about what exactly is to be sustained by different pathways (or self- reinforcing trajectories of change) within socio-technical-ecological systems and for whom, and to create possibilities to develop alternative social, technological and environmental pathways to sustainability that favor the rights, interests and values of marginalized and excluded people.

In line with these aims, the research was guided by the following research questions:

1. What processes are involved in the prioritization of particular environmental management options and technological interventions for waste management in Indian cities; specifically, what types of issues are formally recognized, which remain unrecognized, how and why?
2. Who gains and who loses from current interventions?
3. If environmental health and social justice are to remain central to waste management strategies - what alternative waste management scenarios, institutional and regulatory arrangements, as well as forms of citizen action, are emergent?

[1]The energy value of a fuel, equal to the heat evolved through complete combustion in oxygen.

[2]The ESRC STEPS (Social, Technological and Environmental Pathways to Sustainability) Centre, steps-centre.org.

The following section of this paper describes the methodology and the specific methods used for this case study. The next three sections (3–5) present empirical results organized around the three research questions. We conclude in section 6 with summaries of the impact of the project and reflections on the lessons learned for achieving socially and environmentally just pathways for sustainable urban waste management.

METHODOLOGY

STEPS methodology can be described in terms of four mutually co-constituting and iterative phases as described by Stirling (2016). Each of these contribute to the process of enhanced appreciation of alternative pathways to sustainability. These four phases are concerned with (1) engaging actors; (2) exploring framings; (3) characterizing dynamics; (4) revealing political actions.

To understand the evolution of dominant and alternative pathways it is important to **engage** with the diversity of **actors** and, together, **explore** the range of narratives and **framings** they represent. Attention to relevant histories, associated networks and prioritization of the views of the most marginal is key. In understanding framings and narratives, it is important to elicit ideas about how sustainability is defined and sought, and how risks (associated with waste management options) are perceived. In the waste management case we were dealing with a highly topical issue in which diverse stakeholders would readily engage. There were strong and polarized views and major contrasts in the values and priorities that that characterized different framings and the narrative of risks and opportunity associated with them. There was a clear dominant pathway of centralized, privatized WTE technologies, but with a number of potential alternatives promoting decentralization, recycling, and greater engagement with the informal sector. To identify the implications of the dominant and alternative pathways it is necessary to **characterize** the **dynamics** of the current trajectory and who wins and loses as it evolves. We were concerned with how and to what extent particular pathways prioritize environmental, health and social justice concerns, and the characteristics that enhance or reduce their ability to do so.

Attention to history remains important through all four phases, to assess how pathways have co-evolved with the wider political economy and come to be shaped and reinforced by local power relations and politics. The goal of **revealing political actions** requires a continual review of key actors and their agency; and learning from previous successful and failed efforts to influence the direction of change in the socio-technical-ecological system. It is necessary to understand what is driving and maintaining particular dominant pathways and what are the key entry points and interventions to facilitate a wider appreciation of alternative more socially and environmentally just pathways.

Each method described below was selected in order to contribute to one or all of the four phases of the pathway analysis, in order to answer our three research questions.

Empirical research for the paper was carried out between 2012 and 2015[3] and involved a mix of ethnographic, participatory appraisal and interviewing techniques alongside reviews of formal academic and gray literature. The research included case study sites in the Indian cities of Ahmedabad, Pune and Delhi. These cities were chosen in order to compare the centralized WTE approach in Delhi with examples of grassroots innovations, and alternative approaches to waste management governance in Pune and Ahmedabad and to provide opportunities for networking and shared learning across the sites. Another key selection factor was the prior long-running involvement of the core research team with communities and other key NGO stakeholders.

Participatory Impact Pathway Analysis (PIPA) workshops provided a platform of shared understanding and purpose which formed the foundation for the other research activities. This method was adapted from Douthwaite et al. (2009), as described in Ely and Oxley (2014) and involved mapping out which stakeholders to engage with and seek to influence during the process of identifying sustainable waste management strategies. Core project partners participated in the first PIPA workshop and then repeated the exercise with external stakeholders both at the start of the research project and on two further occasions as the project evolved and relationships between actors shifted. Following the mapping of actors, discussion was held on the relative influence of difference stakeholders, their potential receptiveness and possible strategies for engaging with them. A series of focus groups and stakeholder workshops and meetings were also organized or co-organized by the research team with local civil society partners and community groups (**Table 1**). Further activities to engage with policy development and or innovations in waste management strategies led by wastepickers associations and others have continued to date.

Forty semi-structured interviews were conducted with stakeholders including government officials representing the central and state governments, local government bodies, waste to energy plant officials, academics, NGO representatives and informal wastepickers and local residents. Standard social science ethical procedures were followed, adhering to the principles of informed consent and confidentiality. Participants were clearly informed that they could withdraw at any time without facing negative repercussions for doing so. In order to acquire specific information on WTE projects in Delhi, applications were filed under the Right to information (RTI) Act. Visits and consultations also took place at WTE sites in Delhi, and a detailed process documentation of informal waste management was carried out in Delhi, Ahmedabad and Pune through the method of shadowing. Shadowing is considered a suitable social science research method for examining day to day spatial-temporal dynamics and social practices (Czarniawska, 2014; McDonald and Simpson, 2014). In our adaptation of this method, the

[3]This empirical research was a part of the ESRC funded collaborative project titled "Pathways to Environmental Health: Moving Between Formality and Informality" involving the ESRC funded STEPS Centre (University of Sussex), Jawaharlal Nehru University (JNU) and Toxics Link, New Delhi along with local community groups and wastepickers associations.

TABLE 1 | Key Outreach and Policy Engagement Activities.

Date	Organized by research team	Attended but not organized by research team
26/3/12	Participatory impact pathways analysis (PIPA) workshop, at JNU, Delhi.	
24/4/12		Joined a protest demonstration and public meeting by workers and residents against WTE incinerator in Ghazipur, Delhi organized by All India Kabadi Mazdoor Mahasangh (AIKMM) and presented about related policy issues.
15/6/12		Participation in photo-exhibition "flowers in the dust" by Kausiki Sarma documenting the lives of wastepickers in Delhi. organized by AMAN Trust.
29/8/12		Joined demonstration and public meeting by workers and residents against WTE incinerator in Rajghat, Delhi organized by AIKMM and shared information on environmental health issues.
19/9/12	Project workshop at JNU, Delhi.	
16/3/13	Session on "pathways to sustainable solid waste management in Delhi" in a daylong workshop on the "problems of waste pickers in Delhi" in collaboration with Lokadhikar and Vidhi Asra motion picture Pvt. Ltd. At World youth center, Delhi.	
1/5/13		Project presentation at Mazdoor Chetna Sabha, jointly organized by AIKMM and national alliance for labor rights, new Seemapuri, Delhi.
24/10/13		Presentation of critique of "draft municipal solid waste management and handling rules 2013" in a workshop on "waste legislation and waste pickers" organized by AIKMM in Delhi.
Nov 2013	Scenario planning workshop with local government officials, academics, residents' welfare associations and NGOs at JNU, Delhi.	
9/1/2014	Workshop on "rethinking municipal solid waste management in Delhi" at the Indian international center, Delhi. with government officials, academics, NGOs, wastepickers associations, and government scientists.	
Feb 2014	Symposium on urbanization and environmental health in Delhi.	

researchers combined non-participant observation with semi-structured interviewing, whilst following individual wastepickers through their daily routine. We also carried out photo mapping; a photographic documentation of routine waste management practices on the ground.

Qualitative data from interviews and secondary sources was analyzed through iterative narrative policy analysis (Roe, 1994), in which themes were identified, documented and reviewed as the research progressed. The first stage of analysis relied on secondary data sources, the narratives outlined in initial scoping interviews and the PIPA exercise. These were then followed up through primary data collection, key informant interviews and workshop sessions.

Formation of the Dominant Narrative Around WTE

Drawing on historical gray and academic literature, **Figure 1** summarizes the evolution of Indian waste management policy in the context of international policy approaches.

The early initiatives on urban waste management in India unfolded around the narrative of waste as a source of risk. This narrative became prominent after the outbreak of the Surat plague in 1994. Shortly afterwards, Almitra Patel, a retired MIT educated engineer, filed a public interest litigation (PIL) before the Supreme Court of India for a violation of Article 21, the right to life and healthy environment (Writ Petition No. 888 of 1996). The Petition argued that "various government

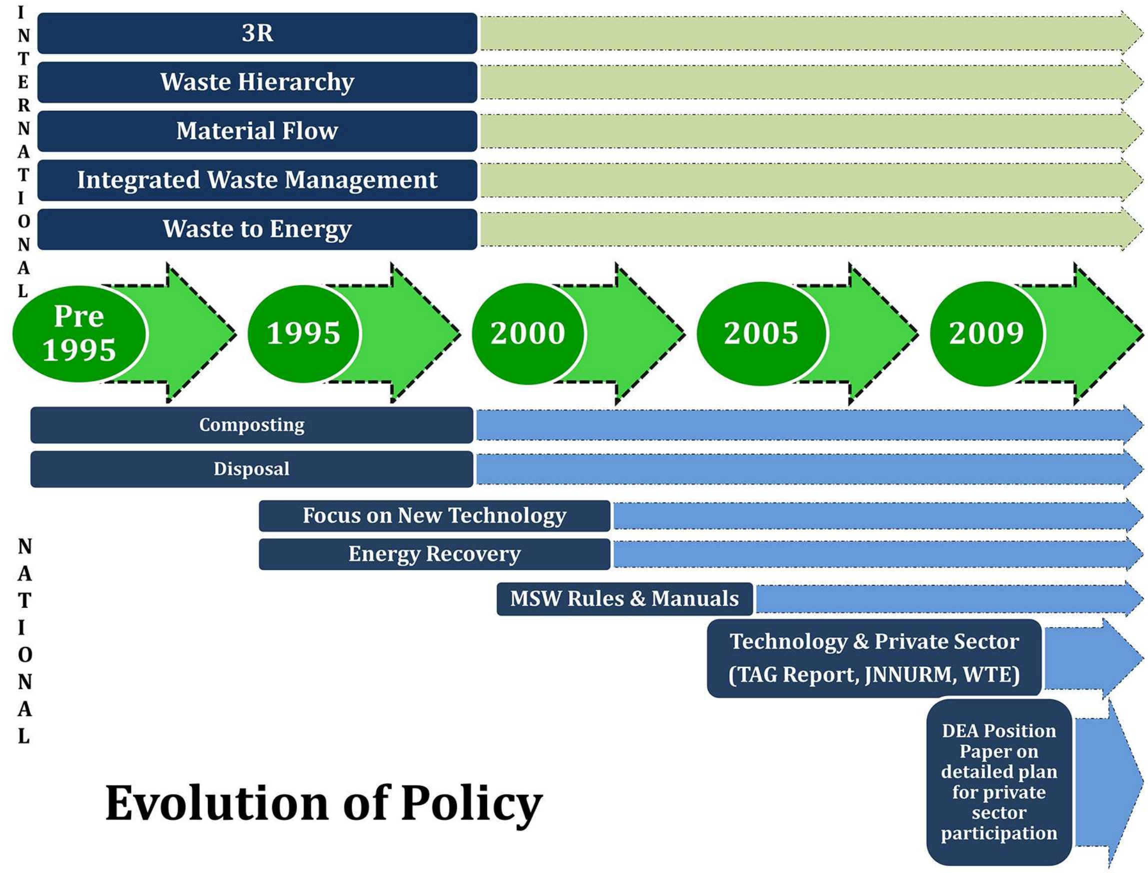

FIGURE 1 | Evolution of waste management policy in India.

agencies had neglected to discharge their constitutional and statutory obligation in relation to the proper collection, handling, transportation and hygienic ultimate disposal or recycling of municipal solid waste" (Rajamani, 2007, p. 297).

In response to Patel's PIL, in 1998, the Asim Burman Committee was formed under the Supreme Court of India to identify deficiencies and make recommendations to improve solid waste management in cities across the country (Burman, 1999). The principal recommendations of this committee were incorporated into the Municipal Solid Waste (MSW Management and Handling) Rules 2,000 notified by the Ministry of Environment and Forest (MOEF) in 2,000. These rules were enacted as one of the many legislations under the Environment Protection Act (EPA) 1986 (MOEF, 2000). The rules outlined the responsibility of multiple authorities dealing with waste within and beyond the city. They provide guidelines for dealing with collection, segregation, storage, treatment and disposal, and also prescribe standards for treatment and disposal of MSW. The rules also recommended that urban local bodies (ULBs) should involve private sector for the management of waste (ibid). Despite the significant role of the informal sector in recycling waste, the rules remained silent on this matter.

While the national level strategy on urban waste management in India was evolving, simultaneously important decisions on waste management were made at international forums. Agenda 21 of the Earth summit (also known as the Rio Summit 1992) proposed major waste related programmes for across the world[4]. Alongside other recommendations, it also suggested that "recovery of secondary materials or energy" from waste could avoid GHG (Greenhouse Gas) emissions in all other sectors of the economy (UNEP, 2010). In this regard, UNFCC adopted the Clean Development Mechanism (CDM) and Joint Implementation (JI) methodologies. In order to achieve these objectives UNEP started various programmes in its member countries. These programmes included Integrated Solid Waste Management (ISWM) based on 3R (reduce, recycle and reuse) approach, Sustainable Consumption and Production, E-waste management, converting waste agriculture biomass and waste plastics into useful energy and/or material resources (ibid).

[4]These programmes include i) waste minimization, ii) maximization of environmentally sound waste reuse and recycling, ii) Promotion of environmentally sound waste disposal and treatment, and iv) Extension of waste service coverage.

It was only after the declaration of the MSW Rules in 2,000 that the narrative of urban municipal waste as a resource of energy generation became prominent. Alongside biomethanation[5], other technological options for generating energy from waste started emerging. In early 2000, the Department of Science and technology (DST) and Technology Information, Forecasting and Assessment Council (TIFAC) initially perfected the refuse derived fuel[6] (RDF) based technology to process municipal solid waste.

The narrative of urban waste as a resource of energy generation gained further momentum in 2005 with the drafting of National Master Plan (NMP) for waste-to-energy under a UNDP/GEF assisted project (NBB, 2005). The NMP recommended recovery of energy from municipal waste through RDF and other options (ibid). In the same year, another government report came out, which discussed various technological options of waste to energy in detail. The report warned, "no waste to energy technology is successful in developing countries, new technologies are coming, after cost benefit analysis these technologies should be adopted" (CPHEEO, 2005). Despite the warning, six WTE projects were planned across Indian cities (including Delhi, Bangalore, Pune and Hyderabad) under the National Programme on Energy Recovery from Urban and Industrial Waste (Dube et al., 2014). The decision to subsidize these projects by the Ministry of Renewable Energy was challenged in the court through PILs. In 2007 in response to the PILs, the court came out with an order that the ministry could subsidize these projects but they should be treated as pilot projects to test the feasibility of waste to energy technologies in India (ibid).

Delhi was the first city to undertake an incineration based WTE project, despite major dissent both within and outside the court. WTE projects based on incineration and refuse derived fuel (RDF) technology started gaining momentum in urban India between 2005 and 2010 with the planning of three projects in Delhi, and expanded in 2015 when the newly elected central government announced four additional WTE projects under the *Swachch Bharat Mission*/Clean India Campaign (PTI, 2015).

Despite the court's jurisdiction of evaluating the pilot WTE projects before making them a popular solution for handling urban waste, several initiatives have been undertaken by various government actors. This has strengthened the narrative of urban waste as a resource of energy generation to gain legitimacy in the policy process. An Indian arm of the Energy Waste Research and Technology Council (WtERT) was co-founded by Columbia University and the National Environment Engineering Research Institute (NEERI) in order to promote WTE technologies in the country (WTER, 2014). Since 2012 WtERT has been active in promoting waste to energy technologies through international conferences and doing certificate courses on WTE technologies etc. In its budget speech of 2013, the then Finance Minister announced a scheme to encourage cities and municipalities to take up WTE projects in Public Private Partnership mode (Pereira, 2013). A task force on waste to energy was constituted to take forward this scheme (Planning Commision, 2014). In 2015 WTE become part of the national level initiative – *Swachch Bharat Mission* (PTI, 2015)[7]. More recently, the new Solid Waste Management Rules 2016 has added a detail section on waste to energy technology (MOEFCC, 2016).

Interviews with key local actors in Delhi identified two distinctive contemporary framings of waste and the waste management system in Delhi which are presented in the **Table 2** in summary and through representative quotes from interviewees.

The narrative around the WTE technology was that it "can kill two birds with one stone" - it can clean the city by scientifically disposing of solid waste and by generating energy it can help reduce the large electricity deficit (Ahluwalia, 2013). This narrative was widely spread by the various proponents of the project. The Chief Engineer of the East Delhi Municipal Corporation (EDMC) propagates it as a more viable option than new landfill sites[8], while the Senior Environmental Engineer of Delhi Pollution Control Committee (DPCC) believes that "it is the future of waste management in India." According to him, due to increasing westernization and changing consumption pattern, there is more use of processed and packaged products. Moisture content in waste is decreasing and calorific value is increasing, which would incinerate better and generate energy[9].

The dominant narrative emphasizes centralization and formal privatization of waste collection and management services through public-private-partnership (PPP) arrangements centered on incineration of waste in WTE plants which simultaneously generate energy and profits while removing the waste problem.

Who Wins and Who Loses From a WTE Pathway

In this section we analyse the trajectory of socio-technical-ecological change and discuss the range of outcomes and impacts on different stakeholders – intended as well as unintended – that emerge as the WTE pathway unfolds. Researchers conducted interviews with officials, waste-picker association members and NGO activists with expert knowledge in order to build a detailed picture of the dynamics of the waste management system in its formal and informal activities. Shadowing with wastepickers gave a unique insight into the informal system of waste management from the perspective of those directly involved.

[5]A method for the treatment of organic wastes through a process of anaerobic digestion generating methane for fuel.

[6]RDF is created by separating out combustible materials from municipal or industrial waste and processing these materials for use in WTE plants, usually by shredding and dehydrating.

[7]Alongside Delhi, the newly elected government announced setting up four more WTE plants under the mission in other Indian cities including Jabalpur, Hyderabad, Nalgonda and Chennai.

[8]There were two sites proposed by the Delhi Development Authority (DDA) for the creation of new landfill sites in Delhi. One was in Jaitpur and another in Madanpur Khadar. While Jaitpur site was discarded due to resistance from the locals, the Madanpur Khadar was also discarded because it falls in the way of an "Air Funnel" (landing zone of flights).

[9]Interview with Senior Environmental Engineer at Delhi Pollution Control Committee (DPCC), date 26-12-2012.

TABLE 2 | Dominant and alternative narratives concerning the problem of solid waste management in Delhi and its proposed solutions.

	Dominant narrative	Alternative narratives
Summary	Centralization and privatization of waste collection and management through incineration turns waste from a problem into a resource for profit.	Waste is already a resource central to the livelihoods of informal wastepickers who provide a service to society and contribute to environmental goals through recycling and waste recovery through composting schemes while WTE creates more problems than it solves.
State actor	"By encouraging WTE, the government can kill two birds with one stone. We can clean our cities by scientifically disposing solid waste and generating electricity and at the same time help reduce the large electricity deficit in the country." Senior official, ICRIER[a]).	
Scientific expert	"With the increasing westernization, WTE plants would be successful in Indian cities because of changing consumption patterns, decreasing moisture content in waste, and increasing calorific value" (senior scientist, DPCC[b]).	"The demerit of such technology is that air pollution can never be avoided even in highly sophisticated plants. The additional cost of the complete pollution control systems is about 30 percent of the power plant cost, which makes it financially unattractive to the already high investment system." (Professor, Dept of Civil Engineering, JMI[c]).
WTE tech firm	"If a single technology is available which handles waste and also gives you power, then I don't think anything else is required." (senior official, jindal ecopolis). "I have been to the okhla plant in Delhi. There is no pollution, and in fact there is no space for the air inside the plant to go outside. You can see the smoke of cigarette but you can't see any smoke in the chimneys." (Director, MNRE[d]).	
NGO		"Why is burning waste the most important thing? We still don't have infrastructure to regulate these toxic emissions, which are critical. Why can't we focus on recycling and composting as a means to tackle the problem of waste management?" (director, toxics link).
Resident		"These plants should not be in the vicinity of any residential colony. It should be far away from any habitation. It is simple—if there is no space in Delhi, then there should not be any WTE plant in the city." (President, Sukhdev Vihar, RWA[e]).
Waste picker		"After all the three WTE plants in Delhi are operational, given their proposed capacity they would require 7,500 MT of waste every day. No recyclables would be left for wastepickers. There would be a major impact on the livelihood of 300,000 informal wastepickers of Delhi." (Chintan, Lokadhikar).

[a] *Indian Council for Research on International Economic Relations.*
[b] *Delhi Pollution Control Committee.*
[c] *Jamia Millia Islamia, Central University.*
[d] *Ministry of New and Renewable Energy.*
[e] *Residents Welfare Association.*

Informal Waste Sector and Privatization

The reconfiguration of waste infrastructure in Delhi started with the process of privatization of collection services. In 2005, the Municipal Corporation of Delhi (MCD) invited private players to engage in the collection and transportation of solid waste (Garg et al., 2007). Before privatization, the informal wastepickers mainly managed door-to-door collection and segregation of recyclables from the waste. The involvement of the private sector in the waste management created major conflict between various government agencies in Delhi and informal wastepickers (Schindler et al., 2012).

It was assumed that bringing in the private sector would improve management efficiency issues, which the informal sector is arguably challenged with, as well as bring in better accountability than the municipal systems offer. Our fieldwork in Delhi shows that despite contracting the private sector for collection and transportation of waste, the informal sector continues to be deeply involved in the process, demonstrating the futility of trying to ignore their role. More than 50 per cent of primary collection is still done by the informal sector. There are many areas in which, either owing to space or manpower constraints, the private sector mechanisms for waste collection

FIGURE 2 | Waste pickers go door to door collecting household waste, usually without pay.

FIGURE 3 | Others waste pickers perform roadside collections.

and segregation do not work and are subsequently dependent totally on the informal sector[10].

According to the study done by the Institute of Human Development, there are 54 kinds of recyclable items in urban waste which are segregated by the informal waste pickers (Bhargava et al., 2012). According to the official figures, the informal wastepickers reduce the waste disposal load by 1,500 MT every day in Delhi. However, this figure is contested by many wastepickers associations, who believe that the figure is much higher. Official data suggests that during 2002-03, waste trading added a social value of Rs. 358.7 crore – or approximately 73.8 million USD – in Delhi (Khandelwal, 2012). The study shows that wastepickers also contribute in the reduction of GHG emission. A study estimates that informal wastepickers in Delhi prevent approximately 932,133 tons of GHG emission every year (Chintan, 2009). These two figures reveal that informal wastepickers play an important role in handling urban waste and preventing GHG emission, hence they should be formally involved in the waste management process keeping in view the challenges of occupational and environmental health related to their work (Wilson et al., 2006; Chikarmane, 2012).

The results from the shadowing exercises with wastepickers reveal more clearly the interactions between informal and formal waste systems through the daily routine of wastepickers in Delhi. The photographs and captions in **Figures 2–8** provide a narrative of this daily routine.

It was clear from the shadowing exercises and key interviews with representatives of wastepicker organizations that the informal sector continues to play an important role in the waste management system alongside formal private companies. At the same time, their role in the waste management system provides a source of livelihood that is vital to thousands of the poorest residents of Delhi. Until waste was recast as an energy resource in India, it was a matter of "negative environmental change" (Heynen et al., 2006). With little formal interest in resources from waste, all the recyclables in the waste stream belonged to the informal wastepicker becoming part of a complex recycling chain, and a major source of livelihoods. The shift in the narrative of urban waste from a source of risk to a resource for energy generation results in the same recyclable waste potentially being sought by WTE plants in order to produce energy, particularly as they are incentivized by the volume of waste they process. This in turn may have serious consequences for the livelihoods of wastepickers and implications for environmental outcomes as different wastes are processed in new ways.

FIGURE 4 | Collected waste is transported to "khatta" (community bins).

Social Justice Outcomes of WTE

According to the government figures, Delhi generates 8,360 Metric Tons (MT) of municipal waste everyday which comprises

[10]Process documentation of collection and segregation by the informal waste pickers in Rohini Sec X, New Delhi.

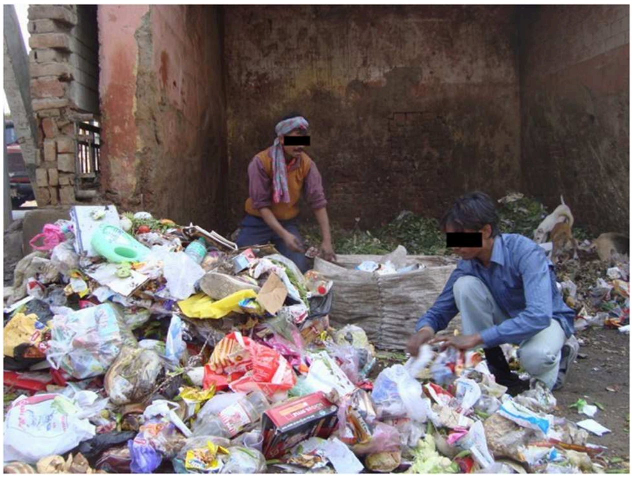

FIGURE 5 | At the khatta, waste is segregated and recyclables are collected.

FIGURE 7 | The recycled waste is collected and stored at the waste pickers' jhuggies where it is further segregated into 54 different types of recyclable.

FIGURE 6 | The recyclable waste is transported by waste pickers to their "jhuggies" (huts).

FIGURE 8 | Scrap dealers buy recyclables from the waste pickers and sell them on through the recycling industry.

of both biodegradable and non-biodegradable waste[11] (GNCTD, 2015). Once all the three WTE plants are operational in Delhi, they would require approximately 6,250 MT of waste per day to produce the projected amount of energy, leaving about 2,110 MT of biodegradable waste and inert material. If the WTE projects manage to do that then it would have significant impact on the informal waste-pickers. A study carried out after 9 months of operation of Okhla WTE plant shows that there is a significant decrease in the numbers of waste workers in the Okhla landfill sites, as recyclables are diverted to the WTE plant. The livelihoods of wastepickers were already threatened after door-to-door collection was handed over to the private companies (Schindler et al., 2012), and WTE projects have further intensified the threat of loss of livelihood. It is estimated that the livelihoods of approximately 300,000 informal waste workers would be lost after all the three WTE plants are operational in Delhi (Bharati et al., 2012).

[11]Despite population growth and increase in the consumption, this official figure has remained unchanged in the past one decade.

Environmental Outcomes of WTE

Despite being claimed as a clean technology by its proponents (DPCC, 2006; IL&FS, 2008), WTE in Delhi is surrounded by controversy in terms of environmental health. The controversy is mainly about the emissions from the WTE plant, the cost of controlling them and the lack of effective regulation. According to an expert in Delhi, the additional cost of the complete pollution control systems is about 30 percent of the power plant cost, which makes it financially unattractive to the already high investment system. The pollution is due to particulate matter, CO2, SO2, NOx, dioxin, and furans. The remaining ash after incineration also contains toxic elements such as arsenic, cadmium, lead and mercury. Treating ash for the pollutant is another costly affair[12]. Other published studies, focusing on WTE technology and emissions, support this argument (Akella et al., 2009; Narayana, 2009; Toller et al., 2009; Shah, 2011).

Lack of regulatory control was another issue that was raised in interviews for this study. For example, according to a DPCC official, the technology used in the Okhla plant is not RDF as specified in the Detailed Project Report (DPR) (CPCB, 2011). It is actually incineration-based technology, where waste is fed directly into the boilers[13]. An evaluation committee constituted by the Central Pollution Control Board (CPCB) has found violation of emission standards by the Okhla plant. According to the committee report, there is a deviation from the technology outlined in the Detailed Project Report and Environmental Impact Assessment reports submitted by the contractors of the project[14]. The report suggests that the modified technology has a risk of producing emissions having severe environmental implications (CPCB, 2011). Another report by a six member committee headed by CPCB on the direction of National Green Tribunal (NGT) in response to a PIL (W.P (C)No.9901, 2009) filed by the people living in the vicinity of the plant shows that the levels of dioxins and furans in the vicinity of the plant were several times higher than the permissible limits[15]. WTE is often presented as a clean technology which will address the considerable environmental concerns associated with older landfill sites. However, it can be argued that, without effective regulation of emissions the incineration of waste may simply redirect the flows of environmental risk; for example, reducing the risk of pollutants leaching into the water while increasing toxic gaseous emissions. The official narrative emphasizes the potential to address certain health hazards whilst making others invisible. Whilst attempting to reduce the environmental and health hazards associated with land fill sites, new centralized technologies are associated with new types of extremely toxic emissions being produced and a lack of proper regulatory mechanisms for controlling them. As one senior environmental NGO representative stated "Why is burning waste the most important thing? We still don't have infrastructure to regulate these toxic emissions, which are critical. Why can't we focus on recycling and composting as a means to tackle the problem of waste management?"

The location of the Okhla plant is in the midst of a densely populated region of South Delhi. The pollution from the plant may have adverse environmental health impacts on people across social strata. Several middle and lower-middle class colonies are located in the vicinity of the plant[16]. Many big private hospitals such as Holy Family, Fortis-Escorts, and Apollo Indraprastha are in close proximity to the plant as well. Two crucial wildlife sanctuaries, the Okhla Bird Sanctuary and the Assola Wildlife Sanctuary, fall within 10 km radius of the plant site (Shah, 2011). The residents of Sukhdev Vihar have filed a PIL against the plant based on environmental health impacts of incineration-based technology and lack of an effective EIA of the plant (W.P.(C)No.9901). The residents in the vicinity of the plant have started complaining about different kinds of health problems. Frequent problems of headache, irritation in eyes, sleeplessness, breathlessness etc. due to the smoke coming out from the plant were reported during the fieldwork. The Resident Welfare Association president expressed concern stating, "these are the common health problems, which we are facing currently but I am sure that if the situation with the WTE plant continues then there are going to be serious health issues in this area."[17]

Environmental health risks are distributed throughout the waste chain in diverse forms such as air and groundwater pollution and occupational hazards for wastepickers. However, the implementation of WTE addresses only the direct impacts of waste accumulation on middle-class neighborhoods and land-fill sites by providing a means of removing waste from residential areas and redirecting it from land-fill. This creates a new potential health hazard in other neighborhoods near WTE plants in terms of air pollution from incineration and leaves the health risk associated with the informal waste sector invisible. On the other hand, while informal wastepickers add a social value to Delhi's economy, privatization of waste management through WTE creates new conflicts with the informal sector which could be mitigated by alternative hybrid arrangements and partnerships.

What Alternatives Are Possible?

Focus groups and stakeholder workshops provided the opportunity to explore past experience and future opportunities for political actions to support alternative pathways of urban waste management. The research team sought to reveal political actions to support alternative waste management pathways on two key levels: top-down policy and bottom-up innovations in waste management practices. These actions were guided by eight principles for reframing urban waste management through a sustainability lens, which were distilled throughout the research process in dialogue with multiple stakeholders. We summarize the eight principles as follows:

1. Waste is not only an environmental policy issue but also touches issues of public health and the livelihoods of informal sector workers.
2. Waste flows are far more complex than is acknowledged in the formal assessments by official agencies.
3. Environmental health and social justice challenges are distributed throughout the waste chain. It is important

[12]Interview with the Faculty member of Department of Civil Engineering, Jamia Milia Islamia, Date 12 June 2013; Interview with Professor from Department of Biochemical and Biotechnology Engineering, Indian Institute of Technology, Delhi, 25 March 2013.

[13]Interview with Senior Environmental Engineer, Delhi Pollution Control Committee, 26 December 2012.

[14]Initially proposed WTE plant was based on MSW > MSW segregation > RDF plant + Bio-methanation plant > RDF Bioler + Electricity. This has been modified/simplified to; MSW > MSW segregation > Direct feed of MSW in WTE Boiler > Electricity.

[15]Interview with President, Sukhdev Vihar Resident Welfare Association, Date: 13 June 2013.

[16]Some of these colonies include Sukhdev Vihar, Haji Colony, Gaffar Manzil, Jasola Vihar, Noor Nagar, Masih Garh, Johri Farms, and Sarita Vihar.

[17]Interview with President, Sukhdev Vihar Resident Welfare Association, Date: 13 June 2013.

to recognize the ways that implementation of centralized technologies can exacerbate these issues.

4. Privatization does not replace the informal sector but emerges alongside it, generating new conflicts between formal and informal which can negatively impact livelihoods of the poor. Nevertheless, there are opportunities (and successful examples) to constructively link formal and informal activities.
5. Multiple options for decentralization are possible alongside centralized approaches (e.g., waste collection/decentralized bio-methanation, joining up community level composting with support for replacing chemical fertilizers with organic fertilizers in local agriculture).
6. Incentive structures could support more sustainable options - they currently only support private sector stakeholders and technocratic solutions.
7. Multiple schemes for people's participation in urban development decision-making have failed. however, there remain possibilities for constructive engagements in policymaking, planning, implementation and review of waste management projects.
8. Environmental health and social justice movements offer key insights into alternative waste management pathways. There are emergent opportunities to strengthen and develop alliances that reach across sectors, class and complementary agendas to build momentum behind alternative sustainable waste management strategies.

The research team engaged with policy-makers, private companies and wastepickers organizations to explore ways in which these principles could be implemented through policy and at the level of day-to-day practice.

Policy

Throughout the project, team members engaged with the wider public, government departments and local actors. A symposium was organized in Delhi on 16th March 2013 in collaboration with the Lokhadikar wastepickers association (project team members). This was a large public event involving government officials, researchers and wastepickers focusing on the lives of wastepickers and their contribution to the city. Following up from the symposium, the team engaged increasingly with the Ministry of Environment, Forests and Climate Change which was overseeing a key piece of waste management legislation (Municipal Waste Management Rules 2000).

This legislation outlines the responsibilities for waste management of local authorities and provides guidelines for how waste is to be managed. It was published for public consultation in October 2013 and a Kamataka High Court ordered that the rules be stayed for being too "regressive." Simultaneously, several groups also raised objections against the rules. The project team's NGO collaborator, Toxics Link, submitted formal objections drawing on the research findings and highlighted the ways in which the rules overlooked opportunities for sustainable waste management strategies. This led to a policy stakeholder forum organized by the project team in January 2014 attended by senior officials from the Ministry of Environment and Forests, the Ministry of Urban Development and the Central Pollution Control Board and a range of other stakeholders representing academic institutions, NGOs and wastepicker associations. One of the research team was subsequently invited to contribute to a government committee responsible for redrafting the rules.

This formal influence on policy was reinforced through a widely viewed interview with one of the project team members on a popular Indian show, Satyamev Jayate, in March 2014. Further, in May 2015 the project team published a policy brief at a high-profile event in Delhi involving government officials, and representatives from wastepickers associations, NGOs, industry and resident welfare associations which was reported in the national press. The policy brief outlined eight principles for rethinking urban waste management through a sustainability lens which were developed in collaboration with the range of actors engaged throughout the research process and was a timely reference for the redrafting of the MSW guidelines published in amended form in May 2015.

Practice

In addition to the formal influence on policy, the research team identified an opportunity for reframing waste management at the level of the day-to-day formal and informal practices of actors engaged directly in waste collection and processing. An alternative vision of urban waste management was identified through interviews and focus groups with wastepickers and NGOs which proposed decentralization of waste management systems to focus more on recycling with a central role for the informal sector and more localized community composting initiatives to handle organic wastes. The example of Pune City was cited as inspiration for such a potential future alternative to the dominant pathway.

The SWaCH initiative in Pune (since 2007) involves an alliance of the Pune Municipal Corporation, citizen and the wastepickers. The citizens are required to do a mandatory at-source segregation of dry and wet waste, while the wastepickers are responsible for door-to-door collection, segregation and decentralized processing (composting) and recycling of waste[18]. The *Parisar Vikas* programme initiated by the Stree Mukti Sanghtana (SMS) in Mumbai with the cooperation of the Municipal Corporation of Greater Mumbai (MCGM) in 1998 is another such example. Under this programme decentralized composting and bio-methanation are being run successfully at many places in 13 wards of Mumbai, including Tata Institute of Social Sciences (TISS), Tata Institute of Fundamental Research (TIFR), various housing societies etc. (StreeMuktiSanghatana, 2014). In a similar vein, Self-Employed Women's Association (SEWA) in Ahmedabad has organized 49,240 wastepickers and cleaners in Ahmedabad[19]. Despite privatization of primary and secondary collection in the city, SEWA has been organizing women wastepickers and has constituted Gitanjali Cooperative Society of wastepickers, which has a stationary unit involved

[18]Interview with Manager, Citizens Outreach at SWaCH on 16 October, 2013, Pune.

[19]Interview with Meenakshiben from SEWA, Ahmadabad on 28 October 2013.

in making various products out of recycled waste. These include notebooks, notepads, diaries, pen, pen stand, paper bags innovative jewelery etc. In addition to wages, they also gain other social benefits because of their association with the cooperative[20].

Through regular interactions between research team members and wastepickers unions and NGOs facilitated shared learning from the research studies in Pune and Ahmedabad which provided inspiration for Delhi's Lokadhikar wastepickers organization to sign a formal contract with a private company to segregate waste for 45 community bins in Rohini Zone. This provides a practical example of principle 4 by demonstrating how informal and formal private sectors can form new synergies which support informal livelihoods. These interactions have also led to a change in perspective among representatives of wastepicker groups (such as AIKMM) from seeing waste management as a narrow labor rights issue to a more integrated vision of the contribution of wastepickers to a range of social and environmental benefits and the potential for linking informal and formal waste management systems. This shared learning has also led to grassroots initiatives to implement decentralized composing technologies through new partnerships between informal waste workers, municipal bodies and resident welfare associations.

Interactions with various stakeholders highlighted the need to consider a mix of scale in the treatment of urban waste. Some waste streams like bio-medical waste, e-waste or plastic waste, construction and demolition waste need technical interventions which work best at larger scale owing to the kind of technologies needed as well as the regulation required to keep their operations within discharge and emission limits (Agarwal et al., 2015). However, degradable urban waste, such as is generated in households, institutions and markets places, by its very nature can be processed using technologies such as composting and bio-methanation, which can be applied at local levels.

Through interviews and focus groups it also became clear that informal wastepickers were mainly concerned with the issue of social justice which they feel is exacerbated greatly by waste management strategies dominated by WTE. While for middle-class residents, issues of environmental health were more important, related to emissions from the WTE plants. In Delhi, despite diverse concerns, both informal wastepickers and middle-class residents came together on a common platform to protest against the construction of specific WTE plants. Several protest marches were organized under the banner of that platform[21] (Krishna, 2011). Such a mobilization is unique in its nature where both set of actors – motivated by different concerns have come together on a single platform. Undoubtedly it is an opportunist alliance, but such an alliance also illustrates that sustainable waste management strategies will require effective engagement well-beyond traditional environmental policy actors, and that there is further potential to influence waste management trajectories by highlighting synergies between environmental, health and social justice perspectives.

CONCLUSIONS AND REFLECTIONS ON IMPACTS

The evidence presented in this paper reveals that waste flows are far more complex than assumed by the technological solution that is proposed. The informal sector plays a significant role throughout the network of waste collection and processing yet is unrecognized in waste management policy. Large-scale privatization and formalization of urban waste infrastructure does not replace this informal sector but emerges alongside it generating new conflicts while opportunities for cooperation are overlooked. Public participation in urban development decisions has been obstructed leading to an obstruction of clear opportunities for constructive engagements with diverse stakeholders in policymaking, planning and implementation.

Analysis of the unfolding dominant pathway reveals that environmental health and social justice challenges are distributed throughout the waste chain and some have been exacerbated by the drive for a centralized WTE approach to municipal waste management. While incentive structures support powerful private sector stakeholders and large-scale technological solutions, possible alternative approaches to waste management are neglected and environmental health and social justice outcomes will deteriorate. In short, the dominant pathway may be sowing the seeds for its own failure as political opposition among the public broadens and grows stronger.

The present waste management strategies in India are being made on the basis of a standardized model of flows of waste in cities that incompletely reflects the situation on the ground in a number of important ways. Debates occurring at different institutional scales including through international networks and national institutions are disparate and disconnected, neglecting critical aspects of social and environmental justice. As a result, there is a failure in addressing urban waste management challenges related to environment, health and social justice. For example, in most of the policy articulations, the removal of waste to other parts of the city (in landfills), or its incineration, is seen to address the problem (MOEF, 2000; CPHEEO, 2005; MOEFCC, 2016). The deeper examination of waste flows, and associated risks reveals that the adverse effects of waste may simply be being moved around the city to impact on different locations and social groups. In terms of environmental hazards incineration may merely move toxic pollutants from the ground to the air and generate ash with adverse health impacts (Agarwal et al., 2015).

The dominant narrative formed around WTE as a total solution to the waste crisis by framing the crisis as an issue of finding the most efficient way of removing harmful waste from the city, to which WTE appeared the perfect solution. This narrative transformed waste from a risk into a resource

[20]Interview with Yashodaben at Geetanjali Co-operative Recycling Unit, Ahmadabad on 28 October 2013.

[21]For more information on numbers of protest that happened against the plant, please check http://www.toxicswatch.org/.

for WTE plants while ignoring the role that waste already played as a resource in the informal livelihoods of wastepickers. It also cast the environmental health hazards associated with waste in narrow terms as controllable threats of pollution from unprocessed waste. This ignored the multiple emergent hazards that are associated with the complex waste management system that incorporates formal and informal sectors. While seeking to solve one environmental health problem, the newly built WTE infrastructure simply shifted the shifted the hazard to one of airborne pollutants, the consequences of which are still emerging.

In response to this analysis and in collaboration with strategic stakeholders, the research team adopted two direct routes for impact, at the level of policy and practice. By engaging with the live debates and emerging policies in Delhi, the research team found opportunities to contribute to the formal policy process around urban waste management. The amended MSW rules published in 2015 reflected many of the eight principles for reframing waste management outlined above. The rules moved beyond an "environmental policy only" perspective on urban waste (principle 1) and included many new stakeholders in the management of urban waste (clause 5 MSW rules 2016). The role of the informal sector was recognized in clause 11 and 15c, reflecting principle 4. There was greater recognition of decentralized technologies such as biomethanation and composting as methods for treating organic wastes alongside centralized WTE solutions (principle 5) with the explicit requirement that communities should be involved in waste management and promotion of decentralized processing alongside support for agricultural use of fertilizers produced from organic wastes [clause 4 (7) and 8].

At the level of practice, a new model of cooperation between formal private sector and informal wastepickers groups began to take shape and continued to evolve beyond the end of the formal research project. The activities with local informal actors in Pune and Ahmedabad supported engagement with wastepickers associations in Delhi and provided the opportunity to explore a wider set of framings and potential pathways of change.

The signing of a contract between Lokadhikar and a private waste management company and the promotion of decentralized composting schemes by the All India Kabadi Mazdoor Mahasagnh both represent a reframing of waste management on the part of wastepickers organizations and waste management companies.

This kind of combination of top-down and bottom-up reframing of waste management points to an alternative pathway of socio-technical-ecological change in waste systems that avoids lock-in to a single top-down technology driven solution. The examples of alternative waste management practices illustrate the range of options for a more sustainable pathway of waste management that combines decentralization alongside centralized approaches, through cooperation between formal and informal waste infrastructures. In addition, the strengthening alliance of environmental health and social justice movements reveals an opportunity to foster such alternative pathways in Delhi's municipal solid waste management. However, there is still much to be learnt and shared from transformative experiments in solid waste management and issues related to scalability and institutionalization.

This research also provides lessons for the role of transdisciplinary research (TDR) in urban sustainability transformations. Recent scholarship emphasizes the key role of transdisciplinary research to co-produce knowledge that challenges dominant narratives and creates new networks that involve and empower marginalized actors (Marshall et al., 2018; Iwaniec et al., 2019). We have shown how the STEPS Pathways approach can be applied in the mode of scholar-activists to empower marginalized actors to reframe debates on sustainable urban waste management challenges and bring social justice and environmental concerns together into a constructive platform. A key element in this process was the combination of methods to analyse the diverse underlying framings of the waste management challenge and the interplay between conflicting narratives, together with empirical studies of the material implications of existing policy trajectories for diverse interest groups.

Through working closely together with long standing policy advocacy groups, local and national NGOS, the academic strands of the work became fully embedded in a process which was intended to contribute to transformative change. This project exemplifies the need to spend significant time and energy on alliance building before and throughout action research initiatives of this type. In order to be influential these alliances need to be agile enough to respond to the changing political context and to evolve diverse pathways to impact at the level of formal policy and grass-roots changes in practices. In these ways the project contributed to two complementary elements of "transformative space making" (Marshall et al., 2018) in the Delhi's waste management knowledge system. First, by engaging with various policy processes, the project built the legitimacy of knowledges of the poor and informal sectors and helped to re-frame the narrative to reflect their perspectives. Second, by fostering new alliances and working with NGOs the research team helped to build readiness among poor and pro-poor actors to engage in opportunities for change in policy and practice.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable data included in this article.

AUTHOR CONTRIBUTIONS

PR carried out the majority of the field work and was responsible for writing much of a first draft of the manuscript in collaboration with FM, PK, and PD. FM was responsible for leading the research study, providing academic inputs throughout the planning, implementation and data analysis, and producing the revised draft of the manuscript. PK was involved in carrying out some of the field work for the study and drafted a portion of the first draft of the manuscript. PD was the Delhi based lead for the study. He provided inputs and advice to guide research activities in Delhi and commented on drafts of the manuscript.

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