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Environmental isotopes ($\delta^{18}O-\delta^{2}H$, ^{222}Rn) and electrical conductivity in backtracking sources of urban pipe water, monitoring the stability of water quality and estimating pipe water residence time

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This study demonstrates the use of environmental tracers (Water isotopes-$\delta^{18}O-\delta^{2}H$, Radon-^{222}Rn, and Electrical Conductivity-EC) as complementary tools for backtracking the water source, estimating pipe water residence time, and monitoring the instability of the water quality. Using the capital of Ethiopia, Addis Ababa, as a case study site, we demonstrate that water isotopes ($\delta^{18}O$ and$\delta^{2}H$) effectively backtrack the tap water to its source (springs, reservoirs, shallow aquifers, or deep aquifers). ^{222}Rn is shown to be effective for discriminating groundwater-sourced pipe networks from those that are dominated by surface waters. Our reconnaissance survey reveals that ^{222}Rn, a tracer previously not considered to determine the pipe water residence time, can be used effectively to determine pipe water residence time in groundwater-sourced pipe networks. We recommend further research to explore the capability of ^{222}Rn as a robust indicator of the pipe water residence time in an urban piped water network. The tracers reveal that 50% of the city obtains its water from groundwater and that the groundwater-sourced areas of the city show the highest water quality instability. The water quality in groundwater-sourced pipes varies depending on pumping stoppage owing to power interruptions. Surface water-sourced pipe water shows seasonal variations in water quality, with occasional large deviations from the normal trends following flow interruptions.

KEYWORDS

isotopes ($\delta^{18}O-\delta^{2}H$), radon (^{222}Rn), tap water, residence time, water quality, backtracking

1. Introduction

Urban water managers need to track the water source in the pipe network and to monitor and modify its quality between the points of treatment and use. It is necessary to track the sources of tap water, as the associated quantity (e.g., water source depletion) and quality risks (e.g., source pollution) differ between the various sources (Wet et al., 2020). For example, groundwater is believed to be more resilient to short-term droughts and less vulnerable to pollution than surface water (Foster et al., 2020), which has a potential knock-on effect on the pipes they supply. The water quality at the point of use may differ from the quality at the source because of the modification processes within the distribution network (Liu et al., 2018), making monitoring the water quality modifications imperative. The International Standards Organization (ISO 5667-5:2006) and WHO recommend municipal water monitoring to detect these changes.

In cities with centralized water sourcing and well-engineered pipe networks, it may be feasible to determine the water source using pipe network maps and the pressure distribution within the system. In rapidly-growing urban centers in developing countries, multiple and decentralized water sources (reservoirs, well-fields, solitary wells, springs, etc.) contribute to the piped network (Price et al., 2019). This makes it challenging to backtrack the water source and determine the residence time of different water sources at the point of use.

The water quality may change along the flow path within the pipe network (Zlatanović et al., 2017; Wee et al., 2021; Zhang et al., 2021). The residence time of pipe water, the infiltration of exogenous substances, in the case of negative pressure in the pipes, as well as the mixing of water from different sources could lead to changes in the water quality. A longer residence time often leads to a greater probability of water contamination within the pipe network (Tinker et al., 2009; Sekozawa et al., 2013; Zlatanović et al., 2017; Geng et al., 2021; Kennedy et al., 2021). Thus, water residence time in pipe network is a variable of interest for urban water utilities; it can be determined by using methods such as hydraulic models (Tinker et al., 2009), chlorine decay model (Bhadula et al., 2021; Geng et al., 2021), or, to a lesser extent, by measuring trihalomethane, a by-product of the chlorine-organic matter interaction (Sekozawa et al., 2013).

Another characteristic of interest in piped networks is the irregular changes in its quality. Irregular changes in the quality of the source water cause microbiological and physicochemical destabilization of pipe materials, which subsequently lead to the release of substances into the drinking water through biofilm detachment and resuspension, which cause health and esthetic issues (Liu et al., 2017, 2018). Thus, monitoring the stability of water quality of a piped network is of interest in urban piped-water quality management. Theoretically, pipes sourced from surface water reservoirs should show seasonal variations in the water quality, and borehole-sourced pipes should show a stable chemical composition, due to the general stability of the groundwater chemistry, compared to that of the surface water. However, this may not be the case if boreholes source their water from different layers of the aquifer, which have different chemistries. The water quality variations in borehole water can occur in response to the degree of pumping and to seasonality (Yager and Heywood, 2014; Piscopo et al., 2020). The systematic and comparative investigation of the stability of the water quality for differently-sourced (surface water, groundwater, etc.) pipe networks is lacking in the literature. As more and more cities in developing nations shift from centralized to multiple decentralized sources (Chávez García Silva et al., 2020), an understanding of the stability of the water quality of piped waters, may be of interest.

This paper aims to test the applicability of environmental tracers as tools for backtracking the pipe-water sources, monitoring the composition stability of pipe-water, and determining its residence time in the pipes. We will demonstrate the capability of water isotopes ($\delta^{18}O$ and $\delta^{2}H$) and Electrical Conductivity (EC) in backtracking the sources of water. We aim to demonstrate the potential use of ^{222}Rn (Radon isotope), something that has not previously been considered, to determine the residence time of pipe water. Furthermore, we will test the potential of ^{222}Rn for discriminating between surface water and groundwater sources in pipe networks. We have used Addis Ababa, the capital city of Ethiopia, as our case study site.

2. Theoretical considerations and methods

Environmental tracers ($\delta^{18}O$–$\delta^{2}H$, ^{222}Rn, and EC) are widely used in hydrology to trace the origin and movement of water in the hydrological cycle (Gat, 1996; Bresciani et al., 2018; Kebede et al., 2021). Water isotopes ($\delta^{18}O$–$\delta^{2}H$) have recently been employed in urban water systems to differentiate between the sources of water in pipe networks and to investigate the reliance of the urban water supply on one source or another (Bowen et al., 2007; Jameel et al., 2016; Nagode et al., 2022). The advantage of water isotopes is that once the source water enters the pipe network, its $\delta^{18}O$–$\delta^{2}H$ composition does not change within the pipes. Thus, $\delta^{18}O$ and $\delta^{2}H$ are powerful conservative tracers for backtracking the sources of pipe water, given that the different sources show different compositions.

^{222}Rn is the other isotope that can be used to trace pipe water sources and estimate water residence time. ^{222}Rn is a naturally-occurring and inert radioactive gas with a half-life of 3.82 days. It is produced in rocks and is abundant in groundwater, but non-existent in surface water. Depending on their residence time and degassing rate, water sources connected to groundwater should show a measurable ^{222}Rn content. Since the half-life of ^{222}Rn is short, it is an ideal isotope for determining the residence time of groundwater-sourced pipe water, as the typical age of water in pipes ranges from a few hours to a few days. Furthermore, ^{222}Rn is an ideal tracer for discriminating between groundwater-sourced pipe water from surface-sourced (reservoir) ones. Given that the residence of water in the pipe network is sufficiently short (e.g., <10 days) and that the source water contains sufficient initial ^{222}Rn, pipe water sourced from groundwater must show detectable levels of ^{222}Rn. All surface-sourced pipe water must show non-detectable levels, as the ^{222}Rn in this water is near zero. No published literature is available on the use of ^{222}Rn for determining the residence time of pipe water and for backtracking the water sources. However, a number of studies employ ^{222}Rn measurements in pipe networks to assess the radioactivity hazard of the water (Thabayneh, 2015; Büyükuslu et al., 2018). The current study is apparently the first in using ^{222}Rn to determine the water source and residence time in pipe networks.

Electrical Conductivity (EC) is a vital water quality parameter that can be measured easily (Bresciani et al., 2018). It correlates with most other dissolved substances in water and is thus widely used as a proxy for other dissolved substances in water (USGS, 2019). Thus change in the EC signifies a change in the water quality, implying EC can be used as a tracer of the water quality changes within a pipe network. Groundwater has a higher EC than surface water due to its chemical interaction with rocks (USGS, 2019). Generally, the shallow layers of an aquifer have a lower EC, compared to the deeper layers (Hem, 1989). Thus, EC can be used to backtrack pipe water to its shallow aquifer, deep aquifer, or surface water sources.

3. Study site characterization and sampling

The study was conducted in the water-challenged city of Addis Ababa. The challenges include complexity of the pipe network, intermittent water supply, and inadequate water quality at the point of use. The city has a complex urban water supply system. Many other cities in developing nations face similar challenges (Oluka et al., 2013; Chakava et al., 2014; Beard and Mitlin, 2021). Firstly, the pipe water is sourced from multiple origins (Figure 1A), including two large surface water reservoirs (Legedadi R and Gfersa R), multiple well-fields (Akaki 1, Akaki 2, Akaki 3, Old Akaki, and Legedadi), solitary decentralized boreholes within the premises of the urban area, and dispersed springs (Figure 1A). Secondly, tens of thousands of households have installed secondary water storage reservoirs (with a 1–5 m^3 capacity) to overcome the intermittent water supply. The reservoirs could alter the pipe water residence time and quality because of the potential backflow from the storage to the pipe network. Thirdly, untreated groundwater from hundreds of boreholes (BHs) is haphazardly injected into the pipe network from multiple decentralized solitary boreholes. The borehole water may be injected directly into the primary or higher-order pipes or singularly, where they are used to supply a specific area (e.g., the high-rise condos) of the city. This increases the risk of adding unaccounted-for pollutants into the pipe networks. Studies have demonstrated that tap water in Addis Ababa is polluted with trace elements, including As, Cr, Ni, Pb, Fe, and Mn (Dessie et al., 2021), turbidity, *E. Coli* bacteria (Mekonnen, 2015; Dessie et al., 2021), and coliforms (Wolde et al., 2020). The causes of pollution are unknown; it could be because the contaminated source or modification of the water quality within the pipes. A systematic investigation has been lacking into whether the above-normal concentrations are due to the water quality characteristics of the source, the infiltration of contaminated water into the pipe network, or the water quality changes within the pipe network.

There is limited literature on the use of environmental tracers for backtracking the water sources, estimating residence time, and understanding the water quality stability. As a result, we designed our sampling and measurement strategy as a reconnaissance survey and thus conducted a number of snapshot measurements at multiple spatial and temporal scales.

We sampled 48 groundwater sources (springs, shallow wells, and deep wells) and ten samples from the reservoirs and stream waters that feed the reservoirs (Gfersa and Legedadi) for $\delta^{18}O$ and $\delta^{2}H$ measurements. We measured the EC of tap water at 510 locations (Figure 1B), which are fairly distributed across the water source map produced by the Addis Ababa Urban Water Utility (Figure 1B). We sampled the tap water at 220 locations (Figure 1B) for $\delta^{18}O$ and $\delta^{2}H$, primarily before the pipes entered the household storage reservoirs. ^{222}Rn samples were measured at 27 selected locations. For the ^{222}Rn measurements, we took samples along the pre-defined flow direction of the pipe water.

For isotopic and EC measurement, grab samples were taken from water sources (water wells, reservoirs, springs and streams) and tap waters. We allowed the tap water to run for 15 s before taking the samples. In all cases, leak-proof doubly capped plastic bottles were used for sample collection for $\delta^{18}O$ and $\delta^{2}H$ analysis. Locations for the spatial sampling of tap waters were chosen to represent the entire city and the water sources. The sites for temporal monitoring of water quality in tap waters were chosen based on a priori knowledge of the water source at the point of monitoring.The Spatial Analyst tool in ArcGIS version 10.3 was used to produce the maps in this work.

Furthermore, on-site EC (25°C) monitoring was conducted hourly at five selected households at the five locations (Sites RS1, RS2, BH1, BH2, SP1 in Figure 1A) for a minimum of 72 h and a maximum of 4 months. Hand-held devices (Hanna™ 98312) with automatic temperature compensation and daily calibration were used to measure the EC of the water. The monitored sites included two predominantly surface water-sourced sites (RS1 and RS2), two solitary borehole-sourced sites (BH1 and BH2), and a site with mixed surface water and spring water source (Sp 1). The purpose of the long-term hourly measurement was to monitor the instability of the water quality within the pipe network accompanying the various sources.

A RAD7 radon electronic detector, fitted with a Big Bottle System for high sensitivity (Durrige Company Inc., 2020), was used to analyze the *in situ* ^{222}Rn content on grab samples of the waters. The detection limit of the device is in the order of 30 $Bq.m^{-3}$. The counting was based on the principle of liquid–gas-membrane extraction (Schmidt et al., 2008). An extraction module, consisting of hollow vinyl fibers allows radon stripping from the water sample into a connected closed-air loop. The water temperature was measured to convert the ^{222}Rn in the air to ^{222}Rn in the water. The overall standard deviation varied between 15 and 20%, which is higher for a low radon content. ^{222}Rn counting was conducted at each site over a period of 2 h in four cycles of 30 min each. The first reading was discarded, and the average of the latter three readings was taken as the mean ^{222}Rn composition of the specific water point. Liquid Water Isotope Analyzer version DLT 100 at Addis Ababa University was used to determine the $\delta^{18}O$ and $\delta^{2}H$ results in per mil (‰) notation calibrated against Vienna Standard Mean Ocean Water (VSMOW). The laboratory standard deviations are 0.2‰ for $\delta^{18}O$ and 3‰ for $\delta^{2}H$.

4. Results

4.1. The $\delta^{18}O$–$\delta^{2}H$, EC, and ^{222}Rn composition of the water sources

The $\delta^{18}O$–$\delta^{2}H$ composition of the water sources shows significant spatial and depth-wise variations. The shallow aquifers (Old Akaki Wellfield) and the cold springs plot near the weighted average $\delta^{18}O$–$\delta^{2}H$ composition of the Addis Ababa summer rains (Figure 2). The deeper aquifers distinctly show the depleted $\delta^{18}O$–$\delta^{2}H$, when compared to the composition of the shallow

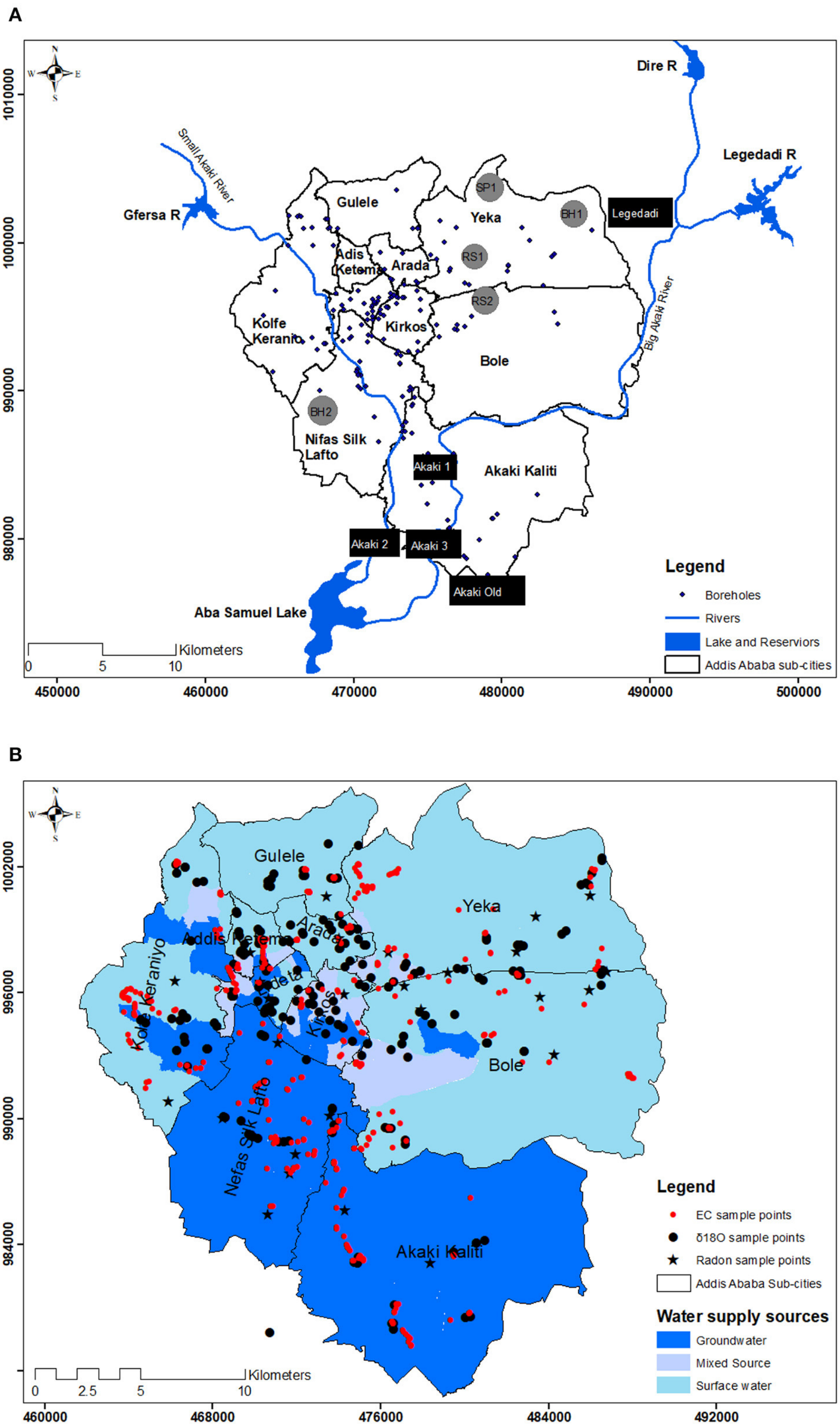

FIGURE 1
(A) Location of the various water sources supplying the city of Addis Ababa and EC monitoring sites, **(B)** Approximate Urban Water Utility water source map and snapshot of tap water sampling sites.

aquifers and the weighted mean rainfall (Figure 2). The two surface water reservoirs and their tributaries showed a relatively enriched $\delta^{18}O$–$\delta^{2}H$ composition, owing to evaporation from their surfaces (Figure 2).

The EC of the groundwater (boreholes and well fields) varied between 400 and 700 μS/cm. The shallow aquifers generally showed a lower EC than the deeper aquifers (Figure 2). The two surface water reservoirs showed EC values ranging between 100 and 170 μS/cm, which were low in the rainy summer (June–September)and high in the dry winter (October–May). The cold springs supplying the northern part of the city showed an EC value that ranged from 40 to 70 μS/cm. ^{222}Rn data in the surface water reservoirs showed values below the detection limit (30 Bq.m^{-3}), and the shallow and deep groundwaters from the aquifers show ^{222}Rn values ranging between 3,000 and 12,000 Bq.m^{-3}.

4.2. Spatial pattern in the EC, $\delta^{18}O$–$\delta^{2}H$, and ^{222}Rn composition of tap water

The EC value of the 510 tap water samples ranged between 100 and 670 μS/cm. The Inverse Distance Weighting (IDW) method was used to make a spatial interpolation and produce the spatial distribution map. The distribution shows a distinct spatial variation, which mirrored the variations in the source water composition (Figure 3A). Two major regions can be recognized from Figure 3A: The tap water in the southern part of the city showed high EC values, compared to that in the northern part. The high EC in the southern sector mirrors that the tap water source is from the Akaki well-fields (Akaki 1, Akaki 2, Akaki 3, and Old Akaki), located to the south of the city. The northern part of the city showed low EC values, which mirrors sources coming from the two surface water reservoirs (Legedadi R and Gfresa R). The EC pattern also distinguished the presence of local groundwater sources within the surface water-dominated pipe networks in the northern part of the city. For example, in the north-west and north-east of the Yeka sub-city and east of the Bole sub-city (Figure 3A), the local high EC values reflect that the source of water is from the solitary boreholes and the newly-developed Ledededi well-field (Figure 1A). The intermediate EC value observed in the Kolfe-Keraniyo sub-city (Figure 3A) mirrors the mixture of water from the solitary shallow boreholes and water from the Gfresa Reservoir.

The $\delta^{18}O$ pattern reflects a pattern similar to that of the EC, but with local differences. The tap waters showing the depleted $\delta^{18}O$ signals (Figure 3B) in the south-western and most eastern sub city mirror the deep $\delta^{18}O$–$\delta^{2}H$ depleted groundwater sources coming from the Akaki well-fields 1, 2, 3, and the Ledededi well-field, while the $\delta^{18}O$ enriched regions reflect the sources from the surface water reservoirs (Legedadi R and Gfresa R). The enriched $\delta^{18}O$ region in the south-eastern sector of the Akaki-Kaliti sub-city mirrors source from the shallow, relatively $\delta^{18}O$-enriched aquifers from the Old Akaki well-field.

The ^{222}Rn in tap water showed a distinct spatial pattern that mirrors the source of the pipe water (Figure 3C). A high ^{222}Rn was observed in the southern sub-city and locally in all the sub-cities reflecting a groundwater source. The northern and north-eastern region shows a low ^{222}Rn, owing to sources from the two surface water reservoirs. The high ^{222}Rn in the surface water-dominated northern sub-cities (Yeka, Bole, and Gulele) indicate that the source of pipe water is from solitary wells and that the addition of groundwater into the pipe network is from the newly-developed Legedadi well-field. All in all, the EC, $\delta^{18}O$, and ^{222}Rn patterns reflect the -source water composition, which mirrors the City Administration's map of the tap water sources, as shown in Figure 1B.

4.3. The temporal pattern of EC in tap water

The hourly monitoring of tap water at the five sites reveals variability in the EC, even when the water source is attributed to a single source. In the surface water sourced Yeka sub-city (Site RS1 in Figure 1A), a diurnal variation in EC was noted for the first 4 days, after which the EC jumped by about 30 μS/cm. While the water temperature variation can explain the diurnal variation, the cause of the jump on the fifth day was unclear (Figure 4A). One plausible explanation may be that the jump in EC marks the transitory passage of the borehole water injected into the system. The long-term (3-month) hourly EC in the surface water-sourced tap water (Site RS2 in Figure 1A) shows daily, seasonal, and other erratic variations. Similar to the RS1 site, the RS2 site shows a diurnal variation (Figure 4B). The EC declined from around 190 μS/cm in June (a dry month) to around 100 μS/cm in the wet month of August. The decline in the EC mirrors the decline of the EC in the source water, owing to the dilution of the reservoir water by rainfall. Site RS2 also shows erratic EC values. The first one is the very high outlier EC that was observed on three occasions (EC > 200 μS/cm). The outlier values were observed following pipe water interruptions and reconnection incidents. The outlier EC values thus reflect stagnation or the infiltration of contaminants into the pipe network, following the negative pressure that developed. The second erratic feature was the high variability in EC at Site RS2 in the month of September (Figure 4B); the cause of this high variability could not be established.

The two groundwater-sourced sites (BH1 and BH2 in Figure 1A) showed a significant EC variation (Figures 4C, D). In BH1, the pump was operated based on the users' water demand. Variations in the EC were linked to the pump operation hours. The EC is generally low at the start of pumping and increases during peak water use. The second site (Figure 4D) showed different EC patterns, after and before the days of water interruption, following a power cut. The higher EC on May 4 and 5 reflected water coming from a deeper level of the aquifer, while the low EC observed on May 8 reflected water coming from the shallow aquifer layers, which was caused by the aquifer recovery on May 6 and 7, following the power cut. The site sourced from the mixing of spring water (SP1) and the surface reservoir water (Legedadi R) (Figure 4C) showed a diurnal EC variation, which mirrored the mixing proportion between the two sources. The EC varied between 35 and 120 μS/cm (Figure 4E), with the low EC end member reflecting the water coming from the spring and the higher EC member, which reflected the water originating from the Legedadi Reservoir.

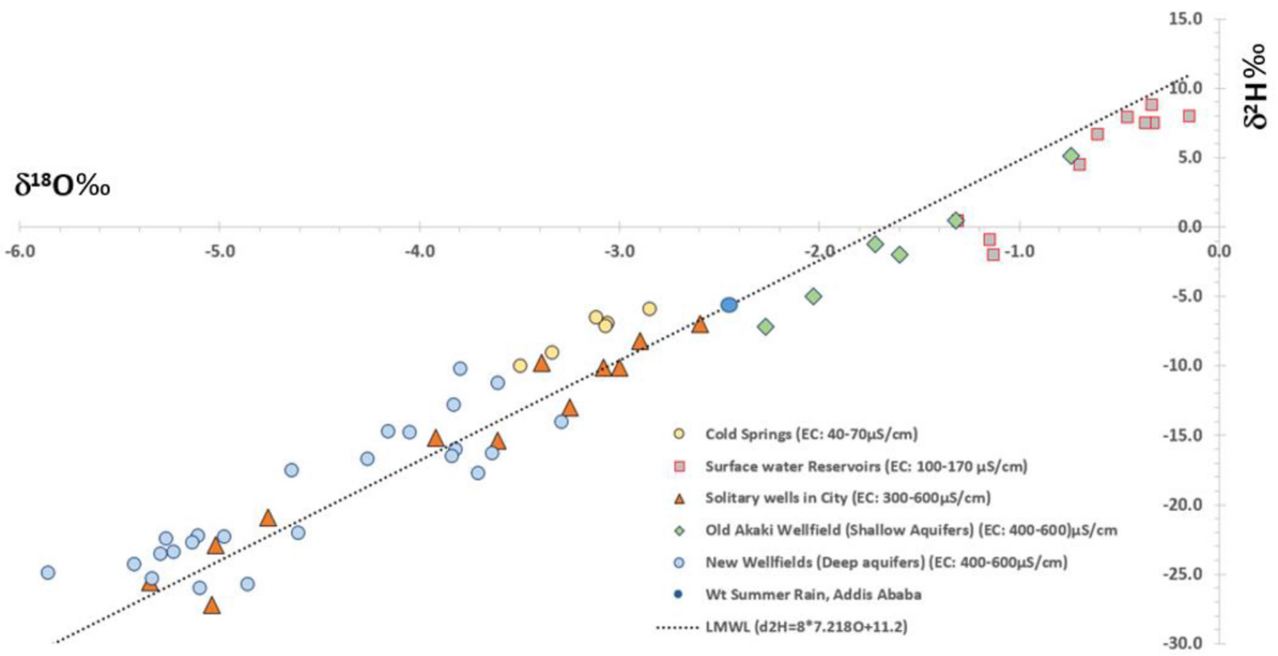

FIGURE 2
The $\delta^{18}O - \delta^{2}H$ composition of the various water sources supplying the city of Addis Ababa. The range of EC values corresponding to each water source is given, along with the legend.

Another notable feature is the fact that borehole-sourced sites (BH1, BH2) showed the highest instability in EC values (Figures 4C, D), compared to the surface water-sourced sites (RS1, RS2). The high variability in solitary well-sourced sites probably reflects variations in the degree of pumping and subsequent variations in the layer of the aquifer from which water is pumped in that particular instance. The surface water reservoir-sourced pipes showed relatively greater water quality stability, with noticeable seasonal changes and an occasional significant departure (Figure 4B). The outlier values in surface water-sourced sites may be due to the infiltration of contaminants into the pipe network.

5. Discussion

5.1. EC, $\delta^{18}O$–$\delta^{2}H$, and ^{222}Rn as tracers of the water source in the pipe network

EC, $\delta^{18}O$–$\delta^{2}H$, and ^{222}Rn effectively distinguished tap water sources. The tracers could also show the presence of locally-injected borehole water in otherwise surface water-dominated pipe networks. In the groundwater-sourced suburbs, the tap water showed a generally depleted $\delta^{18}O$, a high EC, and a measurable amount of ^{222}Rn. The taps connected to shallow boreholes show an enriched $\delta^{18}O$, compared to the deep groundwater-sourced taps. The tap waters sourced from surface water reservoirs show a relatively enriched $\delta^{18}O$, a low EC, and a ^{222}Rn content that was below detection (<30 Bq/m^3). This work reveals that such tracers can effectively discriminate the water sources in pipe networks offering the opportunity to use the tracers as complementary tools in urban pipe system water quality monitoring studies and monitoring design.

5.2. ^{222}Rn as a water residence time indicator

Urban water engineers conventionally use chlorine-based decay equations or hydraulic models to estimate the water residence time. Chlorine-based pipe water residence time computations are prone to error because of the non-conservative nature of chlorine. Depending on the water temperature and the initial concentration, chlorine interacts with the pipe wall and leads to a non-constant decay rate, which adds errors to the residence time computations (Tinker et al., 2009; Bhadula et al., 2021; Geng et al., 2021).

One of the important findings of the current research is that ^{222}Rn can be used as a potential tracer to determine the residence time of pipe water, potentially complementing chlorine decay or hydraulic model-based estimations. The advantages of ^{222}Rn include its non-reactive nature and its half-life, which is within the usual water residence time in urban pipe networks. We propose the simple radioactivity equation (Equation 1: modified from http://www-naweb.iaea.org/napc/ih/documents/global_cycle/vol%20i/cht_i_06.pdf to estimate the residence time.

$$^{222}Rn_t = {}^{222}Rn_o e^{-\lambda t} \tag{1}$$

where $^{222}Rn_t$ is the composition at the downstream end of the pipe network, $^{222}Rn_o$ is the initial concentration of ^{222}Rn at the point of entry in the upstream location λ is radon decay

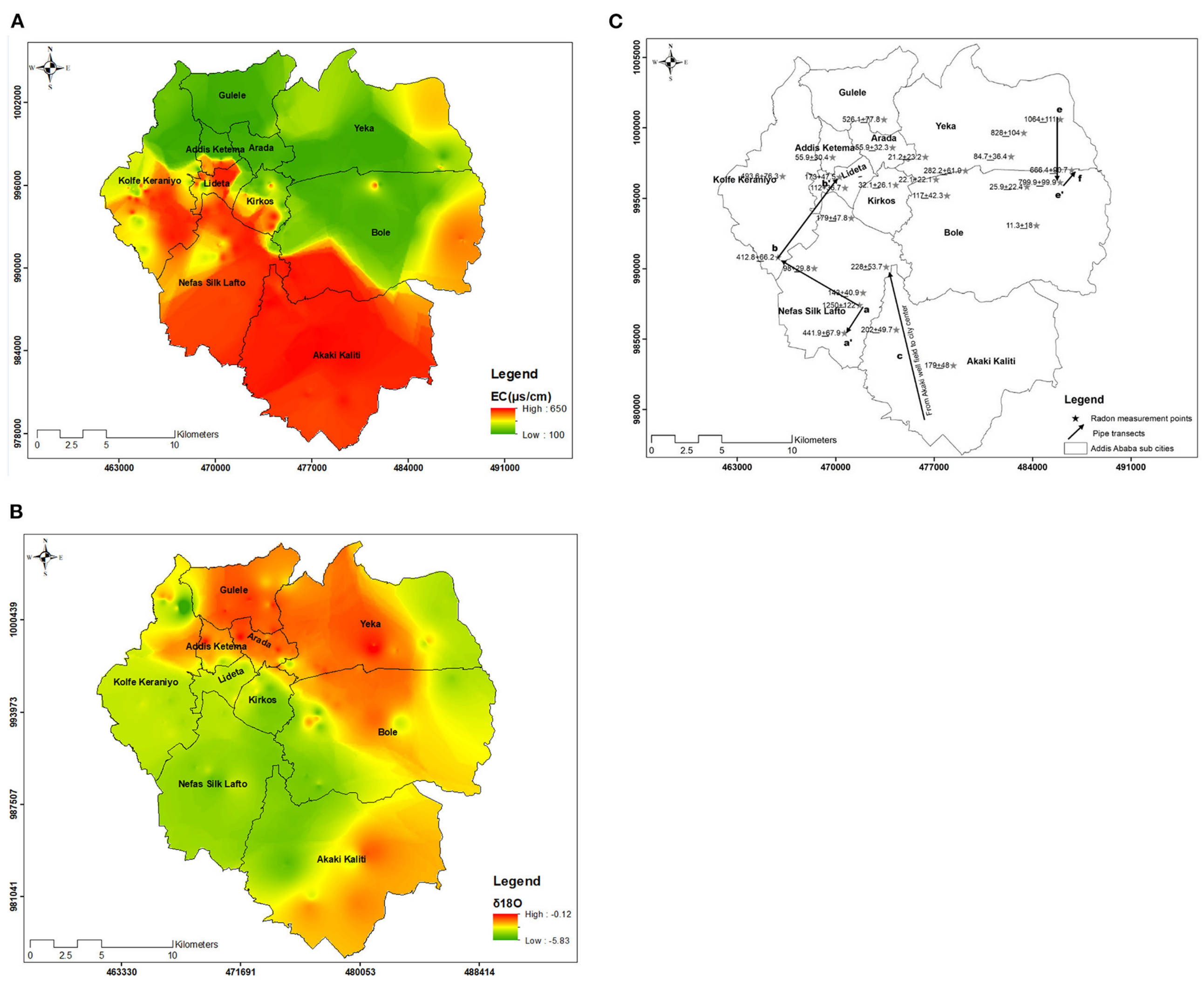

FIGURE 3
(A) The spatial pattern of EC, **(B)** the spatial pattern of $\delta^{18}O$(‰), and **(C)** the ^{222}Rn (Bq/m^3) composition in selected tap waters.

constant and is 0.181/day, and *t* is the time it takes for the water (residence time) to flow from the upstream entry point to the downstream point.

The disadvantage of ^{222}Rn may be its loss to degassing in the pipe network if there are storage reservoirs between the two ends of the pipe for which the residence time estimation is required. Degassing may lead to a loss of ^{222}Rn, and it may thus overestimate the residence time if Equation 1 is to be used. The residence time may be estimated easily under conditions where degassing is negligible. Degassing may be negligible if a large volume of water flows through the pipes daily and if the number of secondary reservoirs is limited. Furthermore, substantial infiltration and exfiltration of air into and from the pipe network can also alter the ^{222}Rn content, which may lead to an overestimation of residence time. Assuming that there is no loss by degassing, no addition of new water into the pipe network, and insignificant infiltration and exfiltration of air, the age equation (Equation 1) can easily be used to compute the residence time.

For our study, it was unrealistic to assume that degassing in the pipe network was negligible if the entire network was considered. Thus, instead of computing the residence time across the entire pipe network, we isolated a specific pipe section with a known pipe layout with no storage to estimate the residence time of water flow from the upstream end to the downstream point. We selected six different transects connecting the upstream and downstream points. The pipe transects along which the age determination has been computed are shown in Figure 3C (transects a–a′, a–b, b–b′, c–c′, d–d′, and e–e′). We took the ^{222}Rn in the upstream and downstream sites as $^{222}Rn_o$ and $^{222}Rn_t$, respectively, and computed the residence time between the two sites.

A quick look into the ^{222}Rn pattern observed in the groundwater-sourced suburbs (Figure 3C) shows a generally declining trend as one moves into the city center from the well-fields in the southern and south-western parts of the city. The residence time estimated by using Equation 12 along the selected transect and the salient features of the selected pipe transect, are

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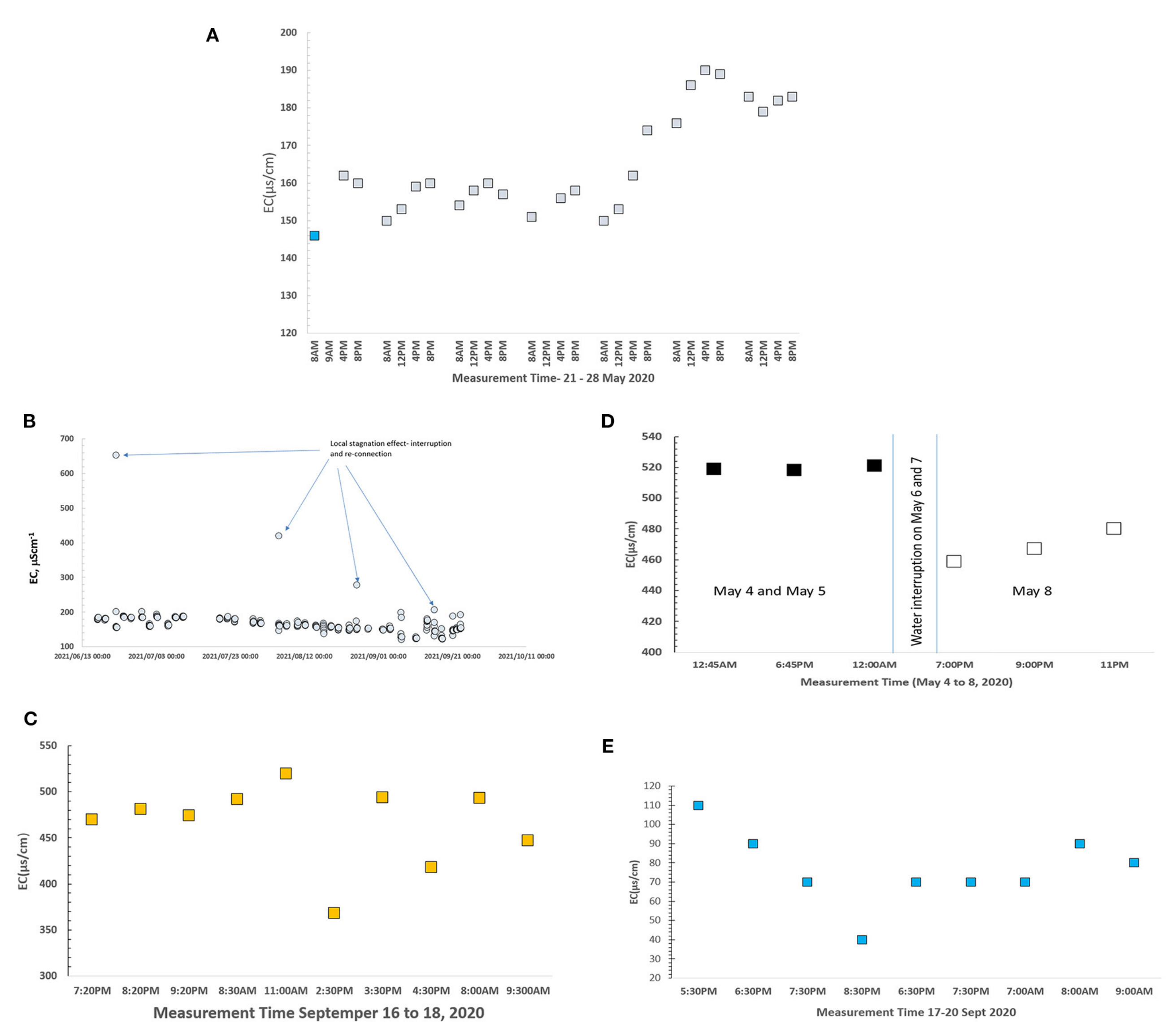

FIGURE 4
EC variation at sites RS1 **(A)**, RS2 **(B)**, BH2 **(C)**, BH1 **(D)**, and SP1 **(E)**. The timing of the measurement of the EC values are given, along with the figures.

presented in Table 1. We do not have independent sources of evidence to validate the estimation. The Addis Ababa Urban Water Utility estimates that 3 days is the mean residence time of water in the entire pipe network (Personal Communication), which suggests the reasonability of the estimates made for the selected pipe section. Apart along section a–a′, there is a good correlation ($R^2 = 0.75$) between the mean residence time and the length of the pipe, which further confirms the reasonableness of the ^{222}Rn-based estimates.

5.3. Stability of the pipe water composition

Using EC as an index of the water quality, we demonstrated that all the tap water showed a significant temporal variation, which potentially implies a temporal chemistry variation in the water. The variations has been observed on an hourly, daily, weekly, and seasonal time scale. Groundwater-sourced sites showed the highest temporal variations compared to surface-water and reservoir-sourced sites. Erratic changes in the EC of the water were noted in the surface water-sourced sub-city. These erratic variations are most likely attributed to stagnation and the infiltration of contaminated water into the pipe network following pipe water interruptions. The snapshot survey demonstrates that the chemical composition of tap water varies in response to the water sources. It also demonstrates that the spot water samples may not represent the long-term water quality properties of tap water. Solitary borehole-sourced tap water showed the highest degree of quality fluctuation. The stoppage of boreholes as a result of power outages was the primary cause of water quality fluctuation in borehole-sourced sites. Surface water-sourced tap waters also showed water quality fluctuations in response to diurnal variations in the temperature, water interruptions, and the infiltration of ambient contaminated water into the pipes.

TABLE 1 ^{222}Rn based residence time estimation for the selected section of pipes in Addis Ababa.

Transect in Figure 3C	R_o (Bq/m^3)	R_t (Bq/m^3)	Pipe length (km)	Estimated residence time (days)
a–a′	1,250 ± 122	441 ± 68	2.2	5.72
a–b	1,250 ± 122	412 ± 66	6.7	6.10
b–b′	412 ± 66	179 ± 48	7.2	4.56
e–e′	1,064 ± 111	799 ± 99	4.5	1.57
e′-f	799 ± 99	666 ± 91	1.2	1.00

5.4. Management implications

Environmental tracers have been proven to be an effective tool for backtracking the origins of tap water and for providing supplementary information on the residence time of pipe water. Backtracking the tap water to its source should provide important supplementary information for managing the water quality risks. The temporal monitoring of tap water shows the presence of unstable water quality at multiple time scales. The water quality of the monitored sites, at any given time, is not only the result of the composition of the source water but it is also affected by the mixing of water sources, the degree of pumping, the water-flow interruptions, stoppages, the reconnection of borehole pumps, etc. The instability in the composition of pipe water reveals the need to consider these variations in the design of urban water quality monitoring. The National guideline determines the number and frequency of monitoring based on the population density. The current work demonstrates that monthly sampling may not effectively capture water quality variations. More frequent monitoring may be needed in cities supplied by solitary boreholes. Monitoring the water quality also needs to be done following water interruptions, as an interruption may lead to compositional changes due to the infiltration of extraneous substances into the pipe network. In addition to the known water quality degraders, such as a high residence time and negative pressure in the pipe network, the current work demonstrates that the urban pipe water quality may be tied to the urban energy supply, as water quality changes can happen in response to borehole stoppages and reconnection as a result of electricity cuts.

6. Conclusion

The current work demonstrates the potential of environmental tracers, such as water isotopes (δ^{18}O–δ^{2}H), radon (^{222}Rn), and Electrical Conductivity (EC), for backtracking the sources of water, for estimating the residence time of water and for monitoring the instability of the water quality in an urban pipe network. The tracers have effectively discriminated between surface water-sourced pipe water from those sourced from groundwater. The groundwater-sourced sites have been further discriminated into shallow groundwater vs. deep groundwater. The use of the ^{222}Rn decay equation provided reasonable age values for the selected known sections of the pipe. To avoid complications from unaccounted radon rise, storage, and sink, we have isolated a specific pipe section with a known pipe layout with no storage, rise, and sink in order to estimate the residence time of water flow from the upstream end to the downstream point. While the non-reactive nature of ^{222}Rn and its half-life is suitable for the estimation of water residence time in the urban pipe network, the impact of (a) degassing of ^{222}Rn, (b) ingress of gasses into the pipe networks and, (c) radioactivity that may arise from the pipe wall, must be the target of future research. Sediment deposition inside pipe walls serving as a source of ^{222}Rn is the other complicating factor that needs further research.

We established that groundwater was the predominant water source for the case study site in the southern part of the city. In contrast, surface water sources dominated the northern part of the city. By using EC and ^{222}Rn, the presence of water originating from solitary boreholes was identified in the surface water-dominated pipe network in the northern part of the city. Water residence time varied from a few hours to 1–6 days. Surface water-sourced (reservoir) pipe networks show a seasonal trend and have relatively high water quality stability, except when it shows outlier values following pipe water interruptions and reconnections. Small diurnal variations in chemistry are noted for the surface water-sourced networks. Solitary borehole-sourced pipe waters show a high water quality variation, probably in response to the degree of pumping and pump stoppages and restarts, following electricity disruptions. This reveals the potential link between the energy supply and water quality in urban settings.

Data availability statement

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

Author contributions

The authors confirm contribution to the paper as follows: SK: study conception, design, analysis and interpretation of results, and manuscript writing. BB: GIS and production of figures and data collection. KH: data collection (δ^{18}O–δ^{2}H, ^{222}Rn) and contribution to writing. AS: data collection (EC). All authors reviewed the results and approved the final version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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