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Traditional irrigation practices sustain groundwater quality in a semiarid piedmont

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Abstract

In semi-arid areas, agricultural practices have been found to significantly alter groundwater quality. Although significant research has been conducted on the impacts of the intensification of irrigated agriculture, many pivotal questions remain relating to the impact of traditional agricultural practices on groundwater quality. In this study, the results of major ions analysis of 91 water samples collected in the semi-arid piedmont of the High Atlas Mountains, central Morocco, are used to assess the impact of traditional irrigation practices on groundwater quality. Despite the use of organic fertilizer in the irrigated area, the NO_3 groundwater concentrations remain low (median = 9 mg/L) and only increase on average by 3.6 mg/L during the irrigation season. All groundwater sampled in the irrigation area has an excellent quality for both drinking and irrigation purposes based on the chemical indices. Overall, groundwater chemistry is controlled by geogenic processes. Relationships between major ion in groundwater reflects the mineral dissolution and ion exchange processes during the trajectory of the streamwaters from the mountain to the alluvial plain via irrigation practices. In comparison, in the non-irrigated area, halite dissolution and/or transpiration processes results in increases in electrical conductivity values that were over twice the values in the irrigated area. The seasonal decrease of electrical conductivity values in groundwater beneath the irrigated area (on average from 841 to 692 μS/cm) is a result of irrigation recharge, which counterbalances effects of salinization mechanisms that can often characterize irrigated arid zones. These results highlight the low impacts of this ancestral hydro-agro system on groundwater quality. Such a traditional irrigation system provides a nexus between food production, low energy costs (streamflow diversions by gravity-fed channels), and low environmental impacts. In the context of accelerations in global change impacts via the rapidly expanding modern irrigation practices, such traditional hydro-agro systems, where possible, should be highlighted and preserved.

Keywords: Traditional agriculture, alluvial aquifer, hydrochemistry, water-rock interaction, ion exchange.

1. Introduction

Agricultural practices have significantly altered groundwater quality (Foster and Chilton, 2003; Duncan et al., 2008; Foster et al., 2018). This is a worldwide issue, and has been documented in many countries including in Uzbekistan (Johansson et al., 2009), Spain (Merchán et al., 2015; 2020), France (e.g. Tweed et al., 2018), Japan (Nakagawa et al., 2021), China (Zhang et al., 2012; Hu et al., 2019), and Tunisia (Haj-Amor et al., 2017). In particular, the transition from non- or traditionally-irrigated areas to the expansion and intensification of modern irrigation practices has had significant impacts on the deterioration of groundwater quality (Scanlon et al., 2007). Areas equipped with modern irrigation techniques and destined for intensive agricultural exploitation have globally increased from 170 to 333 Mha between 1965 and 2015 (FAO and IWMI, 2018). Keeping in mind that many rural areas around the world use groundwater for domestic purposes without any treatment (Ravindra and Garg, 2007; Buschmann et al., 2008; Coyte et al., 2019), actions are required to protect groundwater quality from impacts of these irrigation expansions. This is particularly the case for alluvial aquifers, which can provide important water supplies (Mvandaba et al., 2018; Xiao et al., 2021), but at the same time are also typically vulnerable to pollution (Wu and Sun, 2016).

Significant progress has been made in identifying the controlling processes of groundwater quality deterioration in irrigation areas (Xiao et al., 2020), which includes both geogenic and anthropogenic influences. Whilst some studies have found that irrigation by surface waters has increased groundwater salinity (Rabemenana et al., 2005; Scanlon et al., 2007), others have found irrigation by low salinity surface water has buffered groundwater from salinization impacts (Stigter et al., 2006; Rotiroti et al., 2019; Jia et al., 2020). Irrigation with diverted surface waters can result in groundwater mounds due to increased recharge. This recharge and rise in the water table can result in more rapid vertical transfers of agricultural chemicals from the surface to the saturated zone (Elmeknassi et al., 2021; Nakagawa et al., 2021), mobilization of evaporites from the unsaturated zone (Durhan et al., 2008), and an increase in the evaporative effects on the concentrations of contaminants in the shallow groundwater (Cartwright et al., 2007; Scanlon et al., 2007), especially under semi-arid climates. In addition, where the surface water used to irrigate is of poor quality, and the hydrogeological conditions allow for rapid infiltration of contaminants that remain mobile (Xiao et al., 2017), the recharge of irrigation waters can result in the widespread transfer of surface contaminants to the aquifer (Exner et al., 2014; Juntakut et al., 2019). This is particularly observed in agricultural regions located down-gradient from cities that are either heavily populated, have high runoff events, and/or have poor infrastructure to treat wastewater from domestic and industrial zones before flowing into the connecting rivers (Li et al., 2016; Panda et al., 2018; Liu et al., 2020).

The majority of the studies regarding the impact of irrigation on groundwater quality have considered the effects of modern irrigation systems, such as drip irrigation and cross-regional transfers (Chen and He, 2003; Jia et al., 2020). In comparison, fewer research has focused on traditional irrigation systems, such as streamflow diversion by traditional irrigation channels called Seguias (Bouimouass et al., 2020) or Acequia (Fernald et al., 2015; Turner et al., 2016). In semi-arid zones, streamflow diversion by traditional irrigation channels is common in irrigated areas adjacent to mountain ranges. Mountains are water towers for the adjacent lowlands because they receive more precipitation due to the orographic effect, and the accumulation of snow and ice contribute to runoff during hot and dry seasons (Immerzeel et al., 2020). Mountain streamflow sustains the downstream areas (Viviroli et al. 2007; Immerzeel et al. 2010) and a recent study showed that almost 1.5 billion people will depend on water contributions from mountain areas by the mid-twenty-first century (Viviroli et al., 2020). However, mountains are highly sensitive to climate and anthropogenic changes (Viviroli et al., 2011, Hock et al., 2019; Immerzeel et al., 2020). With worldwide decreases in snow already observed over the last decades (Berghuijs et al., 2014; Malek et al., 2020; Immerzeel et al., 2020), and decreases forecasted under climate change (Marchane et al., 2015; Baba et al., 2018; Hajhouji et al., 2020; Immerzeel et al., 2020; Viviroli et al., 2020), traditional irrigation areas and related groundwater renewal processes will be affected.

In traditional irrigation areas, particularly in semi-arid regions, flood irrigation is often an important source of groundwater recharge (Foster and Perry, 2009; Jimenez-Martinez et al., 2009; Bresciani et al., 2018; Rotiroti et al., 2019; Bouimouass et al., 2020). This recharge has also been found to improve groundwater quality, for example via the dilution of groundwater salinity (Rotiroti et al., 2019). In contrast, Juntakut et al., (2019) found that traditional gravity-fed irrigation resulted in greater nitrate concentrations in groundwater compared with center pivot-irrigation systems. Further investigation and characterization of groundwater quality under such traditional irrigation practices, in the context of climate change and population growth, is critical for water resources especially in semi-arid regions.

In the piedmont of the High-Atlas Mountains in the semi-arid Haouz plain, central Morocco, traditional irrigation is the main groundwater recharge source (Bouimouass et al., 2020). The area preserves a traditional agriculture where local small-scale farms have limited use of organic fertilizers for growing wheat and olives trees, irrigated by diverting the streamflow of the High-Atlas Mountains via channels known as Seguias. Groundwater from the alluvial aquifer is the sole drinking water resource for this rural area and it is used without any treatment. In this study area, we investigate the impacts of irrigation water recharge on groundwater quality via the evolution of salinity, nitrate and major ion concentrations in waters from the high elevation mountains to the piedmont. The results are used to determine whether the current traditional irrigation practices provide a model for sustainable agricultural practices and groundwater resources for a semi-arid region.

2. Study area

2.1. Location, climate and hydrology

As is the case for the whole of North Africa, Morocco is characterized by an arid to semi-arid climate with high inter-annual variability and several periods of below average precipitation (Jarlan et al., 2016). Piedmont areas along the High-Atlas in Morocco benefit from a milder climate and from streamflow generated at high altitudes (Toubkal peak at 4167m) by rainfall and snowmelt. The study area is crossed by the Ourika stream and extends from the High-Atlas Mountains to the edges of the Haouz plain, in central Morocco (Fig. 1). The Ourika stream, which drains a watershed in the High-Atlas of 492 km^2, is one of the main tributaries of the Tensift basin (Fig. 1). The climate varies from arid to semiarid in the plain, and from semiarid to sub-humid in the High Atlas Mountains. The mean annual rainfall ranges from 200 mm in the plain to 600 mm in the mountains as both rain and snow. In the High-Atlas Mountains, streams are fed by rainfall and snowmelt (Marchane et al., 2015; Hajhouji et al., 2018). The snowmelt contributes on average 15% to 30% of the streamflow (Boudhar et al. 2009; Boudhar et al., 2016). Therefore, the streamflow is high during winter and spring and low during summer and autumn. The average inter-annual flow-rate of the Ourika stream is 4.92 m^3/s at the Aghbalou gauging station (Fig. 1).

2.2. Geology and hydrogeology

The High-Atlas mountains extend from Morocco to Tunisia, the highest part is the High-Atlas of Marrakech encompassing the study area. The High-Atlas of Marrakech is characterized by a heterogeneous bedrock (Fig. 2), involving complex lithological and structural variations (Delcaillau et al., 2011). The upper part of the High-Atlas Mountains is dominated by a massif of Precambrian granodiorite rich silicates such as plagioclase and amphibole (Juery, 1976). The middle part is formed of Triassic and Visean sandstone and siltstone. The lower part of the High-Atlas, overlooking the piedmont area, is characterized by the presence of Triassic conglomerate, red sandstone, silt and clay containing evaporite mineral deposits, topped by infraliassic basalts, and by Eocene limestone and conglomerates of Mio-pleocene (Ouanaimi, 2011). The piedmont is formed of Neogene and Quaternary alluvial deposits that extend northward over the Haouz plain. They represent the main aquifer.

The piedmont area of the High-Atlas in the Tensift basin contains a large unconfined aquifer and two confined aquifers (with very limited spatial extent). The unconfined aquifer in the Haouz plain consists of alluvial fans and fluviatile deposits of Neogene and Quaternary age. The aquifer covers almost 6000 km^2 and it constitutes the principal groundwater resource of the Haouz plain. It is characterized by a heterogeneous transmissivity varying from $5x10^{-5}$ to $9x10^{-2}$ m^2s^{-1} with an average of $6.7x10^{-3}$ m^2s^{-1} (Sinan and Razack, 2006). The unconfined aquifers are encompassed in the Eocene and the Turonian–Cenomanian limestone. Little knowledge is available on the hydrogeological characteristics of these aquifers characterized by high spatial heterogeneity. In the study area, belonging to central Haouz, the Neogene and Quaternary alluvial fan are as thick as 50 m, followed by a thick basement up to 121 m consisting of Miocene clay and marls (Sinan, 2000). The Eocene confined aquifer consists of 100 m of limestone, followed by a 60 m of impermeable marls and red sandstone (Sinan, 1986). The second confined aquifer of Turonian–Cenomanian limestone is 45 m thick lying above a 50 m of Cenomanian clay forming its basement (Sinan, 2000). The present study targeted the alluvial aquifer where groundwater levels can raise to up to 4 m during wet season in the riparian zone and be as deep as 50 m away from the Ourika wadi (Bouimouass et al., 2020). From the dry season to the wet season, groundwater levels substantially increase due to recharge by in-channel streamflow losses and mainly by surface water irrigation (Bouimouass et al., 2020).

2.3. Land and water use

Human settlements in the study area are in form of small villages with population often not exceeding 200 person and are dispersed all over the rural area, except for some towns where population can be of several thousand persons (Fig. 1). These small settlements use septic tanks (up to 5 m) for their domestic wastes which are potentially threating groundwater quality especially where the aquifer is shallow. Since hundreds of years, the area hosts traditional agricultural practices, consisting of a subsidence production system composed mainly of olive trees (Fig. 3A) and wheat. This traditional agriculture has been secularly irrigated by a large network of gravity-fed surface irrigation earth channels (locally named Seguias) that divert the streamflow (Fig. 3B, C, D and E). This hydro-agro-system is similar to the so-called spate irrigated systems, which are particularly found in areas where mountain catchments border lowlands, in the Middle East, North Africa, West Asia, East Africa and parts of Latin America (Van Steenbergen et al., 2011). This type of traditional irrigation is used to expand irrigation from the piedmont to the plain. During the last century, after the French colonization in Morocco, this type of traditional irrigation on the plains has been increasingly replaced by modernized agriculture, as it is the case for most of the plains around the world (Scanlon et al., 2007), with resultant impacts on groundwater quality and quantity (Hu et al., 2019). Nowadays, traditional irrigation is largely restricted to piedmont areas.

The study area offers the possibility of investigating two areas of contrasting land and water use. The western side of the Ourika wadi is characterized by extended cultivable lands irrigated by the streamflow that is diverted via the network of irrigation channels (Fig. 1). In comparison, the eastern side of the Ourika wadi is crossed by few irrigation channels, and crops depend mainly on rain-fed irrigation. In this study, we refer to these two areas as irrigation and non-irrigation areas respectively.

3. Material and methods

3.1. Sampling and analyses

In this study major ion data of precipitation, surface water, springs and groundwater are compared. Precipitation (n=8) were collected in three different elevations spanning the plain, piedmont and high elevations during November 2017 and February 2018. Surface water (n=12) and mountain groundwater (n=12) were collected in two sites in Ourika wadi and two springs with different elevations at a monthly basis from September 2017 to March 2018 (except for October 2017). Groundwater (n=55) collected from 27 wells were sampled during four field campaigns in September 2017, November 2017, December 2017 and March 2018. Sampling locations are presented in Figure 1. The sampling sites were chosen as private irrigation and domestic supply wells spanning different land use (irrigated area, non-irrigated area), with depth ranging from 12 to 50 m pumping water from the phreatic aquifer. Some wells were sampled multiple times depending on access. Samples were collected during or immediately after pumping for irrigation and conserved in 300 ml high-density polyethylene bottles and preserved cold until analysis.

The physical parameters (temperature, pH, and EC) were measured in the field using a portable pH meter sension+ for pH (Hach) and temperature and a portable conductivity meter for EC (Hanna instruments). All samples were analyzed for cations (Ca^{2+}, Na^{+}, Mg^{2+}, K^{+}) after being filtered at 0.45 µm and acidified with HNO_3 and anions (Cl^{-}, SO_4^{2-}, NO_3^{-}) using ion chromatography (Dionex; ICS1100 and autosampler AS-AP) at the laboratory of Hydrogeology of Avignon University. The alkalinity was measured using a HACH digital titrator at the end of the day. Triplicate analyses for each sample were used to assess the analysis uncertainty and the relative standard deviations was around 3%. The quality of water analyses is assessed using the charge balance error (CBE). Water samples having a higher concentration of cations show positive CBE, while negative CBE is credited to higher concentrations of anions (Bozdag et al., 2015). CBE was computed by Equation (1);

$$\%CBE = \frac{[\sum cations - \sum anions]}{[\sum cations + \sum anions]} \times 100 \qquad (1)$$

where ionic concentrations are expressed in milliequivalent per liter. According to the standard protocols, only those water samples were accepted that had less than ±5% CBE (Xiao et al., 2021).

3.2. Water suitability for domestic and irrigation uses

Major ions and physiochemical parameters have long been recognized as important indicators for water quality (Vaiphei and Kurakalva, 2021). Common parameters include electrical conductivity (EC) as a measure of salinity (Thorslund and Vliet, 2020; Banna et al., 2014), pH to monitor acidity levels of drinking water (Vaiphei and Kurakalva, 2021), nitrogen species as an indicator of the impacts of agricultural activities on groundwater (Teng et al., 2019), and other major ions such as sodium and chloride that have be used to detect seawater intrusion, evaporate dissolution, and fertiliser contamination (Bresciani et al., 2018; Rajmohan et al., 2021). Such indicators of water quality are valuable in that they are relatively easy and cheap to measure, and are therefore ideal to monitor water quality across regional and remote hydrogeological basins and/or over long timeframes. In order to analyse the information provided by these physiochemical parameters, water quality indices have been established based on different statistical methods (Simões et al., 2008; Sun et al., 2016). Some of the most widely used water indices used in irrigation areas are the sodium adsorption ratio (SAR), residual sodium carbonates (RSC), sodium percentage (% Na) and Kelly's ratio (KR) (Kelly, 1993; Vincy et al., 2015). These indices have been widely used and proven to be effective in assessing and monitoring groundwater quality (Celestino et al., 2019; Talib et al., 2019; Xu et al., 2019).

The water quality index was also used in this study to analyse potential impacts of irrigation in the groundwater resource quality. This is a widely used tool to assess the suitability of groundwater for drinking supplies (Talib et al., 2019). The WQI relies on the concentrations and the weight coefficient of the chemical elements. The coefficients are based on the impact of each element on the human health (Xiao et al., 2019). The WQI is calculated according to the following equation:

$$WQI = \sum[W_i \times \left(\frac{C_i}{S_i}\right) \times 100] \quad (2)$$

Where C_i is the concentration of each parameter, S_i is the corresponding standard WHO values (WHO, 2017) and W_i is the relative weight of each parameter computed following the equation:

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \quad (3)$$

Where w_i is the weight of each parameter and n is the number of parameters. Table 1 shows the relative S_i and W_i for each parameter used (Talib et al., 2019).

Nitrate (NO_3^-) concentrations were also used in this study as an indicator of groundwater contamination by leaching of (mineral and organic) fertilizers or septic waste, as they are important for health concerns (WHO, 2011).

Similar to drinking water, there are several indices used to assess the suitability of groundwater and surface water for irrigation (Talib et al., 2019; Xu et al., 2019; Xiao et al., 2020). The indices sodium adsorption ratio (SAR), residual sodium carbonates (RSC), sodium percentage (% Na) and Kelly's ratio (KR) were used in this study to consider the sustainability of the current irrigation practices, and were computed using the following equations:

$$SAR = \frac{Na^+}{\sqrt{(Ca^{2+} + Mg^{2+})/2}} \quad (4)$$

$$RSC = (CO_3^- + HCO_3^-) - (Ca^{2+} + Mg^{2+}) \quad (5)$$

$$\%Na = [\frac{(Na^+ + K^+)}{(Na^+ + K^+ + Ca^{2+} + Mg^{2+})} \times 100 \quad (6)$$

$$KR = \frac{Na^+}{Ca^{2+} + Mg^{2+}} \quad (7)$$

where all the ions are expressed in milliequivalent per liter

4. Results

4.1. Hydrochemical properties from the mountain to the piedmont

The electrical conductivity (EC) is very low for mountain streamflow (average = 273 µS/cm), increases slightly for mountain springs (average = 328 µS/cm), and more substantially for piedmont groundwater (average = 807 µS/cm) (Table 2). For groundwater, only 14 of the 55 groundwater samples exceed 1000 µS/cm, and two samples exceed 2000 µS/cm (well W17). The groundwater EC is lower in the irrigation area (mean = 727 µS/cm and max = 1094 µS/cm) than the non-irrigation area (mean = 994 and max = 2620 µS/cm). From the dry (September to November) to the wet (January to March) season the EC decreased in streamflow from 324 µS/cm to 244 µS/cm in average, and in the groundwater beneath the irrigation area from 841 µS/cm to 692 µS/cm (Table 2). The pH is higher in the mountain stream water (an average of 7.94 and a maximum of 9.1) than in piedmont groundwater (an average of 7.58 and a maximum of 8.37).

The major ion compositions are similar in streamflow and springs, but undergoes a concentration increase in the piedmont groundwater (Fig. 4, table 2), which is enriched particularly of Ca^{2+}, Mg^{2+} and HCO_3^-. The irrigation area mostly has lower major ion concentrations compared with groundwater from the non-irrigated area (Fig. 4); the largest differences are observed for Na^+ and Cl^-, whose mean values increase by 46 and 44 % respectively in the non-irrigated area.

On the Piper diagram (Fig. 5), the hydrochemical facies of the streamflow is of Ca-HCO_3 type similar to that of atmospheric precipitation (rain and snow). Compared to precipitation, a slight enrichment of Na^+, Mg^{2+} and SO_4^{-2} is observed. The majority of the groundwater in the piedmont also has a Ca-HCO_3 facies (Fig. 5). It shows in addition two secondary facies, Ca-Mg-Cl and Na-Cl related to specific enrichment in Cl^-, Na^+, and Mg^{2+}. Indeed, 7 wells located close to the Ourika wadi exhibit Ca-Mg-Cl facies. 3 wells in the non-irrigated area, W17, W19 and W27, have Na-Cl facies; they are close to a tributary, Elmaleh wadi (Elmaleh in Arabic means the salty), which drains the low-altitude halite-rich terrains.

Figure 6 shows that most of the major ions (Cl^-, HCO_3^-, Na^+, Ca^{2+}, and K^+) have decreased from the dry to wet season in terms of median, maximum and minimum. This is also reflected in the decrease of EC from the dry to wet season, and these results indicate that a dilution in the wet season has occurred following irrigation using streamflow diversion. In contrast, SO_4^{2-} and Mg^{2+} concentrations increased in terms of the median during the wet season, and NO_3^- showed a significant increase from the dry to the wet season.

4.2. Nitrates

Nitrogen is an important plant nutrient that is naturally present in the environment, but often in very low concentrations (< 10 mg/L; Hill, 1996). The multiple natural origins of nitrates are related to evaporative enrichment of dry and wet deposition, biogenic sources through bacterial activity in soil, or to a geogenic origin (Stadler et al., 2008). In the study area, additional sources of nitrogen might also originate from fertilizers (from animal waste) or animal and domestic sewage.

The results of the nitrate (NO^{-}_{3}) in this study show low concentrations in the streamflow (average = 3.2 mg/l, and a max of 8.2 mg/L) and springs (average = 3.8 mg/l, and a max of 7.2 mg/L), and in piedmont groundwater, the nitrate concentrations are higher (10.1 mg/l in average). Furthermore, nitrates increase slightly from the dry season (average = 8.4 mg/l) to the wet season (average = 12 mg/l). This is explained by an accumulation of NO^{-}_{3} in the soil during the dry period and its leaching from the soil by rainfall and irrigation returns that are more important during the wet period. Despite this increase in NO^{-}_{3} during irrigation recharge, the groundwater NO^{-}_{3} concentrations in the irrigation area remains well below the WHO standards fixed at 50 mg/L (WHO, 2017).

4.3. Quality of drinking and irrigation water

Domestic water needs in the study area are supplied by groundwater. The small towns, that are host to tens to hundreds of inhabitants, use community-managed wells and some inhabitants still use their own wells to meet their domestic needs. Groundwater from these wells is usually used without further treatment, but occasional chlorination, which constitutes a potential health risk if the quality of this water is or becomes unsuitable for human use. Groundwater is also used for irrigation in the study area during extended dry periods. In the irrigated area, groundwater is used during summer and autumn months when streamflow is absent. In the non-irrigated area, rain-fed agriculture is dominant but some farmers use groundwater to irrigate olive fields.

The overall quality of groundwater can be assessed by the water quality index (WQI) (Talib et al., 2019, Sadat-Noori et al. 2014). WQI values are classified into five categories (calculated using the parameters …): excellent (<50), good (>50), poor (>100), very poor (>200) and water unsuitable for drinking (>300). The WQI values ranges from 3 to 95 with a mean of 24. According to this classification, almost all groundwater and surface water are “excellent” for drinking purposes. Only the 03 samples of the non-irrigated area and contaminated by salts are close to the “poor “quality category. Although groundwater is of good quality from a mineral perception, additional biological analyses are needed to fully assess the adequacy of groundwater to human use.

The suitability of groundwater for irrigation is assessed through the Wilcox diagram (Fig. 7) and various irrigation water quality indices, such as SAR, RSC, %Na and KR (Table 3). As a conclusion, most of the water is suitable for irrigation. Those few presenting unsuitable characteristics due the Na^+ content correspond to the samples collected from the well W17, which is characterized by high Na^+ and Cl^- concentrations and located outside of the irrigated area. Compared to the others wells in the study area, the well W17 is influenced by the dissolution of evaporites.

5. Discussion

5.1. Origins of ions in mountains water and groundwater

The natural chemical composition of water is potentially influenced by atmospheric precipitation, evaporation, transpiration, evaporite dissolution and rock weathering. In mountain waters Ca^{2+}, HCO_3^-, Na^+, Mg^{2+}, SO_4^{2-} ions are likely sourced firstly from precipitation and secondly from the weathering of silicate minerals in the crystalline rocks of the High-Atlas massif. The piedmont groundwater samples show similar facies with mountain water, however their relatively higher concentrations of Na^+, Cl^-, and in a lesser proportion of Ca^{2+}, Mg^{2+} and HCO_3^- suggest additional sources of mineralization.

On the Na^+/Cl^- versus Cl^- scatter diagram (Fig. 8), samples with Na/Cl ratios close to 1 with increasing Cl^- concentrations indicate either halite dissolution (Hao et al., 2020; Talib et al., 2019), evaporation or transpiration is the major process increasing Na^+ and Cl^- concentrations. The groundwater samples from the non-irrigated area exhibit little changes in the Na^+/Cl^- ratio with high Cl^- concentrations (> 10 meq/L). A previous study by Bouimouass et al. (2020) using the stable isotope values of groundwater for the same samples, showed no evidence of evaporation effects. Therefore, high Na^+ and Cl^- concentrations in groundwater are driven by either Triassic halite dissolution and/or transpiration processes. For Cl^- concentrations lower than 10 meq/L, there are greater variations in the Na/Cl ratio that indicates either contributions from rock weathering reactions (Na/Cl > 1) or ion exchange effects (Na/Cl < 1). Based on the Na/Cl ratio, the piedmont groundwater is divided into two groups (Fig. 6). The sodium enriched group n° 1 (where Na/Cl > 1), which is similar to the mountain streamflow Na/Cl ratios, is mostly located in the irrigation area. The sodium depleted group n° 2 (where Na/Cl < 1) is predominantly composed of samples located along the Ourika wadi.

For group n° 1 (Na/Cl > 1) representing the irrigation area, the enrichment of Na could be due to weathering by the streamflow in the mountains of the Na-silicate such as albite and plagioclase (equations 8 and 9) (Gao et al., 2020) since Na-silicates are largely present in the High-Atlas as granodiorite and granite.

$$2NaAlSi_3O_8 \text{ (Albite)} + 9H_2O + 2H_2CO_3 = Al_2Si_2O_5(OH)_4 + 2Na^+ + 2HCO_3^- + 4H_4SiO_4 \quad (8)$$

$$(Na_{0.82}Ca_{0.18})Al_{1.18}Si_{2.82}O_8(\text{Plagioclase}) + 1.18CO2 + 1.77H_2O = 0.82Na^+ + 0.18Ca^{2+} + 1.18HCO_3^- + 0.59Al_2Si_2O_5(OH)_4 + 1.64SiO_2 \quad (9)$$

In the HCO_3^- versus Na^+ plot (Fig. 9a), water samples falling along the 1:1 and 1.18:0.82 lines indicate albite and plagioclase weathering might increase HCO_3^- and Na^+ in water (Kim et al., 2002; Zhang et al., 2020). All streamflow and mountain groundwater lie along and above the line 1.18:0.82 indicating contribution from weathering of albite and plagioclase to Na^+ and HCO_3^- in these waters. The majority of the piedmont groundwater samples lie on or between the two lines (Fig. 9a) implying that weathering of albite and plagioclase is responsible for amounts of Na^+ and HCO_3^-. The groundwater samples contaminated by salts plot far to the right of the 1:1 line. The additional sources of HCO_3^- ion could originate from various sources including calcite dissolution (equation 10), and Ca-silicates weathering such as anorthite (equation 11), pyroxene (equation 12) and amphibole (equation 13) (Zhang et al., 2020). Based on chemical reactions 10, 11, 12 and 13, samples falling along the lines 1:1, 2:1, 1.7:1, 7:2 in figure 5b are due to the dissolution of carbonates such as calcite and dolomite, and the weathering of Ca-silicates such as anorthite, pyroxene and amphibole, respectively. All mountains streamflow and springs samples, and most of the piedmont groundwater samples fall between the lines 1:1 and 1.7:1 (Fig. 9b) indicating that the dissolution of calcite and some Ca-silicates such as pyroxene contributes to HCO_3^- concentrations in these waters.

$$CaCO_3 + CO_2 + H_2O = Ca^{2+} + 2HCO_3^- \quad (10)$$

$$2CaAl_2Si_2O_8(\text{Anorthite}) + 4CO_2 + 6H_2O = 2Al_2Si_2O_5(OH)_4 + Ca^{2+} + 4HCO_3^- \quad (11)$$

$$CaMg_{0.7}Fe_{0.3}Si_2O_6(\text{Pyroxene}) + 3.4CO_2 + 2.3H_2O = Ca^{2+} + 0.7Mg^{2+} + 2SiO_2 + 3.4HCO_3^- + 0.3H^+ + 0.3Fe(OH)_3 \quad (12)$$

$$Ca_2Mg_5Si_8O_{22}(OH)_2(\text{Ampibole}) + 14CO_2 + 22H_2O = 2Ca^{2+} + 5Mg^{2+} + 14HCO_3^- + 8H_4SiO_4 \quad (13)$$

For group n° 2 (where $Na/Cl < 1$) representing the piedmont groundwater along the wadi, the ion exchange processes and anthropogenic sources of Cl^- (Celestino et al., 2012) could be responsible of Na depletion or Cl^- enrichment. The plot of $Na^+ + K^+ – Cl^-$ versus $Ca^{2+} + Mg^{2+} – SO_4 - HCO_3^-$ (Fig. 9b) shows a linear relationship with a slope of -0.83, close to -1, indicating the occurrence of ion exchange (Garçia, 2001; Yang et al., 2016). Cation exchange processes were analysed using the chloro-akaline indices (CAI-I and CAI-II), which are widely used as indicators of ion exchange occurring in aquifers (Schoeller, 1965; Li et al., 2013; Talib et al., 2019). The indices, expressed by the equations 14 and 15, are negative when the cation exchange occurs, meaning that Na^+ is released from the medium in exchange with Ca^{2+} and

Mg^{2+} in water. However, positive indices mean that Na^+ is adsorbed in the medium simultaneously with the release of Ca^{2+} and Mg^{2+}, known as reverse ion exchange.

$$\mathrm{CAI-I} = \frac{Cl^- - (Na^+ + K^+)}{Cl^-} \qquad (14)$$

$$\mathrm{CAI-II} = \frac{Cl^- - (Na^+ + K^+)}{HCO_3^- + SO_4^{2-} + CO_3^{2-} + NO_3^-} \qquad (15)$$

Piedmont groundwater samples are almost equally distributed between positive and negative CAI-1 and CAI-2 values (Fig. 9c) (25 samples with positive values, 23 with negative values and 04 with CAI-I and CAI-II equal to 0). This indicates that both base cation exchange (positive CAI-1 and CAI-2 values) and reverse ion exchange (negative CAI-1 and CAI-2) potentially occur. Along the wadi (group 2), the base cation exchange dominates implying depletion of Na^+ in groundwater. Reverse ion exchange characterizes groundwater beneath the irrigation area (Group 1), it induces a release of Na^+ of the aquifer matrix in groundwater and adsorption of Ca^{2+} and Mg^{2+} (Carol et al., 2012; Zaidi et al., 2015).

Ca^{2+} in water could also be due to gypsum dissolution, alongside SO_4^{2-}, as indicated by the equation 17. A Ca^{2+}/SO_4^{2-} ratio around 1 indicates that these ions are derived from gypsum dissolution. The majority of samples (Fig. 9f) are plot to the left of the 1:1 line indicating an excess of Ca^{2+} over SO_4^{2-} ; the Gypsum would be responsible of low amounts of Ca^{2+} and Mg^{2+}.

$$CaSO_4\ (\text{Gypsum}) = Ca^{2+} + SO_4^{2-} \qquad (17)$$

5.2. Hydrochemical evolution from the mountain to the piedmont

In the high-Atlas Mountains, the streamflow and springs are supplied by rainfall and snowmelt, and flow through large outcrops of silicates rocks formed of Precambrian Granodiorite and Gneiss containing plagioclase, amphibole and micaschist, as well as Visean and Triassic siltite and sandstone rocks. They have a Ca-HCO_3 facies similar to that of atmospheric precipitation, and a slight enrichment in Na^+, Mg^{2+} and SO_4^-. In mountains streamflow and springs, Na^+ and HCO_3^- are strongly correlated ($R^2 = 0.84$, table 4), their main source is Na-silicates weathering. The Ca-silicate weathering also contributes to the loading of Ca^{2+} and Mg^{2+}. The pyroxene, amphiboles and calcic feldspar are common minerals in basic rocks and are easily weathered (Jacks 1973; Bartarya 1993; Rajmohan and Elango, 2004). Therefore, these minerals are also likely to contribute to the ionic composition of the waters in the mountains. The elevated SO_4^{2-} might also be due to the dissolution of gypsum.

In the piedmont, groundwater is generally fresh (EC average = 713 µS/cm), with a dominant Ca-HCO_3 facies similar to the streamflow. This similarity results from the recharge of the alluvial aquifer in the piedmont via irrigation of the streamflow waters, and also from in-stream losses (Bouimouass et al., 2020). Therefore, piedmont groundwater primarily inherits the hydrochemical characteristics of the high-altitude mountain water. When evolving in the piedmont and compared to streamflow, groundwater acquires a higher total mineralization and exhibits two secondary facies, Ca-Mg-Cl and Na-Cl.

The generally higher ion content of the groundwater in the piedmont compared to the recharging streamflow could be explained by transpiration processes and water-rock interactions in the alluvial aquifer. In this semi-arid study area, even though the evaporative demand is high (around 1600 mm/year), evaporation effects on piedmont groundwater were not detected from the stable isotope data presented in Bouimouass et al., (2020). This could be explained by the rapid infiltration of irrigation water, the recharge of unevaporated mountain streamflow, and by a deep unsaturated zone (4-50 m depth) that increases during the summer months (Bouimouass et al., 2020).

The secondary Na-Cl facies in piedmont groundwater was observed in the right side of the wadi in the non-irrigation area, and is either due to halite dissolution from Triassic deposits or transpiration. The Ca-Mg-Cl facies was observed near the wadi, along with the Na^+ depletion; this can be ascribed to cation exchange inducing Na^+ adsorption and, Ca^{2+} and Mg^{2+} release in groundwater. Beneath the irrigated area, reverse ion exchange was related to Na^+ enrichment; it seems that the irrigation recharge transfers Ca^{2+} and Mg^{2+} that are adsorbed by clay minerals whilst Na^+ is released in the groundwater. The occurrence of this process might be explained by the dynamics of the seasonal recharge of the diverted streamflow from the Ourika wadi. Traditional irrigation by flooding relatively large lands with streamflow induces more interaction between surface water and sediment matrix during percolation.

5.3. Effects of the traditional irrigation on the groundwater quality

In our piedmont study area, the irrigation area has the prime location of being at the foot of a major mountain range that is lowly populated and cultivated, and where streamflow is supplied by rainfall and snowmelt generally from winter to early summer. The diverted streamflow by a network of irrigation channels managed by community-driven systems is of low EC and NO_3 (273 µS/cm and 3.2 mg/L respectively), and such features constitute favorable factors of groundwater quality since the streamflow is the main groundwater recharge source. The piedmont groundwater beneath the irrigated area is characterized by excellent to good chemical quality regarding both drinking and irrigation use indices. The substantial induced recharge from irrigation flow leads to seasonal groundwater renewal, and counterbalances effects of salinization mechanisms that often characterize irrigated arid zones (Foster et al., 2018). Almost all the ions showed a dilution from the dry to the wet season. The results of this study highlight a system where the irrigation practices have not adversely impacted groundwater resource quality. The irrigation practices have not significantly adversely altered processes controlling the major ion composition, nor are there significant transfers of nitrogen-based fertilizers to the shallow groundwater. Thus, the traditional irrigation practices in this mountain piedmont, which have been in place for hundreds of years, are considered a low impact practice in terms of groundwater resource quality and even an enhancing factor of groundwater quality.

More intensive and modern agricultural and irrigation practices are currently observed in the neighboring plain. Within this plain, the intensive modern agriculture has had severe impacts on groundwater quantity, with hydraulic heads decreasing by 1 to 3 m/year (Fakir et al., 2015, Le Page et al., 2021), the groundwater nitrate concentrations are increasing (Boukhari et al., 2015), and the soil salinity as well (Sefiani et al., 2019). This expansion of irrigated agriculture threats the existence of the traditional agriculture system of the piedmont and disturb its ecosystem. The studied traditional irrigation piedmonts, irrigated by high mountain streamflow, is one of the rare sustainable human exploits that is likely to remain as a low environmental impact practice. Such systems represent a strong connection and a long history between water and users to ensure sustainability and drought survival, and have constituted a main driver of socio-economic activities for centuries. A key success of survival of such ancestral systems is the sense of mutualism between the users. This mutualism, defined by Gunda et al., (2018), is the feeling of collective well-being including social identity, pride of place, and maintenance of historical traditions. For those piedmonts, the current traditional agricultural practices should be maintained and enhanced in order to preserve their groundwater resources sustainability as they provide a nexus between food production, low energy costs (streamflow diversions by gravity-fed channels), and low environmental impacts. This will also benefit groundwater resources in down-gradient areas since piedmonts are generally favorable recharge zones in (semi)arid basins (Wilson and Guan, 2004; Liu and Yamanaka, 2012). The traditional agriculture could be improved by introducing organic agriculture (FAO, 2013) that could increase the financial incomes of farmers, better optimize irrigation water and increase its value.

6. Conclusion

The present study investigated the impact of groundwater recharge from a traditional irrigation system on groundwater quality in a semiarid piedmont. Groundwater hydrochemistry is controlled mainly by water-rock interactions rather than anthropogenic activities. Groundwater chemistry is influenced by both the chemical characteristics of the streamflow acquired in the mountains, and by local hydrochemical processes that occur during infiltration and recharge via the alluvial plain. Groundwater benefits from substantial seasonal recharge from diverted streamflow irrigation, which counterbalances the potential effects of salinization mechanisms common in irrigated areas of (semi)arid zones, such as evaporation and leaching of saline soils. Nitrate concentrations slightly increase with irrigation season but remain well below the permissible limits for drinking water. Almost all groundwater and surface water are "excellent" for drinking and irrigation purposes. The current state of groundwater chemistry in the piedmont of the High-Atlas is a heritage of hundreds of years of exploitation. The hydrological processes, the irrigation practices and the use by local farmers of organic fertilization have preserved the traditional hydro-agro-systems that are close to sustainable agricultural systems. Protection measures of these irrigation systems should be considered in the framework of adaptive strategies for sustainable management and for water heritage, as this system is undergoing severe pressure climate change effects and by the expansion of intensive modern agricultural practices overexploiting the water resources.

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Tables

Table 1: WQI index.

Parameter	S_i (mg/l)	Weight	Relative weight
TDS	1000	5	0.13
Cl^-	250	5	0.13
SO_4^{2-}	250	5	0.13
F^-	1	5	0.13
NO^-_3	50	5	0.13
Na^+	200	4	0.10
Mg^{2+}	150	3	0.08
Ca^{2+}	200	3	0.08
K^+	12	2	0.05
HCO_3^-	250	1	0.03
		$\sum W_i = 38$	$\sum W_i = 1$

Table 2: Statistics of the field parameters and major ions.

Hydrochemical variables (mg/l)	Mountain streamflow ST (n=11)			Mountain springs SP (n=14)			Groundwater irrigation area (n=39)			Groundwater non-irrigation area (n=16)			WHO (2017)
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	
pH	6.64	9.05	7.94	7	9.1	7.72	7.00	8.2	7.5	7.0	8.4	7.8	6.5-8.5
EC	104.0	563.0	273.1	77.0	943.0	328.2	293.0	1945.0	726.7	258.0	2620.0	994	
TDS	79.0	423.0	194.5	54.0	705.0	241.3	216.0	1130.0	491.2	198.0	1615.0	655.3	500
Na^+	3.3	24.7	11.7	2.6	55.4	15.39	18.1	257.7	53.6	10.2	425.5	100.0	200
K^+	0.5	2.1	1.2	0.3	3.6	1.42	0.6	1.4	3.0	0.2	2.9	1.1	200
Mg^{2+}	3.0	9.5	7.2	1.9	21.5	7.5	6.6	16.6	30.5	7.8	46.9	25.4	NA
Ca^{2+}	11.5	69.7	29.5	7.4	38.4	21.49	30.5	129. 9	64.4	27.0	111.4	59.3	200
Cl^-	3.2	32.2	14.8	2.4	79.9	19.53	17.4	462.8	93.4	7.8	719.3	167.4	250
$SO4^{-}_{2}$	6.9	27.1	16.3	5.6	70.4	23.03	11.0	91.5	29.1	2.5	149.8	39.9	200
HCO^{-}_{3}	49	256.0	110.5	27.0	371.0	132	112.2	370.9	222.8	131.8	398.9	247.3	NA
$NO3^-$	0.5	8.1	3.2	1.9	7.1	3.8	1.2	22.5	10.1	2.4	22.1	10.1	50

Table 3: Statistics of the irrigation water quality indices in the study area.

Indices	Groundwater			Surface water			Permissible limit	Unsuitable samples
	Min	Max	Mean	Min	Max	Mean		
SAR	0.2	13.4	1.6	0.2	0.8	0.5	≤ 18	-
RSC	-4.0	1.1	-0.8	-0.5	-0.1	-0.3	≤ 2.5	-
%Na	12	83	30	14.3	27.5	19.6	≤ 60	3
KR	0.1	4.9	0.5	0.1	0.3	0.2	≤ 1	3

Table 4: Linear relationship (R2) between various parameters of groundwater in the study area.

	pH	EC	TDS	Na	K	Mg	Ca	Cl	SO4	HCO3	NO3
pH	1										
EC	-0,32	1									
TDS	-0,34	0,99	1								
Na	-0,25	0,96	0,93	1							
K	-0,2	0,53	0,52	0,46	1						
Mg	-0,18	0,51	0,59	0,34	0,05	1					
Ca	-0,47	0,49	0,54	0,25	0,54	0,41	1				
Cl	-0,29	0,97	0,94	0,98	0,52	0,35	0,39	1			
SO4	0,05	0,7	0,7	0,63	0,57	0,5	0,38	0,64	1		
HCO3	-0,38	0,39	0,5	0,21	0,12	0,77	0,57	0,19	0,19	1	
NO3	0,26	-0,11	-0,05	-0,2	-0,26	0,47	-0,02	-0,22	0,02	0,28	1

Figure 1: Map of the study area and sampling points. (a) Morocco, (b) Tensift basin, and (c) sampling points in the Ourika watershed, the wadi gauging station and some principal irrigations channels (Seguias).

Figure 2: Pictures from the study area. A: a panoramic view of the agricultural crops over the piedmont, B: a Seguia diverting water directly from the Ourika stream, C, D and E: different types of Seguias in the piedmont.

Figure 3: Geology and cross section of Ourika watershed.

Figure 4: Boxplots of the major ions in groundwater (GW), spring (SP) and surface water (SW).

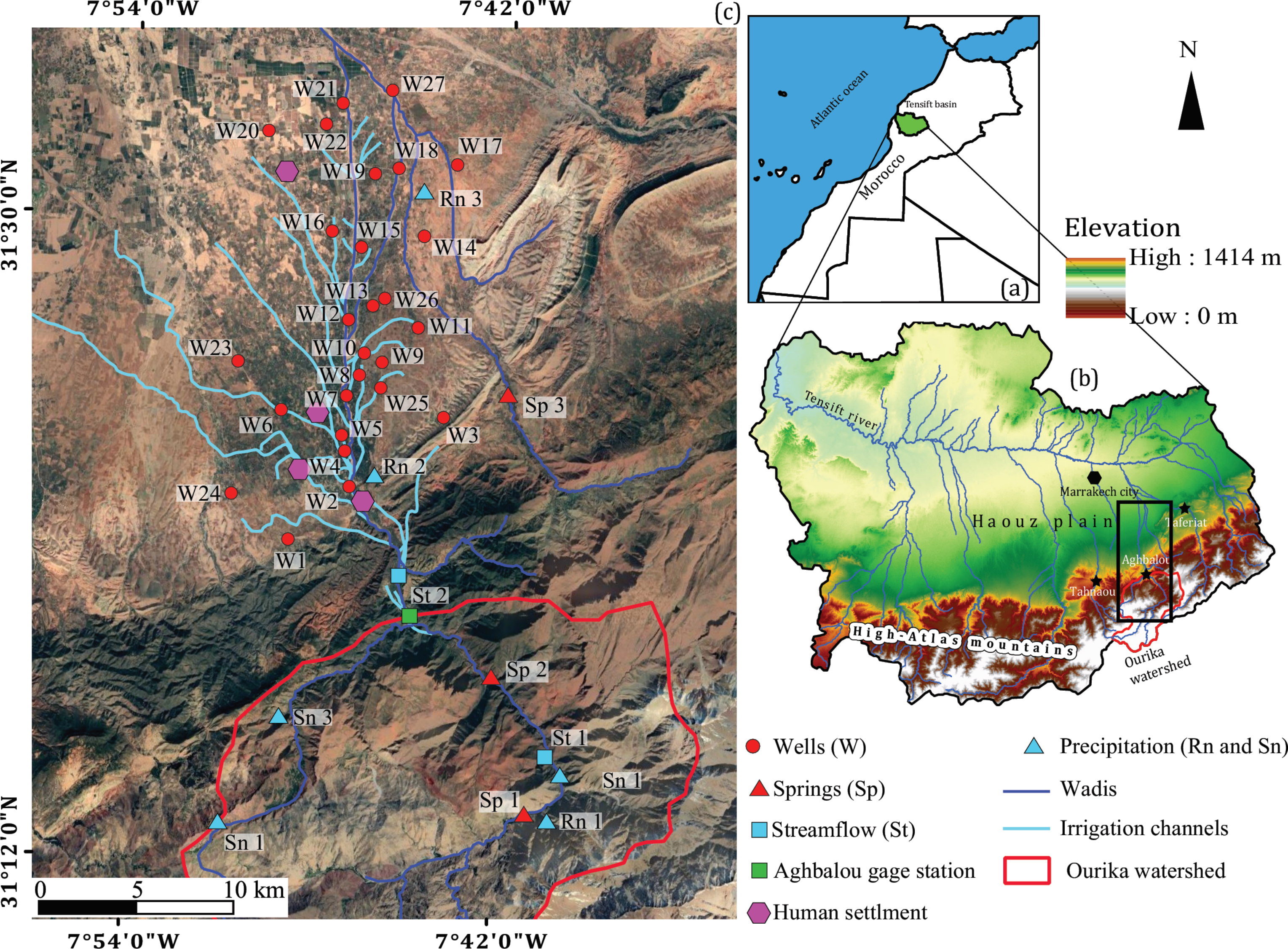
Figure 5: Piper diagram. Pink color refers to dry season and blue color refers to wet season.

Figure 6: Seasonal variation in EC and major ions concentrations.

Figure 7: Wilcox diagram. Red color refers to dry season and blue color refers to wet season.

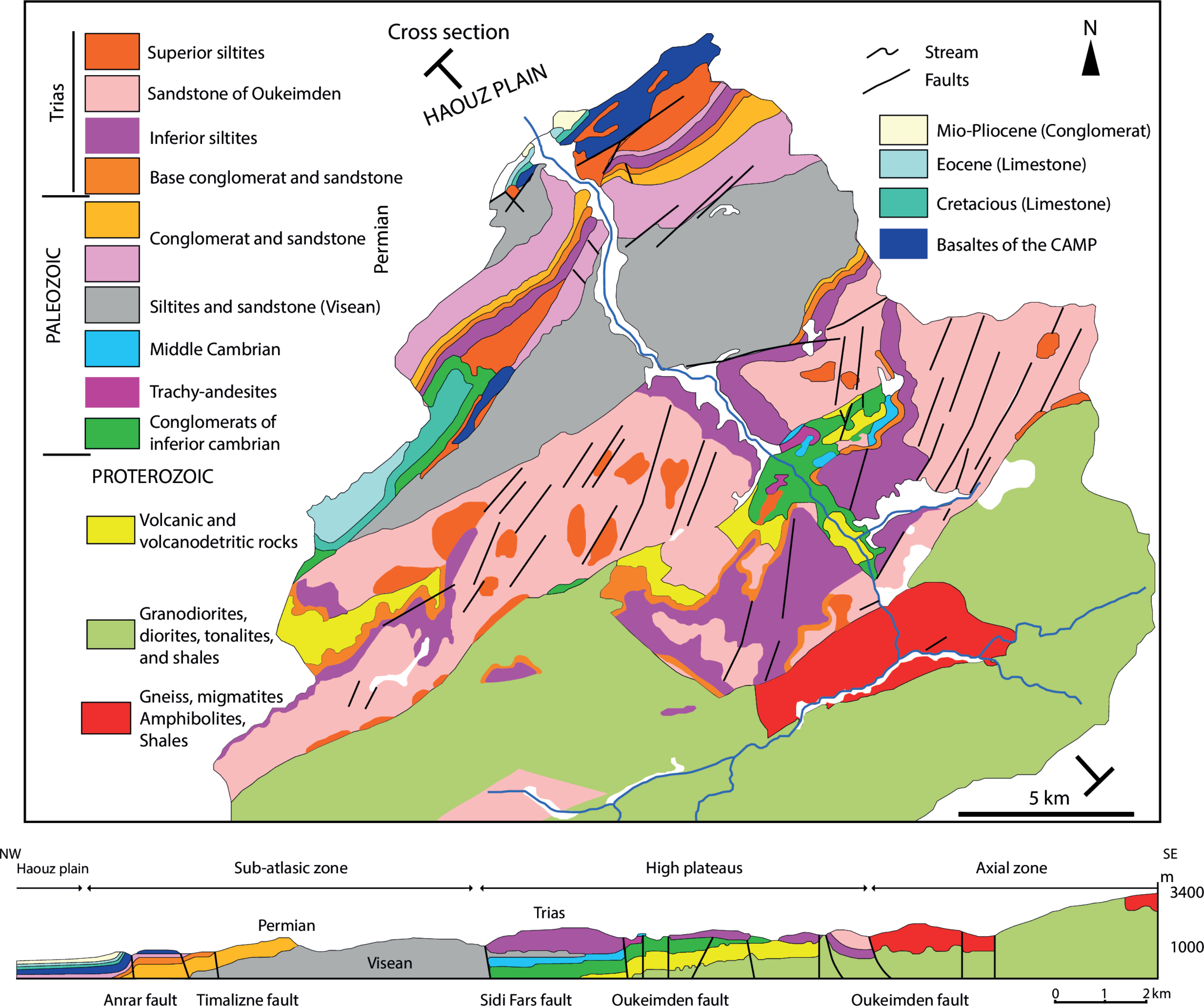
Figure 8: Plot of Na/Cl ratio versus Cl. Red color refers to dry season and blue color refers to wet season.

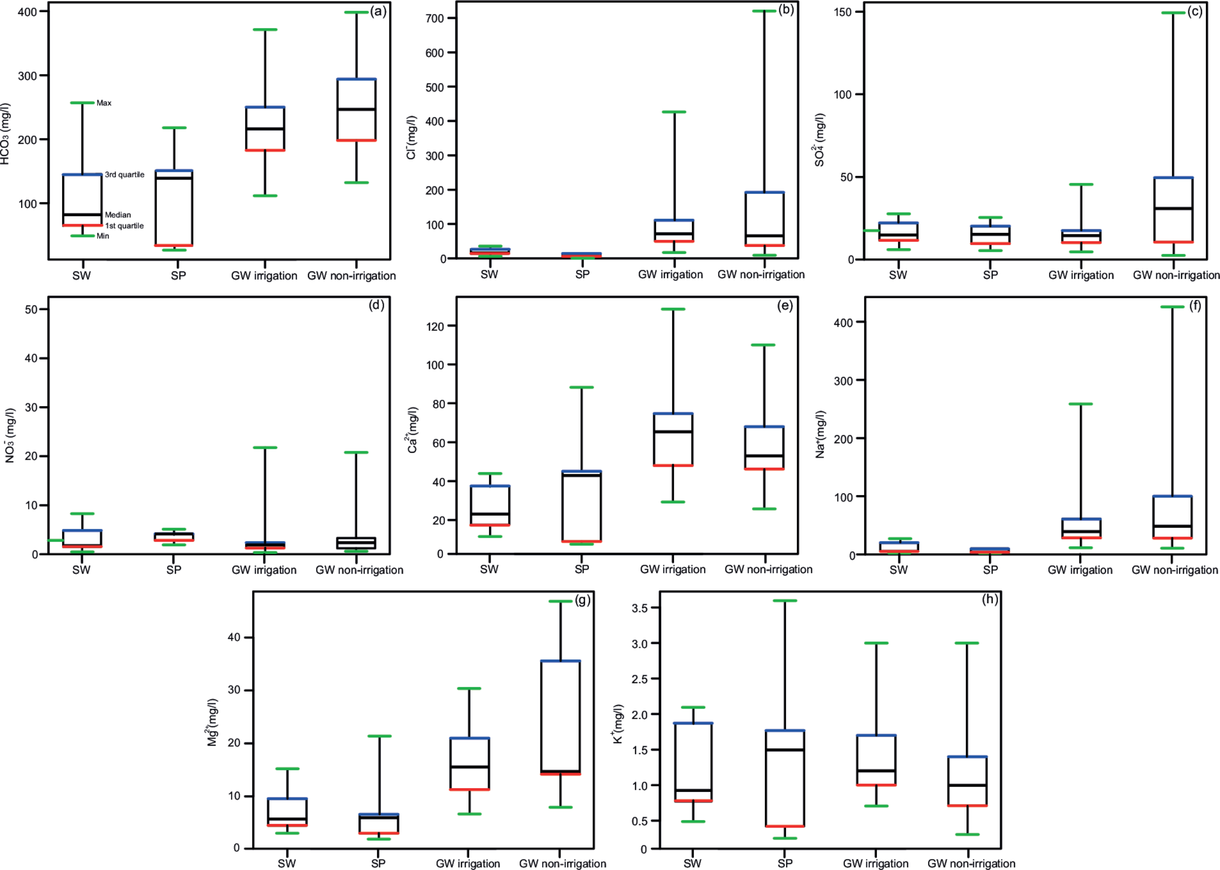
Figure 9: Scatter plots of ions. Red color refers to dry season and blue color refers to wet season.



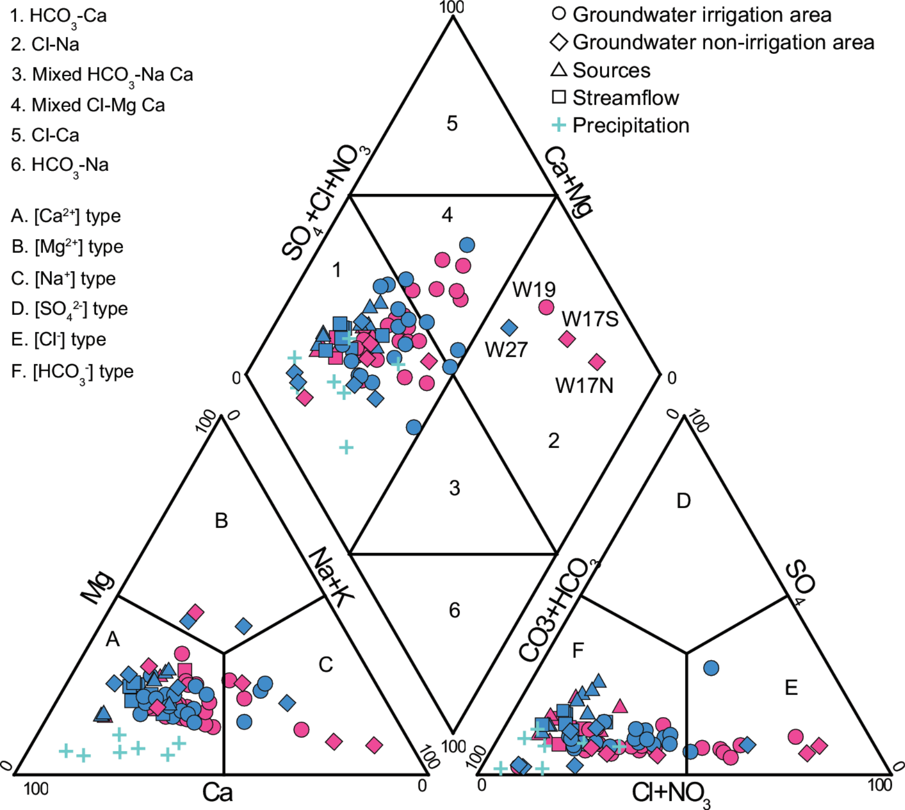
7°54'0"W
7°42'0"W
31°30'0"N
31°12'0"N
W21
W27
W20
W22
W18
W17
W19
Rn 3
W16
W15
W14
W13
W26
W12
W11
W23
W10
W9
W8
W7
W25
Sp 3
W6
W5
W3
W4
Rn 2
W24
W2
W1
St 2
Sp 2
Sn 3
St 1
Sn 1
Sp 1
Rn 1
Sn 1
0 5 10 km
(c)
Atlantic ocean
Tensift basin
Morocco
(a)
N
Elevation
High : 1414 m
Low : 0 m
(b)
Tensift river
Marrakech city
Haouz plain
Taferiat
Aghbalou
Tahnaou
High-Atlas mountains
Ourika watershed
Wells (W)
Precipitation (Rn and Sn)
Springs (Sp)
Wadis
Streamflow (St)
Irrigation channels
Aghbalou gage station
Ourika watershed
Human settlment


A
B
Stream
1st order Seguia
C
2nd order Seguia
1st order Seguia
D
3rd order Seguia

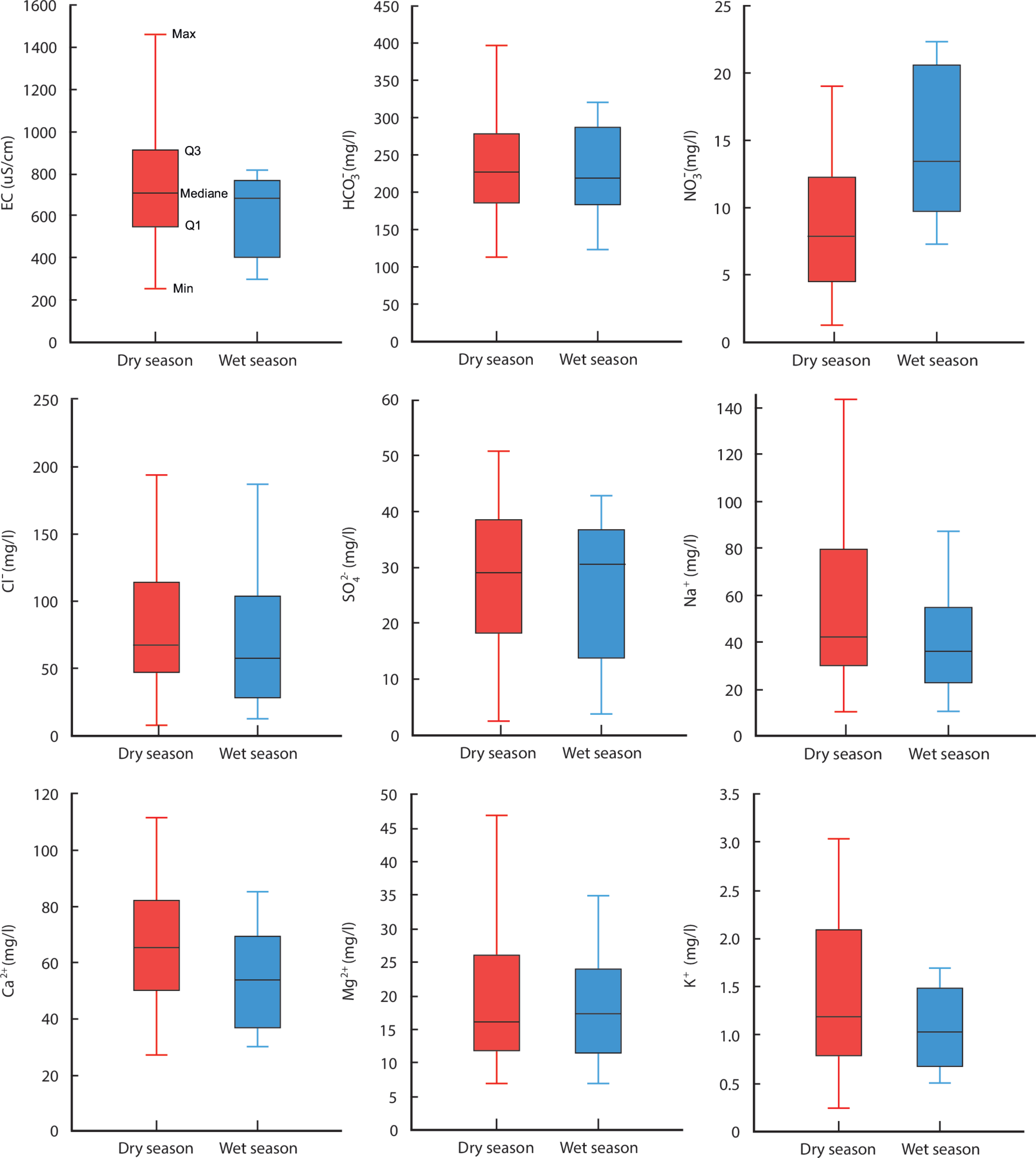

Cross section
HAOUZ PLAIN
N
Stream
Faults
Trias
Superior siltites
Sandstone of Oukeimden
Inferior siltites
Base conglomerat and sandstone
Conglomerat and sandstone
Permian
PALEOZOIC
Siltites and sandstone (Visean)
Middle Cambrian
Trachy-andesites
Conglomerats of inferior cambrian
PROTEROZOIC
Volcanic and volcanodetritic rocks
Granodiorites, diorites, tonalites, and shales
Gneiss, migmatites Amphibolites, Shales
Mio-Pliocene (Conglomerat)
Eocene (Limestone)
Cretacious (Limestone)
Basaltes of the CAMP
5 km
NW
Haouz plain
Sub-atlasic zone
High plateaus
Axial zone
SE
m
3400
1000
Permian
Trias
Visean
Anrar fault
Timalizne fault
Sidi Fars fault
Oukeimden fault
Oukeimden fault
0
1
2 km



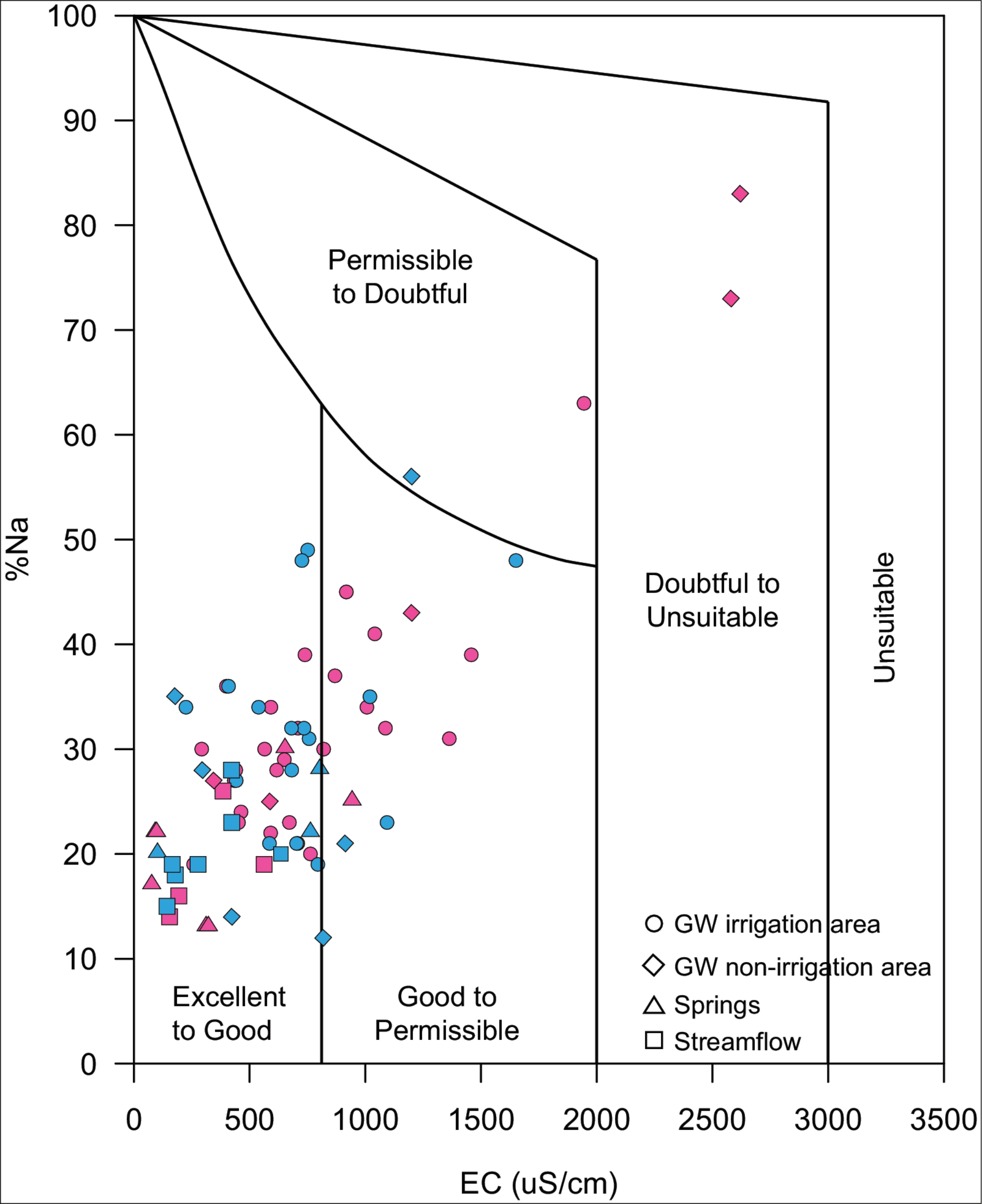
(a)
HCO_3 (mg/l)
Max
3rd quartile
Median
1st quartile
Min
SW
SP
GW irrigation
GW non-irrigation
(b)
Cl^-(mg/l)
(c)
SO_4^{2-} (mg/l)
(d)
NO_3^- (mg/l)
(e)
Ca^{2+}(mg/l)
(f)
Na^+(mg/l)
(g)
Mg^{2+}(mg/l)
(h)
K^+(mg/l)



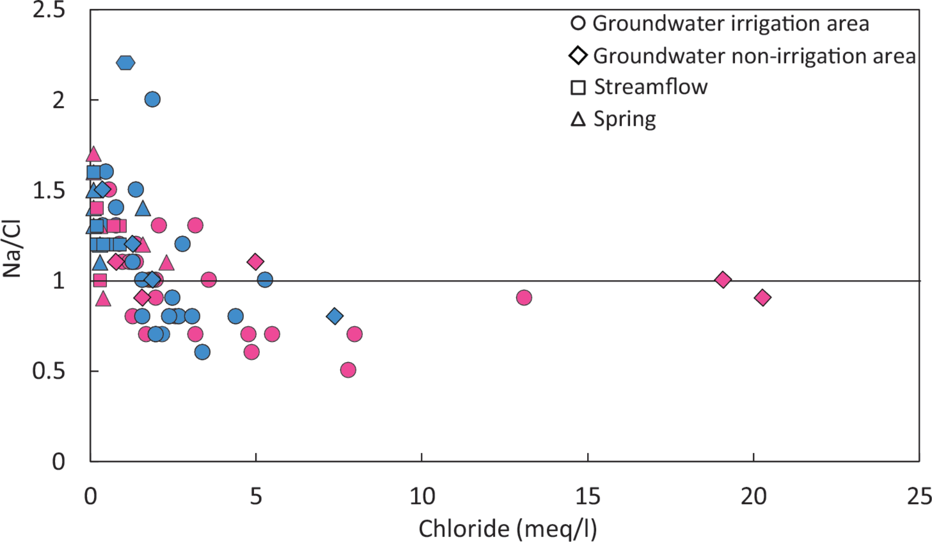
1. HCO3-Ca
2. Cl-Na
3. Mixed HCO3-Na Ca
4. Mixed Cl-Mg Ca
5. Cl-Ca
6. HCO3-Na
A. [Ca2+] type
B. [Mg2+] type
C. [Na+] type
D. [SO42-] type
E. [Cl-] type
F. [HCO3-] type
Groundwater irrigation area
Groundwater non-irrigation area
Sources
Streamflow
Precipitation
SO4+Cl+NO3
Ca+Mg
W19
W17S
W27
W17N
Mg
Na+K
Ca
CO3+HCO3
SO4
Cl+NO3
A
B
C
D
E
F
1
2
3
4
5
6
100
0



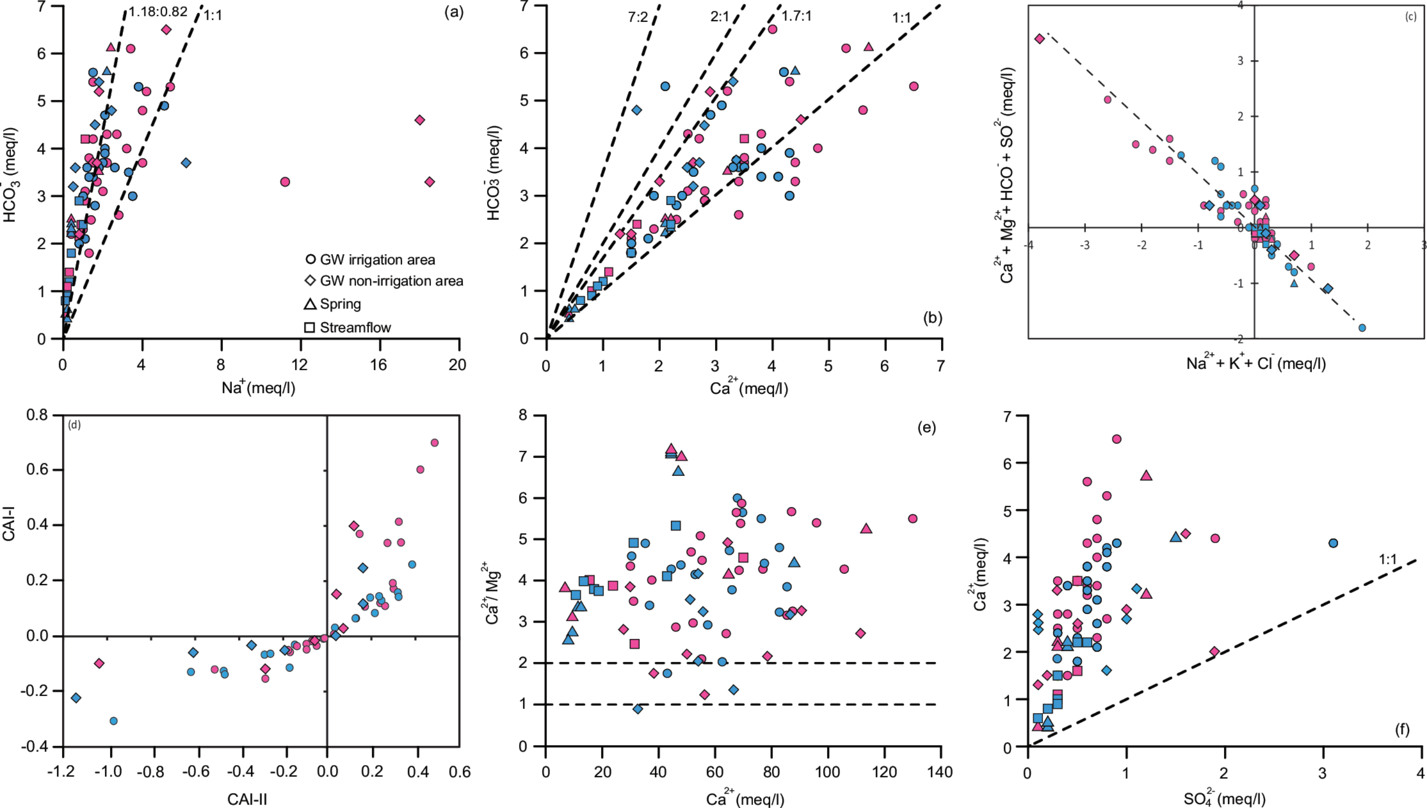
EC (uS/cm)
Max
Q3
Mediane
Q1
Min
0
200
400
600
800
1000
1200
1400
1600
Dry season
Wet season
HCO_3^- (mg/l)
0
50
100
150
200
250
300
350
400
450
NO_3^- (mg/l)
0
5
10
15
20
25
Cl^- (mg/l)
0
50
100
150
200
250
SO_4^{2-} (mg/l)
0
10
20
30
40
50
60
Na^+ (mg/l)
0
20
40
60
80
100
120
140
Ca^{2+} (mg/l)
0
20
40
60
80
100
120
Mg^{2+} (mg/l)
0
5
10
15
20
25
30
35
40
45
50
K^+ (mg/l)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5



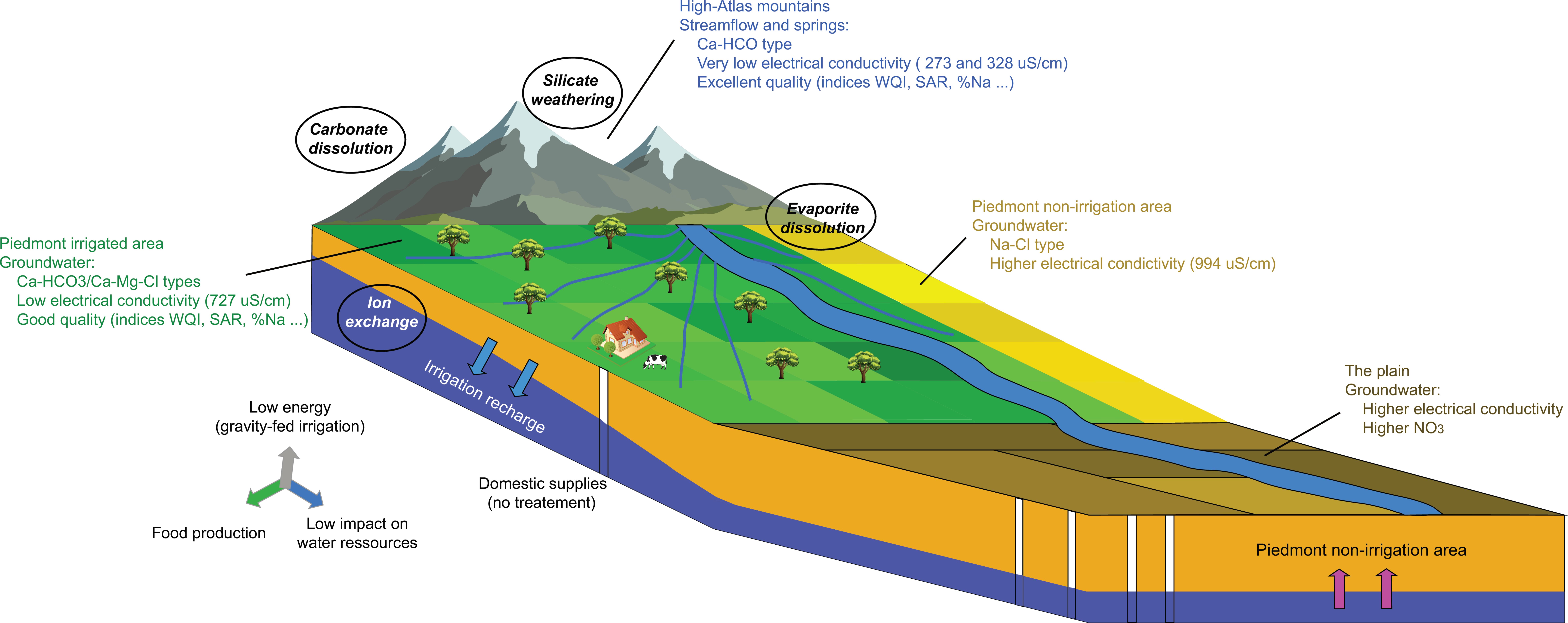
100
90
80
70
60
50
40
30
20
10
0
%Na
0
500
1000
1500
2000
2500
3000
3500
EC (uS/cm)
Permissible to Doubtful
Doubtful to Unsuitable
Unsuitable
Excellent to Good
Good to Permissible
GW irrigation area
GW non-irrigation area
Springs
Streamflow



Groundwater irrigation area
Groundwater non-irrigation area
Streamflow
Spring
Na/Cl
Chloride (meq/l)
2.5
2
1.5
1
0.5
0
0
5
10
15
20
25



(a)
1.18:0.82
1:1
HCO_3^- (meq/l)
Na^+(meq/l)
GW irrigation area
GW non-irrigation area
Spring
Streamflow
(b)
7:2
2:1
1.7:1
1:1
HCO_3^- (meq/l)
Ca^{2+}(meq/l)
(c)
$Ca^{2+} + Mg^{2+} + HCO^- + SO^{2-}$ (meq/l)
$Na^{2+} + K^+ + Cl^-$ (meq/l)
(d)
CAI-I
CAI-II
(e)
Ca^{2+}/Mg^{2+}
Ca^{2+}(meq/l)
(f)
1:1
Ca^{2+}(meq/l)
SO_4^{2-}(meq/l)


High-Atlas mountains
Streamflow and springs:
Ca-HCO type
Very low electrical conductivity (273 and 328 uS/cm)
Excellent quality (indices WQI, SAR, %Na ...)
Silicate weathering
Carbonate dissolution
Evaporite dissolution
Piedmont non-irrigation area
Groundwater:
Na-Cl type
Higher electrical condictivity (994 uS/cm)
Piedmont irrigated area
Groundwater:
Ca-HCO3/Ca-Mg-Cl types
Low electrical conductivity (727 uS/cm)
Good quality (indices WQI, SAR, %Na ...)
Ion exchange
Irrigation recharge
The plain
Groundwater:
Higher electrical conductivity
Higher NO3
Low energy
(gravity-fed irrigation)
Domestic supplies
(no treatement)
Food production
Low impact on water ressources
Piedmont non-irrigation area