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Performance evaluation of a community-based water management organisation using integrated water quality monitoring

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ABSTRACT

Community-based water management organisations (CBWMOs) play an important role in providing water services worldwide. However, there is some debate as to their capacity to sustain a safe drinking water supply considering the current socioeconomic and climate scenarios. Here, we present an integrated water quality assessment of the supply system of a CBWMO in Concepción of San Ramon, Costa Rica. Major ions, trace metals, and coliforms were analysed in the households and water sources over a 1-year period. The spring risk assessments and the water quality of the main river in the catchment were also carried out. We found that although the supplied water meets adequate standards, spatial and temporal changes in the water quality of the sources exist. Springwater composition is mainly driven by rock–water interaction processes, but early signs of potential anthropogenic pollution were found. The springs showed concentrations of NO_3^- above natural levels and microbial contamination in 37 and 18% of the cases, respectively. River water quality showed a distinct composition, which is consistent with the anthropogenic pressures in the catchment. This study provides useful information on how water quality assessments can be used beyond regulatory processes to improve planning by CBWMOs to ensure water security.

Key words: community-based water management, Costa Rica, drinking water, surface water, water quality, water supply

HIGHLIGHTS

- Water is supplied at safe drinking standards for human consumption.
- Water composition is mainly driven by rock–water interaction processes.
- Contrasting spatial and temporal variations in water composition related to the source.
- Surface water quality is likely affected by agriculture and faecal pollution.

1. INTRODUCTION

Sustainable water resource management remains a challenge worldwide (Hering & Ingold 2012; Mdee *et al.* 2022), especially in terms of access to drinking water and sanitation. Nearly one-quarter of the global population lacks access to safely managed drinking water, while over half of the population, ~4.2 billion people, lacks adequate sanitation services (WHO 2021). The aim of reducing such disparities by 2030 is outlined in the United Nations Sustainable Development Goals (United Nations 2015). This undoubtedly represents a considerable challenge, particularly in developing economies or rural settlements where limited economic, technical, and human resources impede effective water resource management (Mena-Rivera & Quiros-Vega 2018; Patton *et al.* 2020). To overcome some of these challenges, a community-based water management model has been widely implemented (Hutchings *et al.* 2015; Tantoh & Simatele 2017; Machado *et al.* 2019). However, there is a general debate on their capacity to ensure both short- and long-term water security (Stedman *et al.* 2009; Mihelcic & Schweitzer 2012; Chowns 2015; Machado *et al.* 2022).

Community-based water management aims to improve water services by delegating responsibility to individuals within the community who work within the framework of a formal committee (Schouten 2003). Community-based water management organisations (CBWMOs) are then responsible for (a) ensuring inclusive decision-making processes, (b) providing training, maintenance, and technical support, and c) ensuring financial stability to adequately sustain the operation of the water distribution system (Day 2009; Mihelcic & Schweitzer 2012). This partially decentralised structure seeks to increase efficiency while also developing a sense of community ownership (Day 2009; Chowns 2015; Kativhu *et al.* 2018). Despite the wide range of responsibilities, the performance of CBWMOs has been primarily evaluated on the basis of improving infrastructure and administrative capabilities (Madrigal-Ballestero *et al.* 2013; Machado *et al.* 2022; Nowicki *et al.* 2022). The considerations of their long-term capacity to maintain adequate water quality have often been neglected. In addition, the influence of socioeconomic factors and operational monitoring on water quality outcomes within these organisations is still underexplored.

In general, data on drinking water quality are still scarce or inaccessible (WHO 2022). Yet, monitoring efforts have shown widespread contamination in both water distribution systems (Bain *et al.* 2014) and water sources (Burri *et al.* 2019; Hoque *et al.* 2021). The risk of consuming unsafe water is highest in rural areas of middle- and low-income countries, where most CBWMOs operate. In terms of monitoring water quality, CBWMOs often rely on government or external support, as it is expensive and time-consuming, which limits testing frequency, the numbers of pollutants analysed, the response time, and their capacity to ensure safe drinking standards. There is also some uncertainty as to whether the outcome of such programmes is used effectively (Ward *et al.* 1986; Timmerman *et al.* 2010; Kumpel *et al.* 2020). Nevertheless, water quality monitoring programmes are essential to ensure compliance with safe drinking standards, improve the operation of the distribution system, identify pollution sources, and assess water security (Charles *et al.* 2020; Nowicki *et al.* 2020; da Luz & Kumpel 2020). To this end, integrated monitoring would require assessment at the point of use, at all the water sources (e.g., wells and springs) and other relevant water bodies (e.g., rivers and lakes). Implementing integrated monitoring programmes, followed by comprehensive data interpretation, is necessary to further evaluate the effectiveness of CBWMOs.

In this study, we present a comprehensive evaluation of the performance of a CBWMO from a water quality perspective, focusing on a rural settlement in Costa Rica. The characteristics of this CBWMO, in terms of capacity and management, make it representative of similar organisations in the country. Our integrated assessment includes seasonal water quality data collected throughout the water distribution system, from sources to the point of use, complemented by a risk analysis of the aqueduct infrastructure. To identify potential anthropogenic pressures, we also analyse water quality in the main river of the catchment. Water quality data is interpreted using hydrochemical and multivariate techniques. We aim to (a) evaluate the capacity of CBWMO to provide safe drinking water, (b) identify the primary driver of water composition in the sources, and (c) identify potential threats that could compromise local water security. We expect to provide a better understanding of the challenges faced by CBWMOs in maintaining adequate water quality and ensuring sustainable water resource management in the region.

1.1. Drinking water and CBWMOs in Costa Rica

Costa Rica has made significant progress in providing safe drinking water access and sanitation services in recent years (Merino-Trejos 2019). In terms of water supply, almost 99.5% of the population has access to water, and between 89.5 and 91.8% receives water that meets drinking standards (Mora-Alvarado & Portuguez-Barquero 2018; Mora-Alvarado *et al.* 2023). On the other hand, sanitation coverage is expanding, but at a slower pace (Vaux *et al.* 2020). Septic tanks are the typical treatment system (75%), with sewerage accounting for only 23.8%. Only 17.6% of wastewater is adequately treated before discharged into fluvial systems (Mora-Alvarado & Portuguez-Barquero 2018). The country faces several challenges that could compromise water security, including inadequate land use, increasing anthropogenic pollution, and global climate change (Bower 2013). Unappropriated agricultural practices and poor urban development have historically contributed to the degradation of water quality (Mena-Rivera *et al.* 2017, 2018; Sanchez-Gutierrez *et al.* 2023). Furthermore, the lack of adequate infrastructure (Esquivel-Hernández *et al.* 2018) and the strong climate variability (e.g., long-term drought and heavy rainfall) in the Central American region (Hund *et al.* 2018; Sánchez-Murillo *et al.* 2020) are highlighted as the major threats to water resource management in the country.

In Costa Rica, CBWMOs manage more than 2,200 aqueducts that supply water for ~1.5 million people. This represents ~29% of the total drinking water supply in the country (Mora-Alvarado & Portuguez-Barquero 2018). The CBWMOs operate most of the aqueducts under the schemes of the *Comités Administradores de Acueductos Rurales* (CAARs) and the *Asociaciones Administradoras de Sistemas de Acueductos y Alcantarillados Sanitarios* (ASADAS). These are both non-profit organisations, but only the latter is previously authorised and audited by the *Instituto de Acueductos y Alcantarillados*; the government's institution responsible for providing drinking water supply and sanitation services (Madrigal *et al.* 2011;

Madrigal-Ballestero *et al.* 2013). Although CAARs and ASADAS play an important role in the supply of drinking water, some of these aqueducts are under highly vulnerable conditions. For instance, 58% of the CBWMOs do not take any action to protect the sources of water, although 87% of systems are supplied from springs and surface waters (PEN 2019), which might be poor quality or highly susceptible to increasing pollution. The use of water sources that do not meet the required standards for drinking purposes has been previously reported (Mena-Rivera & Quiros-Vega 2018; Gómez-Cruz *et al.* 2019; Sánchez-Gutiérrez *et al.* 2020a, b). Given that 34% of aqueducts do not undertake any control of water quality and 25% do not have continuous disinfection (PEN 2019), there is some uncertainty as to whether CBWMOs provide safe drinking water to the population.

2. MATERIALS AND METHODS

2.1. Study area and drinking water distribution system

The Cañuela River catchment is located in Concepción of San Ramón, in the providence of Alajuela, Costa Rica (Figure 1). The catchment drains an area of approximately 9.5 km^2 with elevation ranging from 970 to 1,630 m. The river flows from the northeast to the southwest, where it discharges into the Grande River. The catchment underlies andesitic and basaltic rocks from the Coenozoic, and the geomorphology is characterised by unstable steep hillslopes of irregular terrain. The climate is characterised by dry (December–April) and wet (May–November) seasons. The average annual temperature and precipitation are 20.7 °C and 1,470 mm, respectively. The Cañuela River is a sub-catchment of the major Grande de Tárcoles catchment, which is an important socio-economic region in the country with a high occurrence of water conflicts (Esquivel-Hernández *et al.* 2018).

The water supply in Concepción of San Ramón is provided by the local ASADA. The current distribution system comprises 16 springs, four connection points (CPs), one pumping station, and three storage tanks, distributing water to four different sectors comprising 71 homes, farms, and other municipal buildings. The system is divided into two sub-units. In the first sub-unit, at the top of the catchment, water is transported by gravity through a system comprising four CPs and 15 springs. CPs are defined as independent chambers that do not drain any spring; for instance, water from S1 is discharged into the

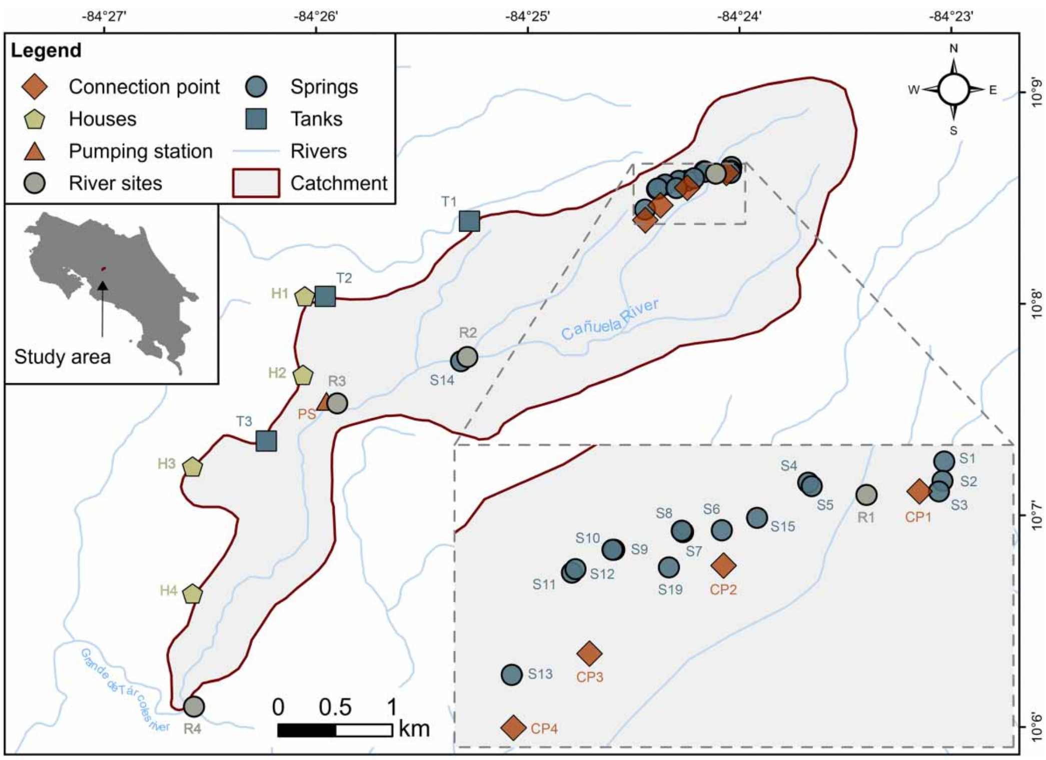

Figure 1 | Sampling sites within the Cañuela river catchment in Concepción of San Ramón, Costa Rica.

spring chamber S2, the latter being then not considered a CP. Water from this upper system is stored in tank 1 (T1, capacity 150 m^3) and distributed to sectors 1 and 2. In addition, a fraction is transported and stored in tank 2 (T2, capacity 75 m^3). In the second sub-unit, located in the middle of the catchment, water from S14 is pumped into tank 3 (T3, capacity 300 m^3) and distributed to sectors 3 and 4. This system only operates when water levels are low in the upper sub-units (T1 and T2). Water is disinfected prior to distribution.

2.2. Surveys

Accessibility, monitoring, and infrastructure conditions were evaluated each spring between May and June 2017. The risk assessment of the springs was divided between the protection zone (i.e., 100–150 m radius) and the spring chamber (Meuli & Wehrle 2001). A semi-structured instrument was also applied in the farms nearby ($n = 13$) to gather information about agricultural practices and identify potential sources of pollution.

2.3. Sampling and analysis

Water samples were collected during four sampling campaigns (October 2016, February, April, and June 2017) from the springs ($n = 60$), households ($n = 16$), and the Cañuela River ($n = 16$) (Figure 1). These include all the springs that supply the distribution system, households in each distribution sector, and river sites at the top, middle, and bottom of the catchment. Samples for the physico-chemical and microbial analyses were collected in high-density polyethylene (HDPE) bottles and non-reusable sterilised vials, respectively. HDPE bottles were previously washed with 3% m/v HCl and de-ionised water. Before collecting the samples from the households, pipes were purged for at least 5 min to avoid potential stagnant water. All samples were transported to the laboratory within 12 h of collection and stored at 4 °C. Temperature, pH, and conductivity were measured *in situ* using handheld multi-parameter Hanna Instruments HI98121 and HI98311 (RI, USA), respectively. Turbidity was measured in an Oakton T100 instrument (Ill, USA) and total dissolved solids (TDS) were determined by gravimetry at 180 °C following filtration through 0.45 μm pore filters (Isopore™, Merck Millipore). Hardness and total alkalinity were determined by titration with standard solutions of EDTA and H_2SO_4, respectively. Ion chromatography (Thermo ICS 5000, CA, USA) was used for the analysis of Cl^-, NO_3^-, SO_4^{2-}, Ca^{2+}, K^+, Na^+, and Mg^{2+}. Concentrations of heavy metals (Cu, Fe, Mn, and Zn) were determined by atomic absorption spectrometry with an air-acetylene flame, and Pb was measured using a graphite furnace with the Zeeman effect (Perkin Elmer Analyst 800, CT, USA). Microbial analyses (total coliform and *Escherichia coli*) were carried out at the Laboratory of Biotechnology at the Universidad Nacional, Costa Rica, following the multiple tube fermentation technique.

River water samples were characterised using additional parameters, including dissolved oxygen (DO), total solids (TS), biochemical oxygen demand (BOD), ammonium ($N - NH_4^+$), and total phosphorus (TP). Hardness, total alkalinity, and microbial analyses were not included in the river water characterisation. DO and temperature were measured *in situ* using a YSI probe ProODO (OH, USA), while conductivity was measured with a handheld Thermo Orion Star A222 probe (MA, USA). The concentration of TS was determined by gravimetry at 105 °C. BOD was determined using the 5-days incubation test (20 °C in the dark) and the modified Winkler method. $N - NH_4^+$ and TP were analysed spectrophotometrically in a Thermo Aquamate 2000E (Cambridge, UK) following the indophenol blue and the stannous chloride methods, respectively. Water samples were acid-digested ($H_2SO_4/K_2S_2O_8$) for phosphorus analysis. All analytical procedures followed the guidelines of the Standard Methods for the Examination of Water and Wastewater (APHA *et al.* 2012).

2.4. Quality control and data analysis

Instruments were calibrated using National Institute of Standard and Technology traceable standards. Procedural blanks, recovery quality controls, and calibration curves were carried out in each batch of analysis. Charge-balance error was estimated for each sample; samples with values greater than 10% were not included in the statistical analysis (springs, $n = 4$). Descriptive statistics of parameters that included values below quantification limits were calculated using robust regression on order statistics (Helsel 2012). Variables were excluded from the statistical analysis if the percentage of non-detects was above 60%. Differences in mean values per season were estimated using a one factor permutation test (Blair *et al.* 1994; Good 1994). Hierarchical cluster analysis (CA) and principal component analysis (PCA) were applied to identify spatial similarities in the water composition of the springs and the river, and the common parameters that were influencing the observed grouping. The suitability of the dataset for the PCA was tested using the Kaiser–Meyer–Olkin and Barlett's sphericity tests ($p < 0.05$). Hydrochemical characteristics were estimated using the Piper diagram (Piper 1944), the Gibbs diagram (Gibbs

1970), ionic ratios, and the chloro-alkaline imbalance indices (CAI1 and CAI2) (Schoeller 1972). Statistical analyses were carried out in R 3.5.1 (R Core Team 2018).

3. RESULTS AND DISCUSSION

3.1. Water supply system and land use

The risk assessment of the springs showed that they are in reasonably good condition (Table S1). Springs are in public areas or land owned by the local ASADA, so there are not any access restrictions other than the difficulty due to the hilly-uneven terrain. None of the springs had fencing around the inner protection zones (i.e., 10–20 m radius), and trees were often very close to the spring chambers, increasing the risk of potential damage. Most of the springs had reasonable drainage and the spring chambers were found well-constructed as no leakage was observed and manhole covers were present. However, none of the chambers was adequately ventilated, and two chambers had some sediments, although not enough to cause any pipe blockage. Two spring chambers could not be accessed, and therefore the evaluation was not conducted. It was reported that a spring chamber is manually disconnected from the water distribution system during the wet season due to the increasing level of contaminants caused by runoff. Water quality and quantity (i.e., flow) can be easily monitored at any spring; however, standard monitoring equipment had not been installed at the time of the fieldwork.

The area of the farms within the study area ranged from 0.5 to 10 ha. The land is used for agriculture (79%), livestock (14%), and conservation/reforestation (7%). Most of the agricultural area is covered by coffee plantations, which usually require NPK fertilisers, insecticides, and herbicides. These products are constantly applied throughout the year. With regards to livestock, the area was predominantly characterised by cattle and chickens. River water was reported not to be usually used in these economic activities, but just occasionally to clean tools or dilute pesticides. Most farmers have been trained in agricultural production (80%). The overall production supplies the local market (52%), the agro-industry (31%), international markets (8%), and self-consumption (8%). Most farms (92%) kept an informal riparian protection zone. This is present several metres along the river channel, but it changes with the area of the farm and the slope of the terrain. The perception of the river status was mostly pristine with little alterations (69%) and the main threads identified included wastewater discharge from farms (38%), runoff (23%), solid waste (15%), agrochemicals (8%), and deforestation (8%). Only 23% of the farms have houses on the property, which are generally used during the harvest season. The number of farmers depends on the time of the year, demand, and the farm's capacity, although a minimum of two people is expected to occupy the land permanently throughout the year. All households have septic tanks, and in just one case, it was mentioned that grey water is directly discharged to the ground nearby. None of the respondents have received any complaints regarding pollution events related to their own economic activity. Of the respondents, 92% consider themselves part of the local ASADA.

3.2. Water quality in households and springs

The summary of the physical, chemical, and microbiological conditions of the households and springs is shown in Figure 2. Descriptive statistics of the complete datasets are given in Tables S2 and S3, respectively. Dissolved ions were found at low concentrations. Alkalinity, which is usually representative of these ions, ranged from 96.8 to 122.2 mg L^{-1} and from 71.5 to 150.0 mg L^{-1} in households and springs, respectively. The mean hardness concentration ranged between 53.8 and 70.2 mg L^{-1} in the houses and between 44.8 and 71.8 mgL^{-1} in the springs. All trace metals (Cu, Fe, Mn, Zn, and Pb) were found below the quantification limits. Total coliforms and *E. coli* were found in only one sample from households, both at 1.9 MPN 100 mL^{-1}. In the springs, total coliforms and *E. coli* were present in 34 and 14% of the samples, respectively.

Despite the differences observed in water composition between the point of use and the source (Figure 2), they were mostly non-significant ($p > 0.05$). Significant differences were only found for conductivity ($p = 0.0084$), Cl^- ($p = 0.0006$), and Na^+ ($p = 0.0003$). These parameters were higher in the households and they are likely related to the residuals of chlorination. In regard to the spatial and seasonal variability, spatial differences among households were negligible ($p > 0.05$) and a significant seasonal effect was observed only for pH ($p = 0.0011$). On the contrary, most of the water quality indicators in the springs exhibited significant spatial differences ($p < 0.05$); except for pH ($p = 0.597$), conductivity ($p = 0.073$), NO_3^- ($p = 0.053$), and turbidity ($p = 0.3$). Seasonal differences in the springs were only observed for pH ($p < 0.0001$), turbidity ($p < 0.0001$), and hardness ($p = 0.0410$), which could be related to the impact of runoff in the spring chambers. Nonetheless, the general results suggest that the water composition remains mostly constant throughout the year.

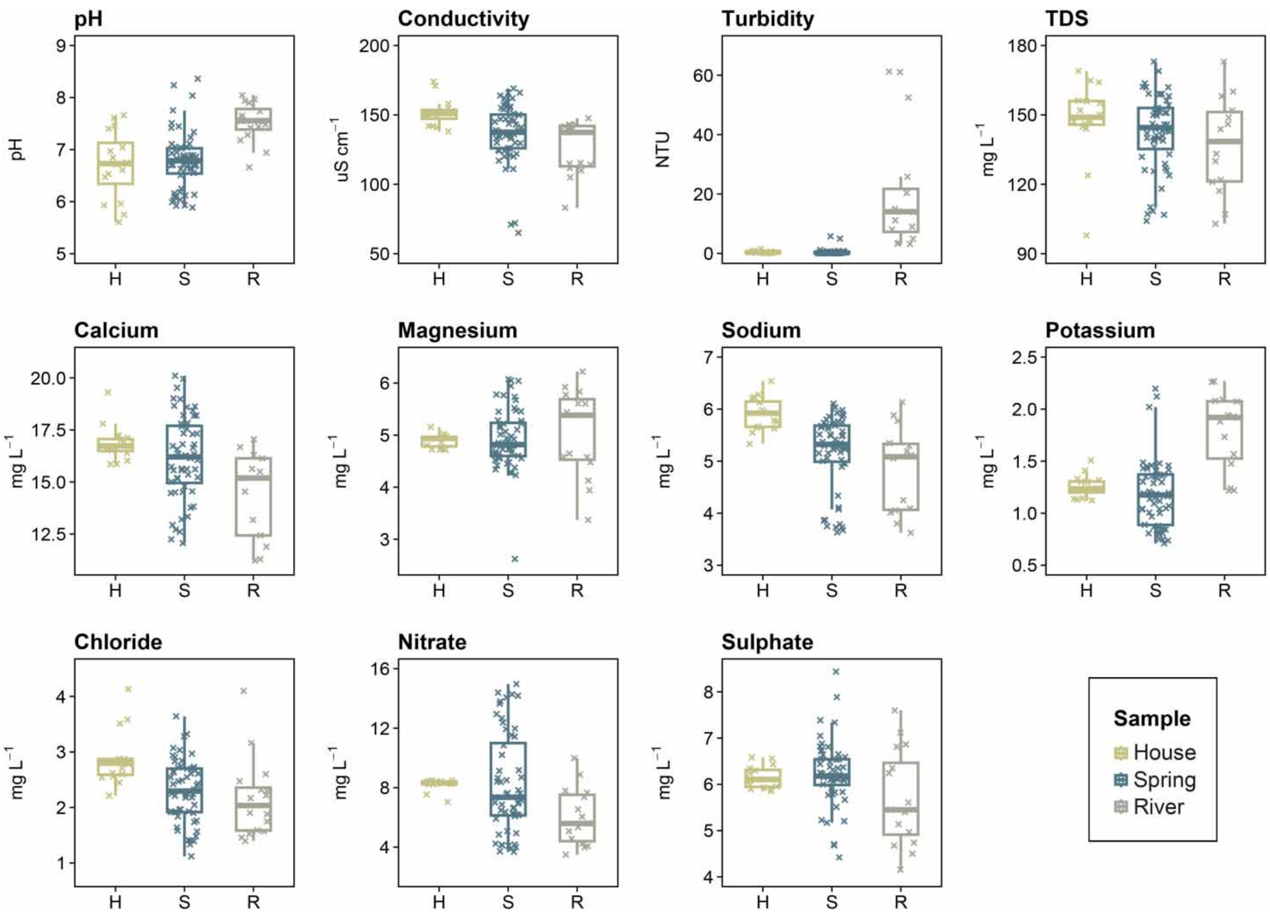

Figure 2 | Boxplots showing the concentration of several parameters in the households (H), springs (S), and river (R) in the Cañuela river catchment in Concepción of San Ramón, Costa Rica.

3.3. Assessment of river water quality

Figure 2 shows a summary of water quality parameters. No statistical comparison between river water and springs and/or households was carried out because the former is not used for drinking purposes. Additional assessed indicators included DO, TS, BOD, $N-NH_4^+$ and TP (Table S4). Oxygen levels were high with an average of 8.32 mg L^{-1} (SD = 0.41). TS ranged from 86.0 to 173.0 mg L^{-1}. BOD and $N-NH_4^+$ were mostly found below the QLs (<2 mg L^{-1} O_2 and < 0.07 mg L^{-1} N, respectively). The mean TP was 0.52 mg L^{-1}. The highest concentration of BOD was observed during a particular sampling campaign in the dry season at the river mouth (31.1 mg L^{-1} O_2), alongside a high concentration of TP (6.13 mg L^{-1} $P-PO_4^{3-}$) and other major ions. Spatial differences were obtained for turbidity ($p = 0.046$), Mg^{2+} ($p = 0.025$), K^+ ($p = 0.005$), Na^+ ($p = 0.046$), SO_4^{2-} ($p = 0.021$), and TP ($p = 0.001$). In general, a decreasing trend in water quality was observed downstream. On the other hand, the parameters that showed a significant seasonal variation included DO ($p = 0.005439$), TDS ($p = 0.04398$), Ca^{2+} ($p = 0.03497$), Mg^{2+} ($p = 0.03994$), and Na^+ ($p = 0.04491$). The concentrations of these parameters were lower during the wet season, likely due to dilution. Similar to the springs and households, trace metals (Cu, Fe, Mn, Zn, and Pb) were found below the quantification limits.

3.4. Drivers of springs and river water composition

Hydrogeochemical and multivariate analyses were carried out to better understand the spatial variability in water composition. Mean values were used because seasonal differences were mostly non-significant. At all springs, the abundance of major cations followed: $Ca^{2+} > Mg^{2+} > Na^+ > K^+$. The abundance of major anions was $HCO_3^- > NO_3^- > SO_4^{2-} > Cl^-$ for 53% of the samples and $HCO_3^- > SO_4^{2-} > NO_3^- > Cl^-$ for the remaining 47%. The sequence of major ions is typical of groundwater with short residence times (Chebotarev 1955); however, the inclusion of NO_3^- is more likely to reflect the impact of anthropogenic activities. Piper diagram was used to characterise the groundwater type, resulting in Ca^{2+}–Mg^{2+}–HCO_3^- classification (Figure S1). This water composition is mainly influenced by rock weathering processes as indicated by the concentration of TDS ($M = 142.7$ mg L^{-1}, SD = 16.2) versus the $Na^+/[Na^+ + Ca^{2+}]$ ratio ($M = 0.218$, SD = 0.015), or the $Cl^-/[Cl^- + HCO_3^-]$ ratio ($M = 0.058$, SD = 0.020) (Table S5).

Potential sources of major ions were evaluated using ratios (in meq L^{-1}). The relationship between the content of $[Ca^{2+} + Mg^{2+}]$ and $[HCO_3^- + SO_4^{2-}]$ suggests that the dissolution of calcite, dolomite, or sulphate minerals (e.g., gypsum or anhydrite) could be the main contributor to these ions in the springs (Figure 3(a)). In the $[Ca^{2+} + Mg^{2+}]$ versus HCO_3^- ratio, most samples are located above the 1:1 line (Figure 3(b)), suggesting that the origin of both Ca^{2+} and Mg^{2+} is more likely the dissolution of carbonate rocks. This was further explored using the Ca^{2+} versus Mg^{2+} relationship. Values of this ratio are related to the weathering of silicates (>2), calcites (between 2 and 1), and dolomites (<1) (Mayo & Loucks 1995; Subramani *et al.* 2010). The samples fell above and below the 2:1 (Figure 3(c)), indicating both the weathering of calcites and silicates. Likewise, the geology of the study area also highlights the presence of silicates. The sources of Na^+ and Cl^- were inferred from the Na^+/Cl^- ratio. In this case, samples were clustered above the 1:1 line, indicating an excess of Na^+ (Figure 3(d)). This is probably related to the processes of silicate weathering and/or ion exchange (Ghesquière *et al.* 2015; Liu *et al.* 2019). At the same time, it showed a low probability of the presence of halite or the significant input of Cl^- from anthropogenic sources.

The ion exchange reactions between the groundwater and the underlying material were evaluated using CAI. Negative values are an indication of normal ion exchange where Ca^{2+} and Mg^{2+} are adsorbed on mineral surfaces, releasing Na^+ and K^+. On the contrary, positive values indicate the sorption of Na^+ and K^+ following the release of Ca^{2+} and Mg^{2+} (reverse ion exchange) (Madrigal-Solís *et al.* 2022). The negative values obtained suggest normal ion exchange (Figure 3(e)). This process also leads to an increase in the concentration of Na^+ and/or K^+, which could explain the high concentration of Na^+ relative to Cl^-. The contribution of ion exchange to the hydrochemistry of the springs is derived from the relationship between $[Ca^{2+} + Mg^{2+} - HCO_3^- - SO_4^{2-}]$ and $[Na^+ + K^+ - Cl^-]$ (Figure 3(f)). Samples do not follow the -1 slope, which is usually an indicator of significant cation exchange (Fisher & Mullican 2012). Instead, a slope of -0.494 was observed. This suggests a partial contribution of cation exchange processes influencing water composition. These results, along with those of the Ca^{2+}/Mg^{2+} and Na^+/Cl^- ratios, suggest that the sources of cations in the water are predominantly the dissolution of carbonate-bearing minerals with a perhaps minor contribution from silicate weathering followed by normal ion exchange.

The main parameters influencing the distinctive water composition between the river and the springs were evaluated using PCA (Figure 4). PC1 explained 44.3% of the total variance and presented positive loadings for Na^+, conductivity, Ca^{2+}, TDS, and Mg^{2+}. PC2, which explains 27.4% of the variance, presented negative loadings for K^+, pH, and turbidity, and positive loadings for NO_3^- and SO_4^{2-}. PC3 explained 10.3% of the total variance, highlighting the contribution of NO_3^-, SO_4^{2-}, and Cl^-. The three PC presented eigenvalues greater than 1. In general, PC1 highlights the spatial distribution of the increasing content of ions in the water (from the northeast towards the river mouth), while PC2 and PC3 likely indicate the influence of anthropogenic activities. Using CA, the springs and river samples were classified into three groups (Figure S2). The first group (A) comprises the springs located on the northeast side of the catchment ($n = 3$) and the first river site at the top of the study area. This group is characterised by a higher pH and concentration of Cl^-. The second group (B) is formed by springs in the northwest slope ($n = 11$). These springs showed a greater concentration of ions and TDS. Two springs, S4 and S5, had a higher concentration of NO_3^- and SO_4^{2-} compared to the other springs within the same group. The third group (C) included one spring and the remaining river sites ($n = 3$). In general, river water was characterised by higher pH and turbidity but also showed an increasing trend in the concentration of K^+ downstream.

The presence of NO_3^- in some springs could be mostly attributed to anthropogenic sources. NO_3^- typically occurs in natural waters at concentrations below 10 mg L^{-1} (Xiao *et al.* 2022). Concentrations exceeding this threshold can originate from livestock manure, untreated sewage, landfill leachate, and from the application of N rich fertilisers for agriculture (Abascal *et al.* 2022). To distinguish between these potential sources, the NO_3^- to Cl^- ratio has been commonly used. Unpolluted waters have a low content of both NO_3^- and Cl^-, while a high ratio is attributed to fertiliser pollution. Furthermore, a low NO_3^-/Cl^- ratio with increasing Cl^- can indicate manure and sewage sources (Su *et al.* 2020; Huang *et al.* 2022). In the springs, NO_3^- exceeded the natural threshold in 37% of the samples, with values up to 14.97 mg L^{-1}. Four springs (S4, S5, S12, and S13) had a high NO_3^-/Cl^- but low Cl^-, suggesting a potential influence of fertilisers (Figure 5(a)). Because NO_3^- and SO_4^{2-} were highlighted in the PCA analysis, their relationship was assessed as Na^+ normalised ratios (Figure 5(b)). Some samples are close to the SO_4^{2-}/Na^+ ratio of 1, which is a common value that reflects agricultural and sewage influence

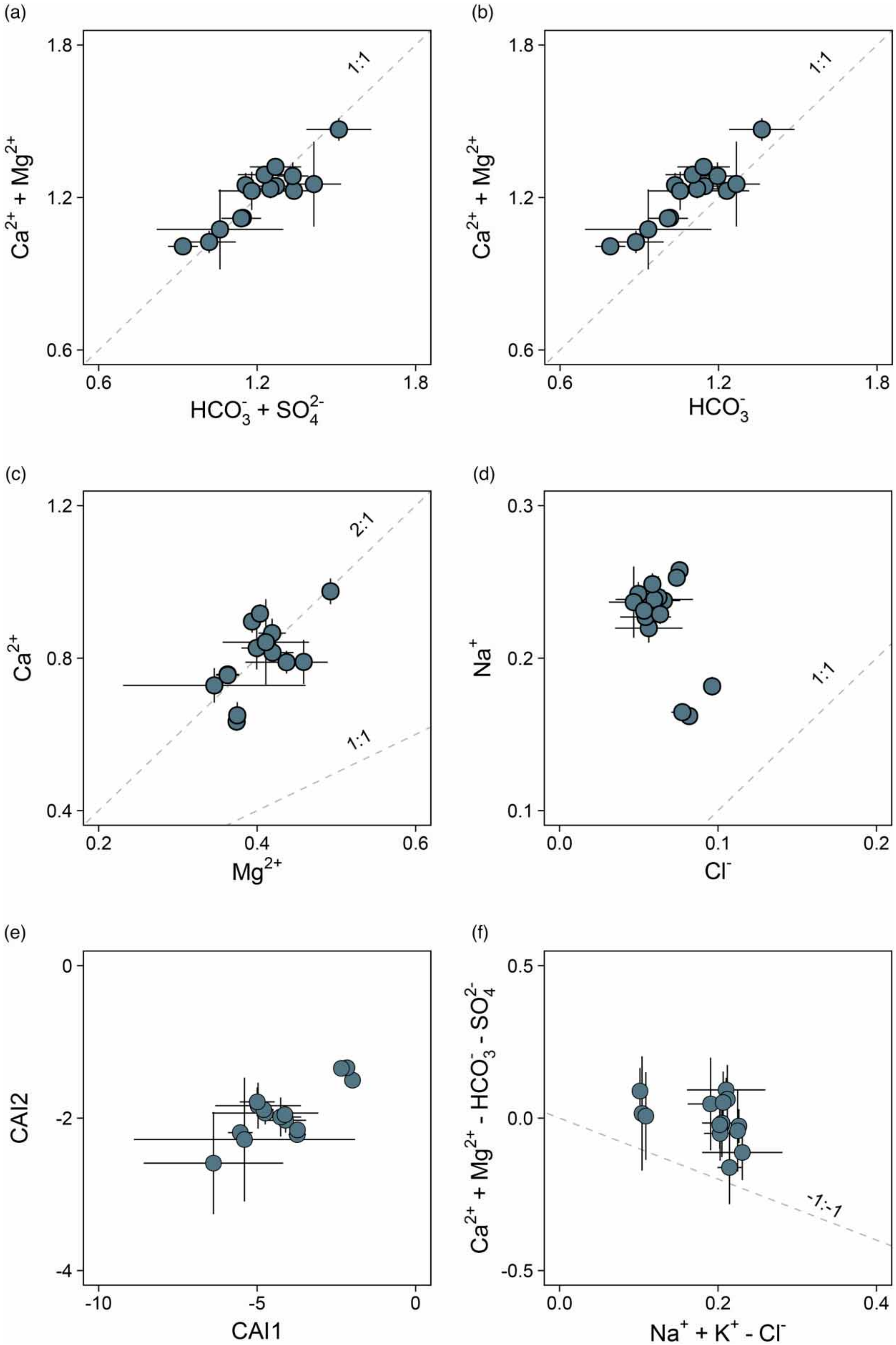

Figure 3 | Relations of (a) $[Ca^{2+} + Mg^{2+}]/[HCO_3^- + SO_4^{2-}]$, (b) $[Ca^{2+} + Mg^{2+}]/HCO_3^-$, (c) Ca^{2+}/Mg^{2+}, (d) Na^+/Cl^-, (e) CAI2/CAI1, and (f) $[Ca^{2+} + Mg^{2+} - HCO_3^- - SO_4^{2-}]/[Na^+ + K^+ - Cl^-]$ in the springs. Mean values (meq L^{-1}) $\pm 1\sigma$ ($n = 4$).

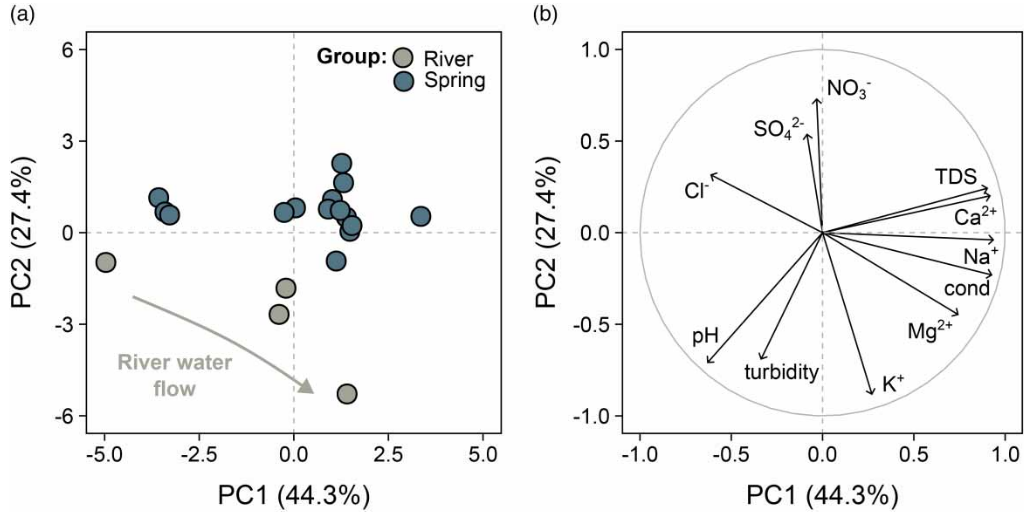

Figure 4 | PCA of the physical and chemical composition of (a) the springs and the river and (b) the loadings of the parameters.

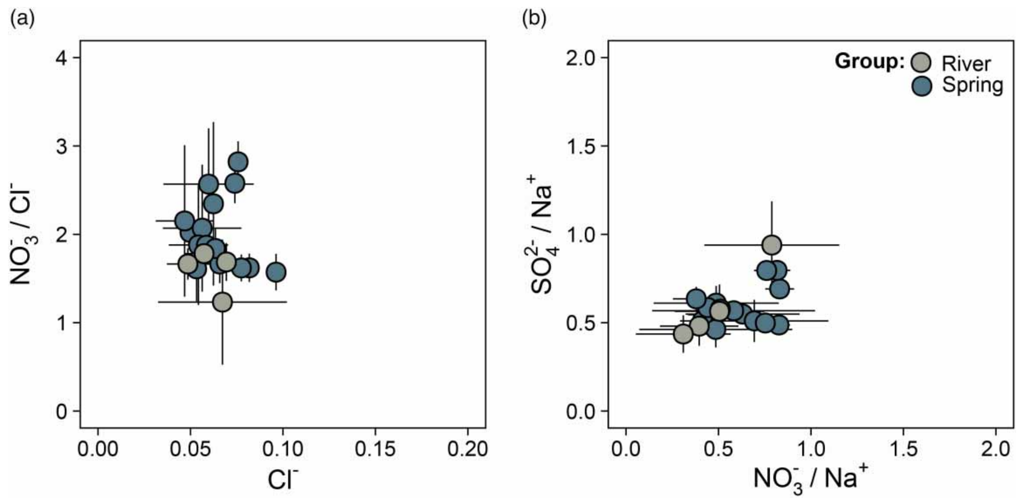

Figure 5 | Relations of (a) $[NO_3^-/Cl^-]/Cl^-$ and (b) $[SO_4^{2-}/Na^+]/[NO_3^-/Na^+]$ in the springs and river water. Mean values (meq L^{-1}) $\pm 1\sigma$ ($n = 4$).

(Roy *et al.* 1999). However, there was a slight trend of increasing NO_3^-/Na^+. Isotopic analysis ($^{15}N–NO_3^-$, $^{18}O–NO_3^-$, $^{34}S–SO_4^{2-}$, $^{18}O–SO_4^{2-}$) are required for a more accurate source apportionment of both ions.

3.5. Synthesis

Water supplied by the ASADA of Concepción of San Ramón presented high levels of compliance with local and international standards for safe human consumption (Table S2). This is achieved by ensuring adequate infrastructure, operation, and maintenance of the distribution system, and by using water from multiple sources. The infrastructure of the spring chambers was acceptable, but it is necessary to define a protection zone and to install fences to minimise the risk of interference and/or to protect instrumentation if it is installed. The spatial and temporal variations in the water composition in the households were not significant and were smaller than the variations within the springs (Figure 2). Microbial pollution was not present in the households, highlighting the efficiency of the disinfection treatment. However, total coliforms and *E. coli* were found in the springs, so they alone cannot be considered as a source of safe water. *E. coli* is an indicator of faecal pollution and, if pathogenic, it can cause illness (Edberg *et al.* 2000). Similar concentrations of *E. coli* have been reported in other drinking water distribution systems in both rural and urban settings throughout the country (Sánchez-Gutiérrez *et al.* 2020b; Barrantes *et al.* 2022).

Water composition in the springs is mainly driven by rock–water interaction processes during groundwater recharge. However, there were significant differences in the concentration of most parameters. This was partially unexpected because, as mentioned above, they are located in a relatively small area and the infrastructure of the spring chambers was adequate, minimising external factors. Most springs are clustered together in the northeast area of the catchment (Figure 2), but several have shown early signs of pollution from anthropogenic origin. Potential sources include fertilisers and faecal pollution, as demonstrated by the concentrations of NO_3^- and *E. coli*, respectively. The impact of these was also noted in the decreasing water quality of the river where the concentrations of TP and most cations increased downstream; in particular, K^+. Loss of both TP and K^+ from soils into surface waters can occur, via leaching and runoff, in areas of intensive agriculture where excessive amounts of fertilisers are used (Skowron *et al.* 2018; Liu *et al.* 2021). This coincides with the current land use as coffee plantations and livestock are abundant in the catchment (Section 3.1), but additional approaches are needed to quantify the impact of the potential sources on water quality. The environmental conditions in the Cañuela River catchment appear to be representative of other areas where CBWMOs operate in Costa Rica. Similar aquifer structures, recharge mechanisms, and environmental pressures have been reported in the Central Valley, Central Pacific and Northern Pacific regions (Madrigal-Solis *et al.* 2020; Sánchez-Gutiérrez *et al.* 2020a, b). Additional local pressures also exist; for instance, in more urbanised catchments where high levels of NO_3^- have been also related to the lack of centralised wastewater treatment facilities rather than only to agricultural practices (Sanchez-Gutierrez *et al.* 2023).

The general water quality information is of interest to the CBMWO not only for regulatory and operational purposes but also for future planning and management. For instance, household data indicated that the CBMWO provides safe managed drinking water. A comparison of the water quality of the springs to drinking water guidelines highlights the need for disinfection treatment. In its role as provider of water services, the CBMWO is then expected to primarily undertake the necessary steps to ensure satisfactory operation of the disinfection system. This type of recommendation can arise from the routine monitoring that is provided by the government; usuallyevery three years (for a similar number of parameters as presented here). However, a more holistic interpretation of the water quality data revealed insights into the complex mechanisms that are driving the water composition of the springs, and the potential sources of pollution. In this regard, the assessment of river water quality was instrumental to identifying anthropogenic pressures. This suggests that CBWMOs should also assume a role that is more orientated towards a broader management of water resources and conservation. In this case, for instance, to reduce the impact of agriculture on groundwater. It is important, however, to consider the legal framework that regulates the scope of the CBWMOs. This is because a multi-sector participatory approach involving the state, local governments, other CBWMOs, stakeholders, farmers, industry, and academia would eventually be needed to address current environmental challenges. Having provided evidence of the need to protect water sources in the long term, the involvement of CBWMOs in the planning and development of such initiatives should be strongly considered.

4. CONCLUSIONS

This study has demonstrated how integrated water quality monitoring is necessary to effectively evaluate the performance of CBWMO to make informed management decisions. In the case of the ASADA of Concepción of San Ramon, Costa Rica water quality data showed that (a) safely managed drinking water is provided to the local population, (b) the main composition of spring water derives from rock–water interaction processes during groundwater recharge, and (c) early signs of pollution from anthropogenic activities, mainly agriculture, are likely impacting the water quality of the springs and the river. It is important to note that the monitoring in this study is limited to two campaigns per season over one hydrological year. Water quality can change significantly at different spatial and temporal scales; especially during periods of heavy rainfall or drought. Such changes are expected to become more notorious in the river than in the springs or in households. Although the characteristics of the ASADA of Concepción are representative of other CBWMOs in the country, we recognise that the capacity to carry out monitoring of water quality is still limited for some CBWMOs; in particular, at adequate temporal and spatial resolutions. Additional topics related to water quality and risk assessment that should also be considered in the context of community-based management include the perception of the community about the water services provided by the CBWMOs, continuity of water service (e.g., shortages or interruptions), the effective communication of water quality data, and the proactive use of this type of information to support water safety plans. Nevertheless, we emphasise the importance of environmental data in supporting evidence-based decision-making regarding water resource management.

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AUTHOR CONTRIBUTIONS

M.L.-E. conceptualised the whole article, developed the methodology, rendered support in formal analysis, investigated and visualised the whole process, and wrote the original draft. L.M.-R. conceptualised the whole article, developed the methodology, rendered support in formal analysis, investigated and visualised the whole process, and wrote the original draft. R.S.-G. rendered support in formal analysis and wrote the review the edited the article. I.V.-G. conceptualised the whole article and wrote the review the edited the article. T.H.A.S. conceptualised the whole article, developed the methodology, investigated the whole process, and wrote the review the edited the article.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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