

Chapter 9

Effect of Climate Change on Sea Water Intrusion in the Essaouira Basin Coastal Aquifer



Mohammed Bahir, Otman El Mountassir, and Mohamed Behnassi

Abstract Groundwater serves as a vital source of potable water for domestic and drinking purposes in various regions globally. However, rising sea levels have led to the encroachment of saltwater into coastal underground aquifers, resulting in a degradation of water quality over time. In the context of the hydrogeochemical examination conducted, it was observed that the groundwater within the Plio-quaternary aquifer exhibits a composition characterized by Cl–Ca–Mg and Cl–Na elements. Specific ionic ratios, such as Br/Cl (approximately 1.5–1.7‰) and Na/Cl (approximately 0.86), in addition to relatively weak values for Mg/Ca and SO₄/Cl ratios, signify the initiation of seawater intrusion into the freshwater reserves of the Plio-quaternary aquifer within the Essaouira basin. This incursion of seawater is substantiated by ionic ratios and is further validated through stable isotopic analysis. By leveraging the combined information from oxygen-18 contents and chloride concentrations, the degree of mixing between seawater and freshwater in the Plio-quaternary aquifer is estimated to range from 12.8 to 15.9%. Furthermore, the stable isotopes approach has shed light on the source of recharge for the Plio-Quaternary and Turonian aquifers, indicating that these aquifers are primarily recharged by Atlantic-origin precipitation with limited evaporation effects. However, it is evident that these freshwater resources have undergone contamination due to the intrusion of seawater.

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167

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1 Introduction

Coastal regions are densely populated, with nearly 70% of the global population residing in these areas (Bear et al. 1999). However, the unsustainable extraction of groundwater, coupled with the proximity to seawater and the effects of climate change, has led to both qualitative and quantitative deterioration of groundwater resources (Bahir et al. 2016, 2018a, c, 2019; Carreira et al. 2014, 2018; El Mountassir et al. 2021a, b, c, d, e; Farid et al. 2013; Hamed et al. 2018; Ouhamdouch et al. 2018, 2019, 2020a, b). The phenomenon of marine intrusion is particularly prevalent in coastal aquifers globally, significantly affecting groundwater resources (Custodio 1997). It is characterized by the migration of saltwater into freshwater aquifers, which can be either temporary or permanent, typically resulting from a drop in the aquifer's piezometric level or a rise in sea level.

Marine intrusion can be attributed to two primary factors: natural and anthropogenic. The natural factor is closely linked to the historical rise in sea levels during the Holocene period (Edmunds and Milne 2001; Vella et al. 2005). Coastal aquifers formed prior to the rise in sea level, which occurred during the Quaternary glaciation period, experienced the influx of marine waters (Abou Zakhem and Hafez 2007). Subsequently, as sea levels stabilized, aquifers with substantial hydraulic gradients managed to repel saltwater intrusion, while those with weaker hydraulic gradients were susceptible to seawater intrusion (Edmunds and Milne 2001; Custodio 2002; Post 2004).

The anthropogenic factor, on the other hand, results from extensive groundwater extraction (Behnassi et al. 2014, 2017). Over-exploitation arises when the rate of groundwater withdrawal exceeds the rate of recharge, leading to a decline in the piezometric level and a subsequent reduction in the hydraulic gradient. According to Custodio (2002), the extent of marine intrusion is contingent upon various hydrogeological factors related to the aquifer, including geometry, permeability, and hydraulic gradient. Importantly, the significance of marine intrusion varies from one location to another (ESCWA et al. 2017). A comprehensive understanding of the aquifer's hydrogeological properties enhances our grasp of aquifer dynamics, facilitating sustainable and informed management practices that aim to minimize or prevent saline intrusion.

In North Africa, the issue of saltwater intrusion in coastal aquifers has been the subject of extensive research, with penetration inland reaching distances of up to 60 km (Sherif 1999). These studies have primarily employed various analytical approaches, including piezometric assessment, examination of hydraulic, geometric, and transport parameters of the aquifers, numerical modeling, and the consideration of climate variability (Sadeg and Karahanoglu 2001). For instance, an investigation by Paniconi et al. (2001) highlighted the onset of saltwater intrusion in the Korba coastal aquifer in Tunisia since 1970, examining the interplay between pumping

practices and recharge scenarios. Similarly, studies in Libya, as conducted by El Hassadi (2008) using a hydrogeochemical approach and a two-stage finite element simulation algorithm, revealed a gradual increase in intrusion from 1960 to 2005, with intrusion extending up to 10 km from the coast in the Gefara plain near Tripoli. On the Algerian coast, research by Morsli et al. (2007) and Belkhir et al. (2012) employed multivariable statistical and geochemical modeling techniques to identify marine intrusion in the region.

Moroccan coastal aquifers have also been affected by saltwater intrusion. The Saïdia sandy aquifer in the northeastern part of the country, for instance, demonstrated intrusion, as evidenced by electrical and logging soundings (El Halimi et al. 1999). In the Temara-Rabat area, which encompasses an aquifer system containing marine deposits, saltwater intrusion was confirmed (Pulido-Bosch 1999). In the southern regions of Morocco, such as the Sahel of Doukkala Abda, groundwater quality deteriorated due to marine intrusion (Fadili et al. 2012; Kaid Rassou et al. 2005).

This study focuses on the shallow Plio-Quaternary aquifer in the Essaouira basin along the Moroccan Atlantic coast to further explore the phenomenon of marine intrusion. The research employs hydrogeochemical and isotopic methodologies to achieve its objectives.

Geographically, the aquifer in question is situated on the Moroccan Atlantic coast, spanning from latitude 31° 24' to 31° 49'N and longitude 9° 52' to 9° 85'W. Its eastern boundary is marked by Triassic outcrops (Tidzi diapir), while its western limit is defined by the Atlantic Ocean (Fig. 1). The study region is characterized by a semi-arid climate, featuring an average annual rainfall of 300 mm and an average annual temperature of 20 °C (Bahir et al. 2020a, b; El Mountassir et al. 2022b). Ouhamdouch et al. (2020a) reported a decline in annual precipitation within the study area by 12–16%, along with a notable temperature increase ranging from 1.2 to 2.3 °C. This reduction in precipitation and temperature rise has led to declining piezometric levels and a deterioration of groundwater quality in the study area.

Geologically, the shallow aquifer primarily comprises sandstones, conglomerates, and is interspersed with sandy marl, limestone, and dolomite (Fig. 1). The aquifer, with a thickness ranging from 5 to 60 m, is underlain by impermeable gypsiferous and siliceous marls of the Senonian period (200 m) (Bahir et al. 2000). According to Mennani (2001), the shallow aquifer exhibits variable permeability, ranging from 0.27 to 132 m/d, and transmissivity values between 4.5×10^{-5} and 6.02×10^{-2} m²/s (Mennani et al. 2001), with the highest values occurring near the Ksob wadi, a prominent recharge area. The piezometric map illustrates a flow direction from the southeast to the northwest, characterized by a hydraulic gradient ranging from 1.2% in the downstream segment to 2.5% in the upstream region. The direction of groundwater flow is largely influenced by the subsurface aquifer geometry.

Groundwater in North Africa

Groundwater serves as the primary source of water supply for various purposes, particularly in arid and semi-arid regions of numerous countries (Bahir et al. 2021c,

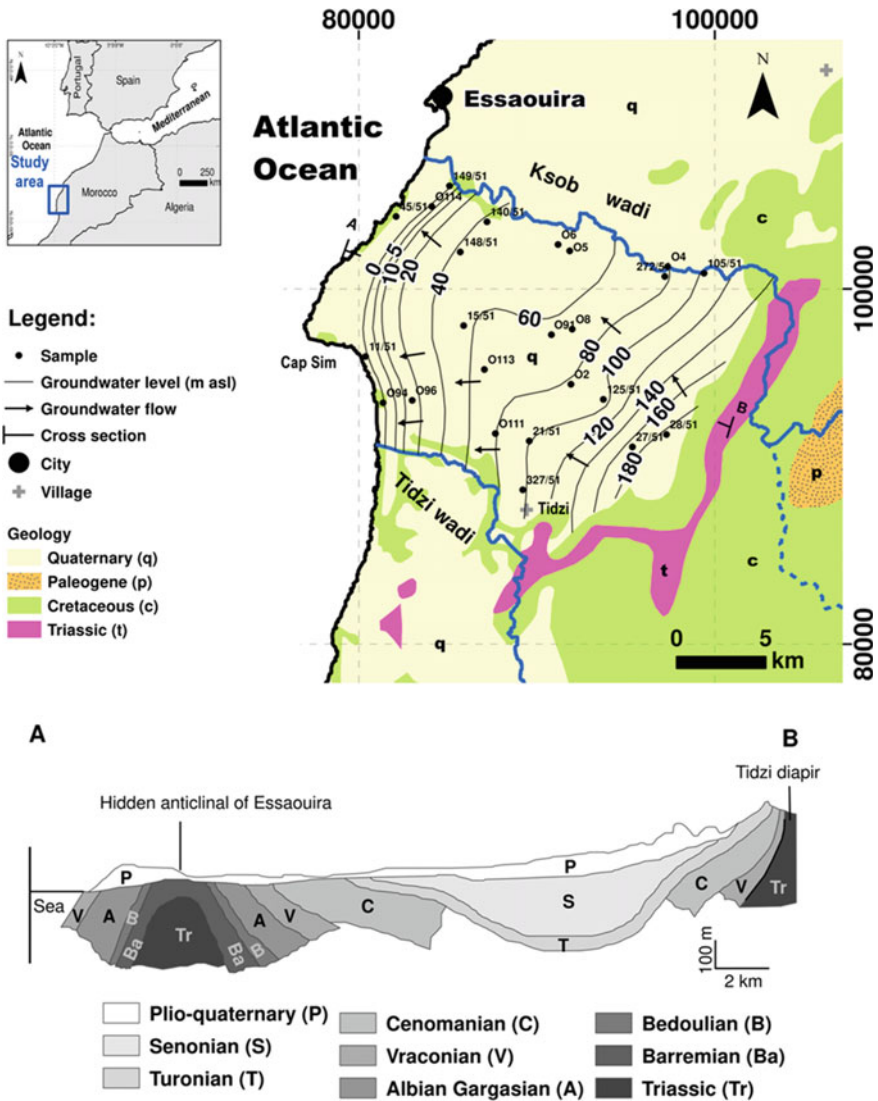


Fig. 1 Location and geological map of study area. Source Developed by the author

2022a; El Mountassir et al. 2022a). On a global scale, approximately 65% of groundwater is utilized for drinking, 20% for irrigation and livestock, and 15% for industrial and mining applications. Groundwater offers several advantages over surface water, including wide distribution, inherent stability, natural regulation, good water quality, and resistance to contamination. However, its utilization is not without challenges, as it is often buried underground and necessitates a comprehensive understanding of its distribution patterns before effective usage.

In recent decades, as urbanization and living standards have improved, the demand for groundwater resources has escalated, subjecting these resources to unprecedented pressures. A recent study published in *Science* by researchers from the University of California, Santa Barbara indicates that groundwater sustaining 2.5 billion people worldwide is at risk of depletion. Debra Perrone, co-author of the study, highlights that up to 20% of the world's wells are located within a depth of merely five meters below the water table. This precarious situation implies that millions of these wells may run dry due to factors such as global warming or excessive extraction (Podgorski and Berg 2020).

In the African context, the continent features around eighty transboundary river and lake basins, as well as approximately forty transboundary aquifer basins. The Africa Water Vision 2025 underscores that groundwater represents the primary, and often the sole, source of potable water for over 75% of the African population. Furthermore, groundwater accounts for more than 95% of Africa's freshwater resources, and the pollution and salinization of this resource are often irreversible on a human timescale.

In arid and desert regions of North Africa, groundwater from depths exceeding 500 m constitutes the sole water source for fulfilling local needs, encompassing agriculture, industry, tourism, and domestic consumption. Similar to many countries worldwide, the populations in southern Mediterranean nations grapple with water stress conditions, defined as those consuming more than 20% of their renewable water resources. Water withdrawal exceeding 40–50% signifies severe water stress. Presently, the United Nations projects that by 2025, 25 African countries will face water scarcity or water stress. According to UNEP (2006, 2010, 2011), an estimated 1.1 billion individuals lack access to clean drinking water, whether from surface or groundwater sources. Contaminated water directly contributes to five million deaths annually, with the majority occurring in sub-desertic Africa.

Water-related challenges, particularly the salinization of groundwater, have become a focal point for both scientific researchers and policymakers on a national level. These concerns have been addressed in numerous studies across Morocco. The country, akin to many Mediterranean nations, has faced recurrent periods of drought since the early 1980s. Its water resources are limited, estimated at 20 billion cubic meters, translating to an average of 700 m³ per year per inhabitant. This situation indicates a notable level of water stress. The number of years experiencing a rainfall deficit has surpassed those with adequate rainfall, with a prevailing downward trend of 23%.

One of Morocco's pivotal aquifers, notable for its extent and geographical location, is the Plio-quadernary aquifer in the Essaouira basin, situated in the western part of the country. To evaluate the evolution of water quality, particularly concerning groundwater, in regions characterized by semi-arid climates and influenced by climate change, the Essaouira basin is employed as an illustrative case. In recent decades, this basin has encountered a sequence of drought periods, leading to the degradation of groundwater quality. The Essaouira basin holds strategic importance within Morocco, accounting for 10% of the total national aquifer reserves, encompassing eight aquifers out of a total of 80. Hence, comprehending the primary processes

governing groundwater mineralization (Bahir et al. 2018b, 2021a, b) is essential for enhancing water resource management in these regions.

Coastal aquifers, particularly shallow ones, often confront vulnerabilities linked to seawater intrusion. This intrusion not only contributes to water resource deterioration but also contributes to the elevated salinity levels resulting from the dissolution of minerals due to evaporation (e.g., halite, gypsum, anhydrite), agricultural and industrial activities, as well as climate change. The present study focuses on the geochemical examination of the Essaouira basin, which is situated along the Atlantic coast of Morocco. The inhabitants of this basin primarily rely on groundwater as their principal water source for both domestic use and irrigation. The outcomes of this research are anticipated to substantially enhance management strategies aimed at safeguarding the scarce groundwater resources in the region. Furthermore, they contribute to a deeper understanding of the status of coastal aquifers within the Atlantic basin.

In recent decades, Morocco has confronted prolonged and unusual drought periods, leading to widespread reductions in free piezometric levels, the depletion of numerous water sources, and diminished wadi flows. The resource mobilization has now approached its limits, and optimal dam locations have already been exhausted. In this context, resource mobilization is becoming increasingly challenging, given the ever-growing demand. This marks the conclusion of the system known as “OFFERTA (OFFER),” as described by our Spanish counterparts.

One of the latest recommendations from the Higher Council for Water and Climate underscores that groundwater, primarily reserved for drinking water supply, will become progressively harder to attain in the future. This difficulty stems from deteriorating water quality due to water stress and the discharge of wastewater into the vicinity of major urban and rural settlements (Niemczynowicz 1999).

The potential of groundwater resources is estimated at 4×10^9 m³, distributed across approximately 80 shallow and deep aquifers within the country's nine basins. These resources are subject to regular monitoring by the Hydraulics Directorate and the National Water Office. Cadi Ayyad University of Marrakesh, Morocco, collaborates with public authorities to study several basins, including that of Essaouira.

Groundwater is an integral component of the hydrological cycle and the subsurface environment. It exhibits interconnections with surface water and continuously interacts in both space and time through processes such as infiltration and drainage. Groundwater is replenished by a portion of infiltrated rainwater, subject to various atmospheric effects, including direct or indirect evaporation.

Moreover, it is intricately linked to the subsurface, where it serves as a vital and active constituent. Groundwater cannot be regarded as a distinct, isolated resource, nor can it be compared to other natural soil resources. Instead, it represents reservoirs of water and dynamic flows, akin to surface water. The renewal of groundwater is influenced by rainwater infiltration, a process that sustains its flow rates.

The spatial distribution of groundwater is notably more continuous than that of surface water, and it is heavily influenced by the geological formations that structure its dynamics. As a result, groundwater exhibits a slow flow rate, characterized by

substantial inertia. While surface water can flow at rates of approximately m^3/s , groundwater flow rates vary significantly, ranging from a few meters per day in porous media to around ten kilometers per day in fractured environments. Renewal periods can vary widely, from several months for water tables with limited reserves and high flow rates to several millennia for deep, quasi-fossil aquifers.

Compared to surface water reservoirs, which can fill and empty in a matter of days or a few months, underground reserves operate on a longer timescale, often spanning years, with additional seasonal fluctuations. Considering these factors, managing aquifer recharge becomes essential for long-term resource management.

The concept of groundwater resources is a multifaceted and relative one, influenced by factors such as spatial scale, reference period, and evaluation criteria. It encompasses a variety of dimensions, including flow, stock, renewal patterns, water quality, accessibility, cost factors, and internal and external constraints within the system (Castany 1982).

From a physical perspective, a distinguishing characteristic of groundwater is the simultaneous presence of both flow and stock, which significantly affects the allocation between renewable and non-renewable resources. The assessments of these two components are contingent on both natural conditions and the socio-economic goals of water usage.

At the socio-economic level, users primarily focus on the development of catchment structures that incorporate local water resources. Unfortunately, these efforts often prioritize water extraction and conservation over resource protection.

On a macroeconomic scale, water resource managers operate at the regional resource level. They possess the technical means for investigation, evaluation, and resource management but lack direct control over groundwater (Bennouna and El Hebil, 2016).

This disparity in how the resource is perceived, depending on the level of analysis, leads to a distinction between:

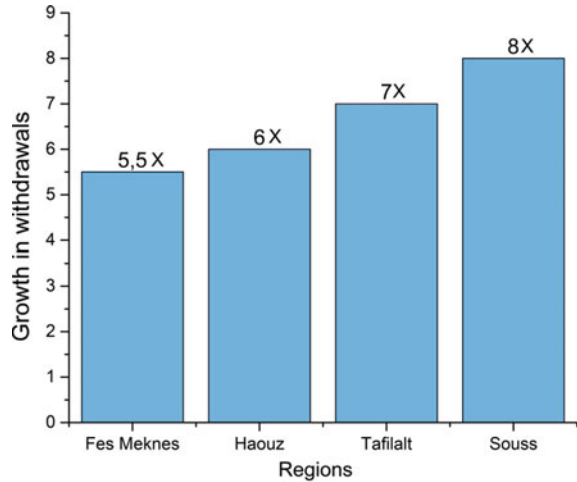
The local resource, which pertains to an individual catchment or group of catchments and serves as a vital element for sustaining water production, albeit with an assessed risk of depletion.

The regional potential of an aquifer system, which is viewed as a resource from an economic standpoint.

In Morocco, groundwater constitutes a significant portion of the country's hydraulic assets, primarily due to its geological composition. The geological features include sedimentary basins with groundwater and confined aquifers (e.g., Souss, Tadla, Haouz, Saiss), karstic limestone massifs featuring substantial springs (such as those in the Middle Atlas), and alluvial valleys closely linked to surface watercourses (e.g., Ziz Valley, Draa Valley). The nation boasts around fifty surface aquifers and roughly thirty semi-deep to deep aquifers.

Estimates based on 40 years of observations suggest that infiltrated rainwater contributes an average of approximately 7.5 billion cubic meters (reduced by a third during recent droughts) to groundwater replenishment. The component with slow renewal rates represents a reservoir with a few billion cubic meters in stock.

Fig. 2 Graph: withdrawals from major aquifers in Morocco versus regions. *Source* Developed by the author



Groundwater plays a pivotal role in socio-economic development, with a total annual withdrawal estimated at 3 billion cubic meters. These withdrawals are increasingly accomplished through pumping, overshadowing gravity-fed sources like khet-taras, springs, and emergences. Out of this three billion cubic meters, approximately 85% is earmarked for irrigation, which aligns with the Mediterranean average and represents 27% of the water resources utilized in this sector. Moreover, groundwater fulfills 55% of the demand for drinking water and industrial usage. Over the period from 1970 to 2016, withdrawals from specific large aquifers more than tripled (Fig. 2).

Irrespective of the influence of climate change, the management of water resources remains a paramount concern that will shape the future of Morocco. The nation is on a trajectory towards experiencing water stress, and by the year 2030, it is poised to confront water scarcity issues, further exacerbated by the emergence of quality challenges such as erosion, salinization, and pollution.

Climate change has the potential to intensify the adverse consequences of spatial and temporal water scarcity, compounding the already considerable degradation of water resources that affects socio-economic development. An analysis of temperature variations and temporal rainfall patterns over recent decades, conducted at various meteorological stations by the national meteorology department (Agoumi 1999), reveals a temperature increase of approximately 2 °C. Additionally, there has been a significant reduction of approximately 30% in cumulative precipitation during the 1978–1994 period compared to the 1961–1977 timeframe. The 1994–1995 season stands out as the driest of the century in Morocco (Hassani My et al. 1998).

An assessment of drought occurrences in Morocco during the twentieth century indicates a heightened frequency and broader geographic scope of droughts between 1982 and 2000. In this period, five drought episodes occurred in Morocco out of a total of eleven during the entire century. The average annual precipitation across the country's entire territory is estimated at 150 billion cubic meters, but it is markedly

unevenly distributed among the various regions. Approximately 15% of the nation’s area receives more than 50% of the total rainfall. Out of these accessible water resources, only 20%, equivalent to 29 billion cubic meters, is considered usable. This allocation includes 16 billion cubic meters from surface water sources and 4 billion cubic meters from groundwater.

Groundwater, owing to its essential characteristics concerning accessibility and distribution, involves an extensive array of stakeholders actively engaged in its utilization. These economic agents, characterized by legal authority, economic influence, or both, have the capacity to directly exploit groundwater resources. Thousands of drinking water production units are responsible for serving both rural and urban populations. These units are divided among:

The National Drinking Water Office (ONEP), tasked with supplying water to major cities and urban centers.

Water distribution authorities operating exclusively in urban and peri-urban areas.

Local communities, providing underground water to 30% of the rural population through wells and boreholes.

Since 1997, water distribution in several large Moroccan cities, including Casablanca, Rabat, and Tangier, has been delegated to multinational corporations, primarily due to the escalating infrastructure costs.

Regarding agricultural use of groundwater, the following notable statistics are observed as significant indicators (Fig. 3):

Mining operations are a significant consumer of groundwater, utilizing it for various industrial processes, mineral deposit dewatering, and phosphate washing. The activities of all these stakeholders can result in a range of problems with different magnitudes and consequences, which can be summarized into three primary impacts:

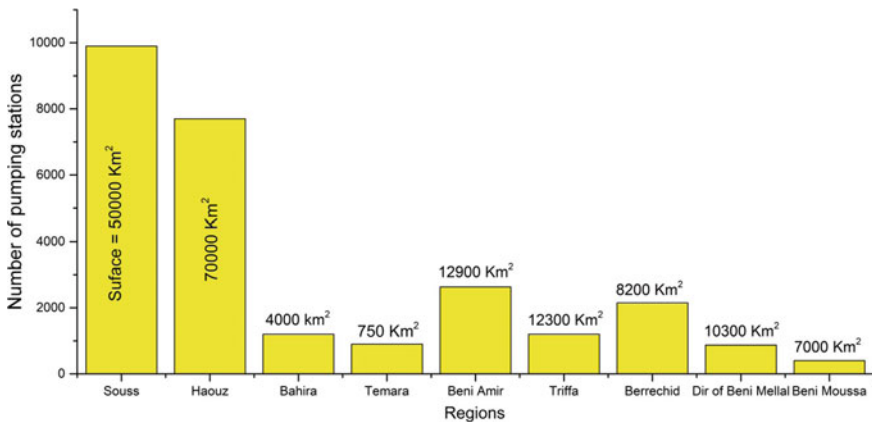


Fig. 3 Number of pumping stations versus regions in km² for agriculture use. *Source* Developed by the author

- Pronounced declines in groundwater levels in heavily exploited regions, including Haouz, Souss, and Sahel, leading to decreased productivity and increased production costs.
- The ongoing reversal of groundwater flow patterns, primarily along the coast, causing the intrusion of seawater and the impairment of hydraulic resources.
- Conflicts between various uses, particularly between the supply of drinking water and irrigation, along with the deterioration of water quality.

At a theoretical level, groundwater exploitation brings about alterations in the condition of the water table and its dynamics over a more or less extensive area, depending on the applied pressures and the characteristics of the aquifer. These modifications impact water levels (leading to declines), point discharges (resulting in reduced productivity), or boundary discharges, occasionally culminating in the reversal of flows between the surface and subsoil or between adjacent aquifers and the interface of seawater and groundwater.

From a practical perspective, investigations into the historical changes in piezometric levels, monitored over 20–35 years, reveal that several aquifers in Morocco have reached a state of over-exploitation, characterized by withdrawals surpassing natural recharge contributions. In certain instances, this situation may not be critically alarming. However, the most intensively utilized or delicate aquifers are susceptible to detrimental effects such as:

- Drying-up or diminished productivity of structures, necessitating periodic deepening and resulting in production losses due to inadequate irrigation, as exemplified in specific areas of Souss and Haouz.
- Dewatering of productive layers, as observed in regions like Temara, Tafilalt, Beni Amir, Beni Moussa, and Dir of Beni Mellal.
- The intrusion of marine water into coastal areas with extensive wetlands, notably along the Sahel region between Oualidia and Casablanca.
- Reduced productivity of collective water supply structures, leading to chronic shortages, as observed in locations like Imintanout, Essaouira, Jbel Hamra in Oujda, and the water production zones serving cities such as Marrakech, Agadir, Oujda, and Fez, among others.

The sustainable development of groundwater resources relies on the effective control and management of these assets, which is a fundamental requirement for responsible stewardship. Achieving this level of control necessitates not only a comprehensive understanding of the underlying physical environment, encompassing the laws and processes governing aquifer formation, renewal, and spatial–temporal evolution, but also requires the identification of the multitude of existing and often diverse stakeholders and the accurate prediction of evolving water demands.

The goal of resource management is to coordinate and organize activities in both temporal and spatial dimensions, aligning them with defined objectives based on the physical conditions of the resource and the economic requirements of its utilization (Loucks and Van Beek 2017). All the pertinent parameters at play necessitate continuous reassessment due to several factors:

- Inherent uncertainties stemming from measurement inaccuracies required for quantitatively understanding flow mechanisms and subsurface storage.
- Influence of climatic variability and potential hazards.
- Incomplete knowledge of the various actors involved and their behavioral patterns.
- Unidentified water demands in terms of both quantity and quality that may emerge urgently.

The selection of specific groundwater exploitation sites is often constrained by various factors. These limitations may be tied to the environmental structure, characteristics of the operational infrastructure, and the configuration of water use. Hydrogeological factors certainly play a role, encompassing the nature and structure of aquifers, their productivities, and water quality distributions. However, economic considerations also impose constraints, such as:

- The maximum allowable depth for resource extraction, whether it is to access the aquifer and initiate production (borehole depth) or to pump water, resulting in production costs that users must accept.
- Restrictions on exploitation to minimize impacts on spring flow rates, the regimes of other catchment areas, or even neighboring aquifers.
- Varying site-specific requirements for operational structures, contingent on their type and the specific water demands they serve.
- For groundwater, management is a matter of applying overarching principles across the resource system, treating it as a common good shaped by natural conditions. This approach establishes a balance between the objectives of exploitation and the goals of resource allocation and conservation, all driven by the broader public interest.

As groundwater is interdependent with surface water, its management is integrated into water management as a whole. It presupposes objectives, stakeholders, and instruments. Given their scale, the objectives in themselves constitute constraints on the exploitation of groundwater. They are multiple and must be reconciled to:

- satisfy the demands for underground water in quantity and quality;
- allocate the resource according to priorities;
- keep the potential resource in quantity and quality;
- keep the productivity and accessibility of groundwater, especially when it is intended for collective use;
- intensify the use of the resource deemed to be underexploited;
- avoid conflict interests between stakeholders.

Thus, these management objectives are in the common interest of both users and the community. The objectives listed above lead to the following question: “the management of groundwater is under whose responsibility?”.

It is the business of managers but still the business of everyone since groundwater is a common good; it is also the business of the state since groundwater is part of the hydraulic domain (2015 Morocco Water Law). It is of interest to those to whom

it offers an accessible resource from which they benefit as well as to those who represent and reconcile multiple and often conflicting interests.

Actions are associated with the money and investigation aspects. The activities consist of investments for investigations only. The direct effects on groundwater are of interest to the operators, which are numerous and diversified because of the following:

- of the extension of aquifers;
- that the operation does not require public utility development like surface reservoirs;
- that the occupants of the land see themselves as ‘rights holders’ over groundwater.

At the level of farmers, microeconomic objectives predominate. They individually manage their production according to their criteria, but not the resource itself. They are normally united since their actions interfere, but paradoxically do not care much about the effects of their actions which accumulate within the same aquifer system.

On the other hand, the authority emanating from public power or management authority has no means of direct action on groundwater before the promulgation of the water law of 1995. It does not have the appropriate power to intervene on the behavior of operators. It only intervenes through various traditional indirect management instruments.

This responsibility lies with the Ministry of Equipment and Water, certain powers of which are delegated concerning agricultural water to the Regional Offices for Agricultural Development. Note that Thermo mineral waters are under the responsibility of the Ministry of Energy and Mines.

As for the water law, nine years after its promulgation, stipulating among other things the creation of hydraulic basin agencies, its effective application is still progressing slowly.

In general, three major constraints affect water resources in Morocco: The scarcity of resources, their irregularity in time and space (Nadifi 1998).

Concerning groundwater resources, there are more exactly 32 deepwater tables (depth ranging from 200 m to more than 1000 m) and 48 surface water tables (shallow water level). The former is difficult to access with a high economic cost, the latter is more accessible, but also more vulnerable to pollution and drought, such as the case of the Plio-Quaternary aquifer in the Essaouira basin (Bahir et al. 2001) ensuring the supply of drinking water to the city (198,400 inhabitants in 2014) and the surrounding rural agglomerations.

During the last decades, the exploitation of groundwater has continued to grow under the combined effects of demographic pressure, the search for satisfactory food self-sufficiency, industrialization, and the political will for balanced regional development. This growth is due not only to new drilling techniques and ever more efficient means of dewatering, but also an unfavorable climatic situation leading to an acceleration of groundwater operations to compensate for deficits in surface flow and rainwater. The combined effects of intensive operating conditions and unfavorable climatic conditions have led to hydrodynamic imbalance regimes, which have almost generally caused alarming reductions in reserves (Haouz, Souss, Angads,

Tafilalt) and, consequently, productivity losses of collective or individual collection works, dewatering of traditional works (*Khettaras*, shallow wells), and reduction in emergence flows.

But one can wonder if these worrying reductions are the result of a provisional state of groundwater and its capacity to regulate and if the more favorable climatic conditions were correcting the broken equilibria. Should we curb and advise against an intensification of these exploitations by freezing this precious natural 'capital'? On the contrary, should we encourage, guide, organize the exploitation of groundwater and take actions accordingly for a better valuation of this natural resource while avoiding irreversible disruption of the balance?

It is legitimate for those responsible of the planning and management of water resources, academics, and those responsible for economic development to ask these questions and seek appropriate answers. Be that as it may, and given the level of exploitation of groundwater, we will agree that a period of rigorous management of these resources, whether renewable or not, is now required, to best adapt quantity, quality, and users in a context where all the natural, socio-economic parameters are not completely mastered, nor controllable. This is what motivated the selection of the Essaouira basin as a case study for both its complexity and fragility.

In arid and semi-arid environments, the precipitations and temperatures are determining parameters for climatic characterization. Studying the evolution of recent climate variability, which is essential for better management of water resources, remains an essential tool for overcoming the problems resulting from the relationship between water needs and their availability.

Climate change is a global phenomenon. In the long term, it involves complex interactions between environmental factors and economic and social conditions, leading to significant regional effects (Filho 2012; Misra 2014; Vennetier et al. 2005), including the Maghreb (El Kharraz et al. 2012).

Morocco, like Algeria (Elouissi et al. 2017) and other Mediterranean countries (Nassopoulos 2012; Taabni and El Jihad 2012) have suffered from several periods of drought accompanied by a water shortage. Over the past decades, numerous studies have shown a downward trend in precipitations and an upward trend in temperatures across North Africa (Meddi and Meddi, 2007; Meddi et al. 2009; Sebbar 2013). Morocco, in particular, has experienced a drop in the average annual precipitation and remarkable warming that began since the late 1970s (Babqiqi 2014; Driouech 2010; Driouech et al. 2010; Sebbar 2013). The changes in climate parameters mentioned above are not the same for all areas and the intensity should be quantified locally to manage natural resources, in particular water.

Due to its geographic location and context, Morocco remains one of the countries most vulnerable to the effects of climate change. The first signs of climate change are already manifesting in changing temperatures and precipitations. The precipitations show an overall fluctuating decrease depending on the region, between 3 and 30% (Babqiqi 2014). Temperatures display an average increase of + 0.6 to + 1.4 °C depending on the region (DMN 2007). ESCAP (2017) forecasts a reduction in precipitation of 8–10 mm/month depending on the scenarios, by the end of the

century over Morocco. This reduction is accompanied by an increase in temperature expected to reach 4 °C.

These changes will undoubtedly have harmful effects on the water resource already characterized by scarcity and a spatio-temporal irregularity. HCP (2013) indicates that Morocco would be exposed to move from a situation of water stress ($< 1000 \text{ m}^3/\text{inhabitant}/\text{year}$) to a situation of water scarcity ($< 500 \text{ m}^3/\text{inhabitant}/\text{year}$) by the 2030 horizon. This situation requires the rational exploitation of available water resources, the recycling of wastewater, and the use of water-saving—and production—techniques. Existing studies on the assessment of the climate change impact on water resources in Morocco remain very rare, general, and regional. It is therefore essential to move towards local studies, otherwise, on the ‘hydrological and hydrogeological basins’ scale. This makes it possible to specify the effects on this vital resource and to recommend the necessary adaptation measures.

2 Material and Methods

A total of 26 water samples representing the groundwater of the shallow aquifer within the Essaouira basin underwent comprehensive chemical and isotopic analysis (El Mountassir et al. 2022c). Of these samples, 24 were specifically dedicated to groundwater, with one sample reserved for rainfall and another for seawater. The on-site measurements of parameters including electrical conductivity (EC), pH, and temperature (T) were conducted using the HI-9829 Multiparametric Instrument. A 200-m probe was employed to gauge the depth of the water table. In order to capture values representative of the natural aquifer conditions, water samples were collected following a pumping duration of 15–20 min. These samples were meticulously preserved in 500 mL clean polyethylene bottles and stored at a temperature below 6 °C before being transported to the laboratory for further analysis.

The chemical element analysis was carried out at the Laboratory of Geosciences and Environment within the Ecole Normale Supérieure of Marrakech, Morocco. The concentrations of chloride (Cl) and sulfate (SO_4) anions were determined using the Mohr technique and the nephelometric technique, respectively. Calcium (Ca) and magnesium (Mg) concentrations were ascertained through the EDTA titrimetric method. Sodium (Na) and potassium (K) levels were measured via flame spectrometry. The contents of bicarbonate (HCO_3) and carbonate (CO_3) were analyzed through titration using 0.1 M HCl acid. Bromide concentration was determined using the Mettler Toledo SevenCompact meter. The ionic balance for all samples fell within the acceptable range of $\pm 10\%$.

The stable isotope composition of the groundwater samples was determined at the Laboratory of Radio Analyses and Environment within the National School of Engineers of Sfax, Tunisia. This analysis was conducted using the laser absorption spectrometer LGR DLT 100 (Penna et al. 2010), with a measurement uncertainty of $\pm 0.1\%$ for $\delta^{18}\text{O}$ and $\pm 1\%$ for $\delta^2\text{H}$. The results are presented in delta values,

expressed in per mil (‰) relative to the Standard Mean Ocean Water (SMOW). Detailed results are presented in Table 1.

3 Results and Discussion

3.1 Chemical Facies

The Piper diagram, initially introduced by Piper in 1944 (Piper 1944), serves as a graphical tool for characterizing the chemical composition of water. It presents a rhombic representation that is constructed based on the concentrations of major water constituents expressed in meq/L. As outlined by Freeze and Cherry in 1979, the methodology involves plotting the percentage of each element onto two equilateral triangles, one designated for anions and the other for cations. The resulting display on the Piper diagram (refer to Fig. 4) reveals that the groundwater within the shallow aquifer of the Essaouira basin exhibits two distinct chemical facies: the Cl–Ca–Mg type, which constitutes 64% of the samples, and the Cl–Na type, which accounts for the remaining 36%. This transition between different facies underscores the intricate hydrogeochemical processes contributing to the mineral composition of groundwater in this aquifer.

3.2 Ionics Ratio

In order to emphasize the role of marine intrusion in the salinization of the Plio-Quaternary aquifer within the Essaouira basin, we incorporated various ionic correlations, the inclusion of the trace element ‘bromide,’ and the examination of stable isotopes in the assessed groundwater samples.

3.2.1 Na/Cl Couple

The Na/Cl ratio serves as an indicative measure of marine influence, particularly in the context of marine intrusion or the initial stages of salinization. Typically, this ratio is lower than the standard marine value of 0.86 in such scenarios (Bouderbala 2015; Jones et al. 1999; Pulido-Leboeuf et al. 2003; Telahigue et al. 2018, 2020). Notably, a Na/Cl ratio less than 1 is distinguishable from a ratio greater than 1, which is typically associated with anthropogenic sources like domestic wastewater (Bear and Cheng 2010).

Table 2 reveals a significant positive correlation between electrical conductivity (EC) and the ions Cl, Na, Ca, Mg, K, Br, and SO₄, underlining the contributions of these elements to groundwater mineralization. With the exception of HCO₃, the

Table 1 Physicochemical and isotopic results of analysed samples

Sample	pH	T (°C)	EC (mS/cm)	Ca (meq/l)	Mg	Na	K	HCO ₃	Cl		
11/51	8.4	17.6	9.74	15.2	19.6	63.7	1.7	2.3	89.1		
15/51	7.8	19.8	1.55	5.0	2.1	5.8	0.3	4.1	7.1		
21/51	7.4	23.3	4.93	17.4	8.2	20.1	0.6	2.7	38.3		
27/51	7.8	22.2	0.92	3.1	1.2	3.3	0.1	3.8	2.8		
28/51	7.6	23.3	1.08	3.4	4.9	3.5	0.0	4.7	8.0		
45/51	8.1	21.5	7.74	15.2	14.6	55.8	1.3	2.3	81.5		
105/51	7.5	22.7	2.19	4.8	5.7	7.8	0.1	4.6	12.0		
125/51	8.0	26.3	2.72	7.5	5.8	7.3	0.3	5.0	15.3		
140/51	7.7	20.3	2.16	5.6	3.7	10.3	0.6	9.0	14.0		
148/51	7.5	21.2	1.60	6.1	2.2	5.2	0.2	5.0	9.0		
149/51	8.1	21.3	6.72	13.2	10.4	56.1	1.1	3.1	74.4		
272/51	7.5	22.0	1.96	4.5	5.0	7.3	0.1	4.4	9.9		
327/51	7.7	21.9	3.61	8.4	5.7	18.0	0.7	4.1	28.3		
O2	7.9	25.2	1.96	4.6	5.4	6.1	0.3	2.7	11.0		
O4	7.5	21.3	1.90	4.7	5.8	7.8	0.1	5.9	12.4		
O5	7.5	22.1	1.77	4.5	6.6	5.6	0.0	5.8	10.8		
O6	7.3	21.7	2.18	6.0	6.3	5.6	0.1	5.5	10.6		
O7	7.8	22.1	1.26	2.9	4.3	5.2	0.1	5.2	5.2		
O8	7.9	20.5	2.73	9.0	6.3	9.6	0.1	3.7	18.7		
O91	7.6	23.2	3.03	8.9	6.4	12.2	0.1	3.3	21.7		
O94	7.4	20.7	6.41	13.4	16.9	58.8	1.5	3.3	72.5		
O96	8.1	20.7	1.84	3.5	2.4	7.9	0.2	3.3	8.7		
O111	7.2	23.6	2.79	7.4	7.2	10.7	0.2	5.7	17.7		
O113	7.4	23.1	3.48	4.5	5.8	18.7	0.2	6.5	21.6		
O114	8.0	20.5	7.25	14.8	11.5	58.3	1.0	2.9	75.3		
Rainfall	6.0	23.8	0.05	0.4	0.1	0.2	0.0	0.4	0.2		
Seawater	–	–	–	20.6	105.6	469.1	10.2	1.8	545.9		
Sample	SO ₄	NO ₃	Br	δ ¹⁸ O (‰)	δ ² H	SI _G	SI _A	SI _H	SI _C	SI _D	IB (%)
11/51	6.7	2.1	0.2	– 1.8	– 8.9	– 1.1	– 1.3	– 4.0	1.0	2.2	0
15/51	1.6	0.1	–	– 4.5	– 23.0	– 1.7	– 1.9	– 6.0	0.5	0.8	1
21/51	3.6	0.2	0.1	– 4.7	– 26.1	– 1.1	– 1.4	– 4.9	0.4	0.6	2
27/51	0.5	0.5	–	– 5.0	– 25.5	– 2.3	– 2.5	– 6.7	0.4	0.6	0
28/51	0.6	0.5	–	–	–	– 2.3	– 2.5	– 6.2	0.3	0.9	– 7
45/51	5.2	1.9	0.1	– 2.1	– 10.2	– 1.5	– 1.7	– 2.7	0.3	0.7	– 2
105/51	3.3	0.0	–	– 2.6	– 19.6	– 2.1	– 2.3	– 5.7	1.0	2.1	– 4

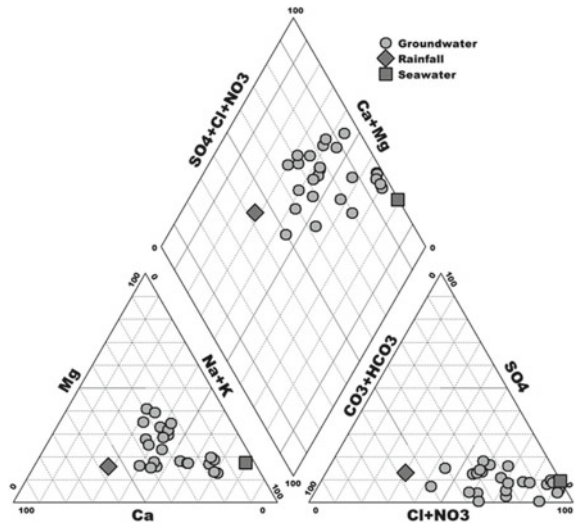
(continued)

Table 1 (continued)

Sample	SO ₄	NO ₃	Br	δ ¹⁸ O (‰)	δ ² H	SI _G	SI _A	SI _H	SI _C	SI _D	IB (%)
125/51	0.6	0.0	0.0	- 3.9	- 25.2	- 1.9	- 2.1	- 5.5	0.8	1.5	0
140/51	1.1	0.2	-	-	-	- 3.0	- 3.2	- 6.0	0.4	0.5	- 9
148/51	0.1	0.0	-	- 3.3	- 18.7	- 1.5	- 1.7	- 5.8	0.2	0.6	- 1
149/51	8.5	0.6	0.1	- 2.3	- 12.5	- 2.5	- 2.7	- 5.0	0.7	1.2	- 4
272/51	3.2	0.1	-	- 4.4	- 29.1	- 1.6	- 1.8	- 5.9	0.4	1.1	- 2
327/51	0.2	0.1	0.1	- 2.9	- 14.6	- 1.6	- 1.8	- 5.7	0.3	0.8	0
O2	2.6	0.0	-	- 4.5	- 24.5	- 1.6	- 1.9	- 5.9	0.4	1.0	0
O4	2.8	0.1	-	-	-	- 1.5	- 1.7	- 5.9	0.2	0.5	- 7
O5	2.5	0.3	-	-	-	- 1.9	- 2.1	- 6.2	0.4	1.1	- 7
O6	2.8	0.6	-	- 4.2	- 27.2	- 1.4	- 1.7	- 5.5	0.8	1.6	- 4
O7	1.9	0.4	-	-	-	- 1.0	- 1.2	- 5.3	0.5	0.9	- 1
O8	2.4	1.1	-	- 4.8	- 29.7	- 1.4	- 1.6	- 4.2	0.2	0.7	- 2
O91	7.4	0.0	0.0	- 4.3	- 24.8	- 1.8	- 2.1	- 5.8	0.6	1.1	- 8
O94	3.7	6.4	0.1	- 3.1	- 13.5	- 1.8	- 2.0	- 5.4	0.3	0.6	3
O96	1.6	1.5	-	- 3.7	- 18.7	- 1.7	- 1.9	- 5.1	0.3	0.8	- 4
O111	1.3	0.3	0.0	- 4.4	- 25.1	- 1.0	- 1.2	- 4.2	0.9	1.8	1
O113	2.7	1.1	0.0	- 4.7	- 22.5	- 1.2	- 1.4	- 4.1	0.8	1.8	- 4
O114	7.5	0.9	0.1	- 2.1	- 12.5	- 1.0	- 1.2	- 4.1	0.8	1.6	- 1
Rainfall	0.1	0.0	-	- 5.8	- 26.2	-	-	-	-	-	- 1
Seawater	56.5	-	-	1.0	4.5	-	-	-	-	-	0

SI Saturation Index, SI_G SI_{Gypsum}, SI_A SI_{Anhydrite}, SI_H SI_{Halite}, SI_C SI_{Calcite}, SI_D SI_{Dolomite}

Fig. 4 Piper diagram of analysed samples. *Source* Developed by the author



strong positive associations between Cl and Na, Ca, Mg, K, Br, and SO₄ suggest that groundwater mineralization is predominantly influenced by processes like evaporate dissolution, evaporation, and seawater contamination. This proposition is further supported by the negative values of saturation indices with respect to halite, anhydrite, and gypsum (Table 1), as well as the Gibbs diagrams (Gibbs 1970), where the majority of samples are situated within the fields of rock-water interaction and evaporation dominance (Fig. 5). A close-to-unity positive correlation is evident between Na and Cl, as well as between Cl and Br, implying that certain samples have been influenced by seawater contamination.

Chloride, recognized as a conservative element, exhibits a robust correlation with sodium in the water samples extracted from the shallow aquifer within the Essaouira basin, as indicated by a high coefficient of determination ($r^2 = 0.99$) (Fig. 6; Table 2). Notably, even in instances where samples are geographically distant from the coastline, the molar ratio of Na/Cl does not significantly deviate from that of seawater. Take, for example, well 15/51, which illustrates this similarity. Consequently, distinguishing between the origins of the water samples, particularly with respect to

Table 2 Correlation matrix for the analyzed parameters

	EC	Ca	Mg	Na	K	HCO ₃	Cl	SO ₄	NO ₃	Br
EC	1									
Ca	0.90	1								
Mg	0.92	0.80	1							
Na	0.96	0.83	0.90	1						
K	0.92	0.81	0.87	0.94	1					
HCO ₃	-0.54	-0.58	-0.48	-0.52	-0.45	1				
Cl	0.98	0.88	0.92	0.99	0.94	-0.55	1			
SO ₄	0.74	0.66	0.66	0.73	0.56	-0.51	0.74	1		
NO ₃	0.52	0.42	0.67	0.63	0.64	-0.29	0.58	0.23	1	
Br	0.97	0.82	0.88	0.97	0.95	-0.80	0.99	0.61	0.51	1

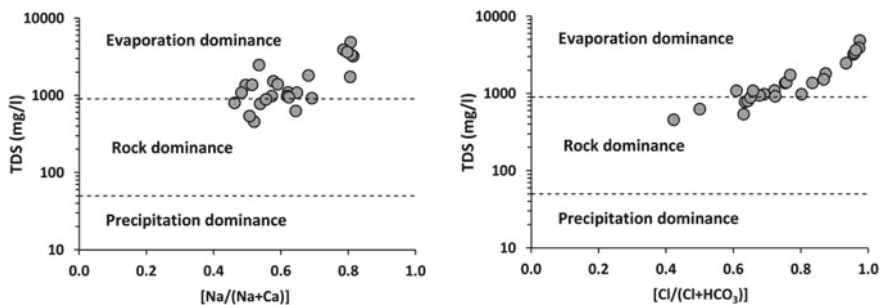


Fig. 5 Gibbs' diagrams. *Source* Developed by the author

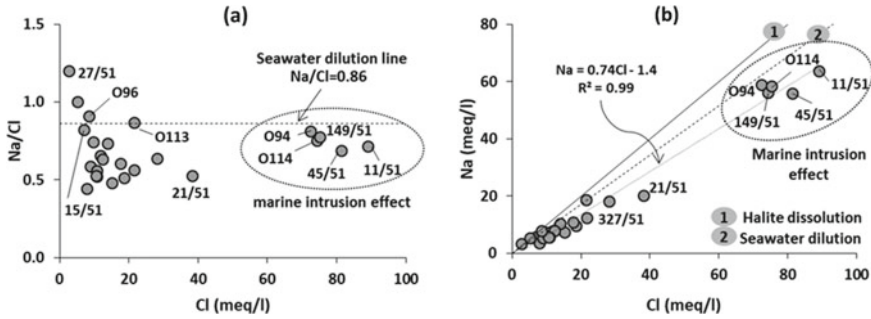


Fig. 6 Correlation diagram **a** Na/Cl versus Cl and **b** Na versus Cl of analysed samples. *Source* Developed by the author

the dissolution of evaporitic formations, which can result in elevated Na and Cl concentrations, remains challenging.

Nonetheless, for this coastal aquifer, the proximity of the sea to permeable sandy formations suggests the possibility of saltwater intrusion in specific regions of the aquifer. This intrusion could provide an explanation for the heightened concentrations of these elements. Moreover, the escalation in Cl levels might also be attributed to the dissolution of marine aerosols transported by the wind.

The average Na/Cl molar ratio in this context stands at 0.7, with a range spanning from 0.4 to 1.2. This average closely approximates the ratio found in seawater (0.86) (Jones et al. 1999), indicating that the Plio-Quaternary aquifer may indeed be subject to seawater contamination in select areas. This is particularly evident in instances where Cl concentrations exceed 70 meq/l, accompanied by a molar ratio of 0.7, as observed in samples 11/51, 45/51, 149/51, O94, and O114.

3.2.2 Ca/Mg Couple

One of the prominent characteristics associated with seawater intrusion is the elevated concentration of calcium in comparison to its content in seawater. The Mg/Ca ratio serves as a natural tracer for discerning the phenomenon of marine intrusion into coastal aquifers (Bouderbala 2015; Pulido-Leboeuf et al. 2003; Telahigue et al. 2018, 2020). This ratio displays an increment corresponding to the proportion of marine water within the mixture, with salinity represented by chloride concentrations (Pulido-Leboeuf et al. 2003). The rationale behind this behavior is that seawater exhibits a Ca/Mg ratio of 0.2, while freshwater typically features a ratio greater than 1. It is worth noting that saline water with a high calcium concentration may arise from various mechanisms, not necessarily linked to the cation exchange phenomenon (Jones et al. 1999). The Ca/Mg ratio diminishes as the proportion of seawater introduced into the mixture increases.

In the present case study, the ratio also experiences a decline in response to the chloride content. For instance, upon comparing point 27/51 (the least mineralized

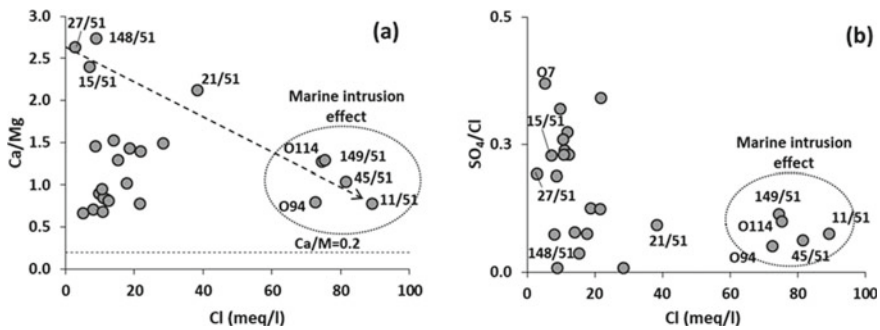


Fig. 7 Correlation diagram **a** Ca/Mg versus Cl and **b** SO₄/Cl versus Cl of analysed samples. *Source* Developed by the author

sample) and point 11/51 (the most mineralized sample), a distinct reduction in the Ca/Mg ratio is evident, coupled with an upsurge in chloride levels (Fig. 7a). This observation suggests a possible marine origin of the mineralization, particularly at well sites such as 11/51, 45/51, 149/51, O94, and O114, where the ratio closely resembles that of seawater and is associated with high chloride levels. In cases where the Ca/Mg ratio exceeds 1, seawater intrusion is unlikely to be implicated in the mineralization. Instead, another hydrochemical process, likely related to water–rock interaction, should be considered. This may involve phenomena such as cation exchange, which results in the release of calcium from the aquifer matrix and the adsorption of sodium from the solution (Gimenez et al. 2010).

3.2.3 SO₄/Cl Couple

As per Pulido-Leboeuf et al. (2003), the SO₄/Cl ratio can be employed as a natural tracer for identifying the phenomenon of marine intrusion in coastal aquifers. This ratio tends to decrease as the proportion of seawater in the mixture increases (Bouderbala 2015; Pulido-Leboeuf et al. 2003; Telahigue et al. 2018, 2020; Tellam and Lloyd 1986).

For the shallow aquifer within the Essaouira basin, all the examined samples exhibit a SO₄/Cl ratio of less than 1, signifying the prevalence of chlorides over sulfates (Fig. 7b). The SO₄/Cl ratio among the sampled specimens ranges from 0.02 to 0.37, with the majority of them displaying a higher SO₄/Cl ratio than that of seawater (0.1) (Fig. 7b). This observation implies a blending of seawater with freshwater. The elevated sulfate content in these samples suggests the presence of additional sources, such as the dissolution of gypsum and anhydrite (Table 1). In particular, samples from wells 11/51, 45/51, 149/51, O94, and O114 exhibit a notably low SO₄/Cl ratio, coupled with high chloride contents. This indicates that the increase in salinity in these wells is primarily attributed to seawater intrusion, corroborating the results obtained through the Na/Cl and Ca/Mg ratios.

3.2.4 Br/Cl Couple

Bromide is recognized as a dependable indicator of the marine intrusion phenomenon (De Montety et al. 2008; Kim et al. 2003; Telahigue et al. 2018, 2020). Similar to chloride, bromide behaves as a conservative element and does not engage in reactions with the aquifer matrix, unless substantial amounts of organic matter are present (Davis et al. 1998). These two conservative elements offer insights into the origin of solutions and help identify potential contributions of marine water, as their concentrations remain unaffected by redox processes and are independent of low solubility minerals (Fedrigoni et al. 2001).

Given the extensive residence time of bromides and chlorides in oceanic masses, the Br/Cl ratio in contemporary seawater remains relatively constant, typically ranging between 1.5 and 1.7×10^{-3} (De Montety et al. 2008; Kim et al. 2003). This stability is preserved when the two elements share a common source. However, seawater can be distinguished from remnants of evaporated seawater or hypersaline waters (Starinsky et al. 1983), which arise from the dissolution of evaporite formations, as well as from anthropogenic sources such as wastewater effluents (Vengosh et al. 1998) or the return of irrigation water.

As seawater evaporates, the Br/Cl ratio remains constant until the onset of halite precipitation. During halite precipitation, the solution becomes enriched in bromide, leading to an increase in the Br/Cl ratio (Ben Hamouda et al. 2011). Notably, the Br/Cl ratio of residual brine continues to rise with increasing quantities of precipitated halite. Consequently, a solution originating from the concentration of seawater before halite saturation exhibits a Br/Cl ratio identical to that of seawater. Conversely, more concentrated brine, which has surpassed the phase of halite precipitation, demonstrates a higher Br/Cl ratio than seawater. Consequently, freshwater dissolving halite to saturation will exhibit a Br/Cl ratio lower than that of seawater, considering that primary halite is the sole chlorinated salt with a Br/Cl ratio lower than that of seawater. Simultaneously, a mixture of freshwater and brine that has undergone halite precipitation will possess a higher Br/Cl ratio than the marine ratio.

The correlation diagram between Br and Cl (Fig. 8a) reveals a robust positive correlation ($r^2 = 0.99$) between these two ions, suggesting a shared origin for bromides and chlorides. In the Br/Cl diagram as a function of Cl (Fig. 8b), samples 11/51, 45/51, 149/51, O94, and O114 fall within the seawater dilution field, displaying a Br/Cl ratio ranging from 1.5 to 1.7. This finding underscores their marine origin of salinity. The elevated bromide concentrations in certain wells, associated with a Br/Cl molar ratio exceeding that of seawater, can be attributed to the abandonment of these wells more than a decade ago and their substantial distance from the recharge zone, facilitating the formation of brines that have undergone the halite precipitation phase. Other data points exhibit lower molar ratios than seawater, indicating that these points are unaffected by the marine intrusion phenomenon and therefore suggest the existence of alternative sources of salinization, such as the dissolution of salts.

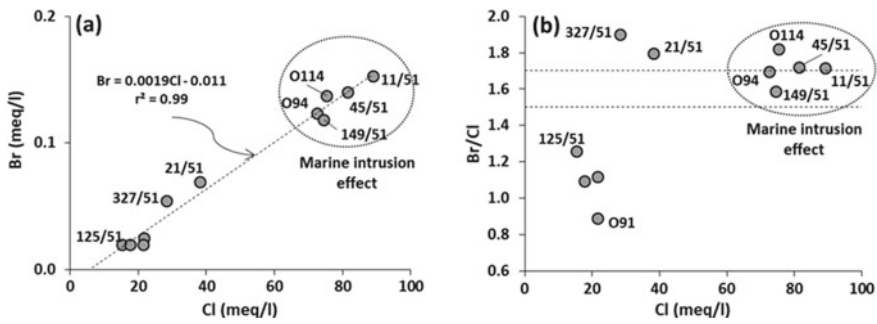


Fig. 8 Correlation diagram **a** Br versus Cl and **b** Br/Cl versus Cl of analysed samples. *Source* Developed by the author

3.2.5 Cl/HCO_3 Versus Cl Plot

The Cl/HCO_3 versus Cl graph (Fig. 9a, b) serves as a means to categorize water types, distinguishing between freshwater and seawater. Since seawater typically exhibits higher chloride (Cl^-) concentrations, while freshwater is characterized by higher bicarbonate (HCO_3^-) ion levels, this plot aids in the differentiation. Revelle (1941) and Todd (1959) established a classification system for water salinization based on Cl/HCO_3 ratios. This system distinguishes between water types unaffected by seawater intrusion or freshwater (< 0.5), those slightly affected by seawater intrusion (0.5–1.3), those moderately affected (1.3–2.8), those adversely affected (2.8–6.6), and those severely impacted by seawater intrusion (> 6.6). The graph essentially classifies water as freshwater, mixed water, or seawater.

The majority of data points in this study exhibit contamination resulting from marine intrusions, with none representing freshwater sources. This pattern is consistent with point 27/51, which displays contamination despite its aquifer recharge (Fig. 9a, 9b).

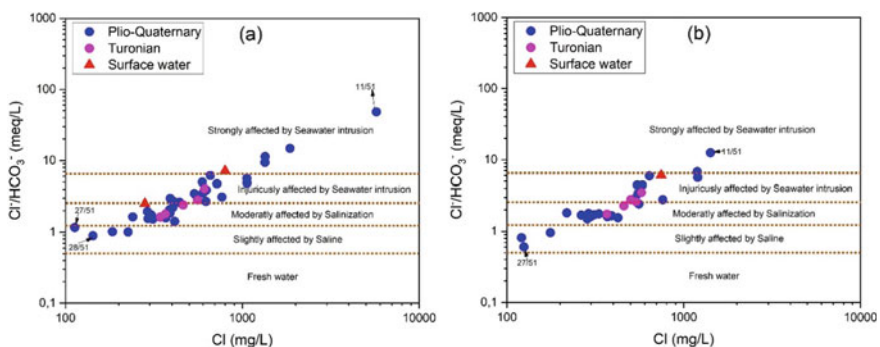


Fig. 9 Cl^-/HCO_3^- versus Cl plot for the campaign 2019 (a), and 2020 (b) (Bahir et al. 2022b)

3.2.6 Saturation Index (SI)

Numerous mechanisms come into play in influencing the hydrochemical composition of groundwater, encompassing groundwater flows, recharge and discharge dynamics, as well as water–rock interactions (Rabey et al. 2018; Teshome 2020). Additionally, the protracted transport of groundwater in the direction of flow is known to have an impact on hydrochemistry, often attributed to mineral weathering processes (Selvakumar et al. 2017). For the quantification of a mineral’s saturation index (SI), Eq. (1) can be effectively applied:

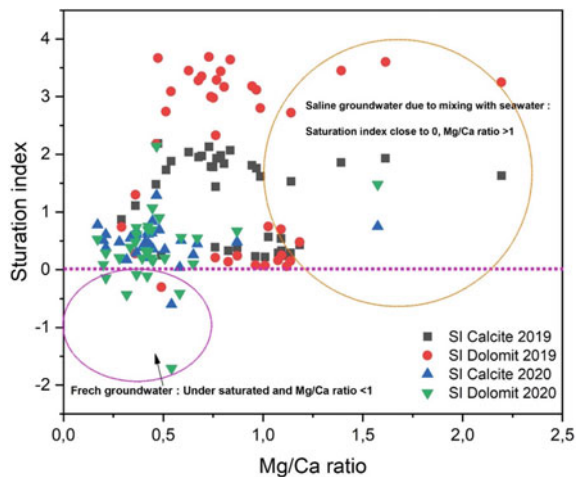
$$SI = \log\left(\frac{K_{IAP}}{K_{SP}}\right) \tag{1}$$

where K_{SP} denotes the mineral’s solubility product and K_{IAP} denotes the ions activity product in a mineral equilibrium process.

The PHREEQC code, developed by Parkhurst and Appelo (1999), was employed to calculate the saturation index for carbonate mineral elements (calcite and dolomite) as well as gypsum (Fig. 10). This analysis enabled the classification of groundwater samples into two distinct groups based on the Mg/Ca ratio and saturation indices. In general, freshwater is characterized by a dominance of calcium, while seawater exhibits a higher magnesium content. Consequently, the Mg/Ca ratio can serve as an indicator of seawater intrusion.

The first group comprises groundwater samples within or near the brown dotted circle (Fig. 10) where the calcite or dolomite saturation index is approximately at or above 0, or along the equilibrium line. These findings indicate saline groundwater with elevated Mg^{2+} content, resulting from the mixing of freshwater and saltwater within the aquifer. For instance, water sample 11/51 shows significant contamination from marine intrusion, featuring a Mg/Ca ratio of 1.57 and an electrical conductivity

Fig. 10 Saturation index versus Mg/Ca ration plot for the campaign 2019 (a), and 2020 (b) (Bahir et al. 2022b)



of 23,850 $\mu\text{S}/\text{Cm}$ (Fig. 2) for the 2020 dataset. Similarly, in the 2019 dataset, eight water samples (11/51, 105/51, 149/51, 272/51, O4, O5, O6, O7) from the Plio-Quaternary aquifer, and two samples from the Turonian aquifer (390/51, 380/51), exhibited contamination due to high salinity. It is worth noting that marine intrusion also affected the entire course of Oued Ksob (O98—downstream, O38—upstream). Groundwater samples with a Mg/Ca ratio > 1 and $\text{SI} > 1$ suggest that Mg^{2+} originated from seawater and was adsorbed by freshwater, leading to the release of Na through a cation exchange process.

Conversely, the second group is characterized by a Mg/Ca ratio of less than 1 and $\text{SI} < 0$. These findings indicate the presence of freshwater in the aquifer system, unaffected by seawater intrusion. The upper region of the study area contains freshwater rich in calcium, while the lower region, aligned with the groundwater flow direction, is enriched with magnesium.

3.2.7 $\delta^{18}\text{O}$, $\delta^2\text{H}$ and $\delta^{18}\text{O}$, Cl Couple

The utilization of isotopic analysis serves as a supplementary approach for ascertaining critical factors related to groundwater sources, regional origins, and the mechanisms governing aquifer recharge (Craig 1961). This method also offers valuable insights into the transformative processes affecting individual water molecules (Geyh 2000).

In the context of the present study, oxygen-18 isotopic values exhibit a range spanning from -1.83 to -5.02 ‰ versus SMOW, with an arithmetic mean of -3.66 ‰ versus SMOW. Simultaneously, deuterium isotopic contents demonstrate a variation ranging between -8.92 and 29.71 ‰ versus SMOW, with an average value of -20.60 ‰ versus SMOW (Fig. 11; Table 1).

The frequency distribution plots depicted in Fig. 12a reveal distinct patterns in the oxygen-18 isotopic content of the analyzed samples. Approximately 45% of the samples exhibit oxygen-18 values falling within the range of -5 to -4 ‰ versus SMOW. Meanwhile, 25% of the samples display values between -3 and -2 ‰ versus SMOW, and another 20% fall within the range of -4 to -3 ‰ versus SMOW. The remaining 10% is distributed, with 5% of samples having oxygen-18 values ranging from -6 to -5 ‰ versus SMOW and another 5% from -2 to -1 ‰ versus SMOW.

In a similar vein, the frequency histograms in Fig. 12b illustrate the distribution of deuterium isotopic contents. Notably, 35% of the examined samples exhibit deuterium values between -25 and -30 ‰ versus SMOW. An additional 25% of samples display values ranging from -15 to -10 ‰ versus SMOW, while 20% present deuterium contents within the range of -25 to -20 ‰ versus SMO. A further 15% of samples fall within the range of -20 to -15 ‰ versus SMOW, with the remaining 5% having deuterium values spanning from -10 to -5 ‰ versus SMOW.

These distribution patterns indicate the coexistence of two distinct groundwater types within the study area. The first group is characterized by depleted stable isotopic

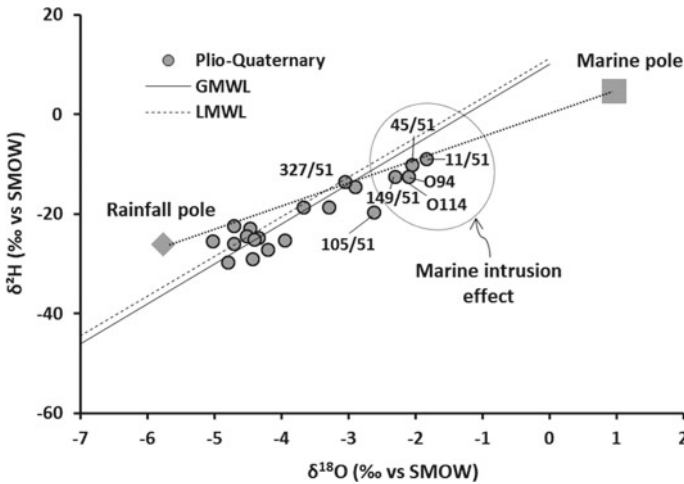


Fig. 11 Correlation diagram $\delta^2\text{H}$ versus $\delta^{18}\text{O}$ of analysed samples. *Source* Developed by the author

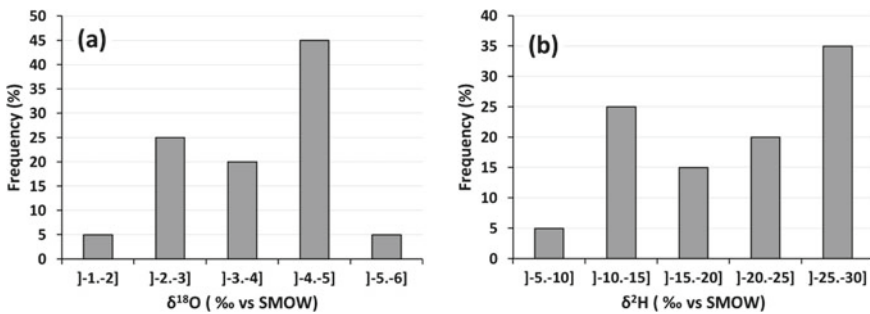


Fig. 12 Frequency distribution of oxygen-18 and deuterium contents in the waters of analysed samples. *Source* Developed by the author

compositions, while the second group is enriched in stable isotopes. These findings suggest that various hydrological processes, such as evaporation and marine intrusion, may have influenced the isotopic enrichment observed in the groundwater.

The distribution of representative samples from both the Plio-Quaternary and Turonian aquifers, collected during the 2018 campaign, is presented on the correlation diagram of $\delta^2\text{H}$ versus $\delta^{18}\text{O}$, as illustrated in Fig. 12. This diagram serves as a valuable tool for elucidating the principal mechanisms governing the hydrodynamic and geochemical dynamics of these aquifers.

An analysis of the diagram reveals that a significant portion of the data points are dispersed in proximity to both the Global Meteoric Water Line (GMWL) introduced by Craig in 1961 and the Local Meteoric Water Line (LMWL) as defined by Mennani et al. in 2001. This distribution pattern indicates that the prevailing recharge mechanism for the Plio-Quaternary aquifer primarily involves direct infiltration of

rainfall originating from the Atlantic Ocean. This is particularly evident in the case of the sampling points located in close proximity to the Ksob wadi. It is important to note that the majority of these points exhibit isotopic signatures indicative of Atlantic-origin rainwater, leading to decreased salinity levels in the corresponding wells. Notably, well 27/51, positioned closest to the freshwater pole (representing rainwater), exhibits a notably low electrical conductivity.

Conversely, some data points diverge from the GMWL and align along a distinct trendline with a slope of less than 8, signifying an evaporation-related process. These specific points are predominantly associated with wells situated in the northeast and south sectors of the aquifer, including O6, 105/51, 125/51, 272/51, and 327/51. The phenomenon of evaporation might take place either before the water infiltration, within the unsaturated zone, or during the sampling process.

To further investigate these isotopic trends, a Freshwater-Seawater line is constructed by combining the isotopic signatures of rainwater and Atlantic Ocean seawater, as outlined by Carreira et al. in 2014. A distinct set of data points is positioned beneath the LMWL and exhibits more enriched isotopic compositions. Notably, this group includes points 11/51, 45/51, 149/51, O94, and O114, and their isotopic profiles suggest the involvement of additional factors contributing to groundwater mineralization, such as evaporation and marine influence. These specific samples are situated in the transitional zone between the ‘rainfall’ and ‘marine’ poles, indicating the potential ingress of seawater into the aquifer at these locations.

Moreover, the combined use of chloride and oxygen-18 content reinforces the conclusions drawn from the earlier analysis. The Cl versus $\delta^{18}\text{O}$ diagram, represented in Fig. 13, underscores the dominance of processes related to the dissolution of evaporite formations and marine intrusion in shaping the groundwater hydrochemistry across the study area.

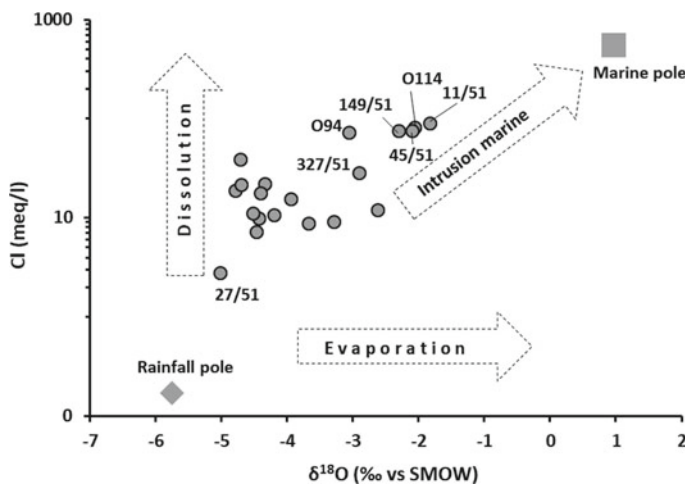


Fig. 13 Correlation diagram Cl versus $\delta^{18}\text{O}$ of analysed samples. *Source* Developed by the author

3.3 Estimate of Mixture with Seawater

The most elevated chloride (Cl) concentrations are prominently observed in specific samples, with sample 11/51 exhibiting the highest recorded value at 89.1 meq/l, located at Cap Sim. Similarly, point 45/51, situated to the north, demonstrates notable Cl content of 81.5 meq/l. Additional samples display Cl concentrations within the range of 70–80 meq/l, exemplified by O114 (75.3 meq/l), 149/51 (74.4 meq/l), and O94 (72.5 meq/l). Conversely, the remaining samples encompass a spectrum of Cl concentrations that vary between 2.8 and 38.3 meq/l.

To quantify the degree of intrusion in each affected sample, a mixing rate (F) with seawater can be computed through a mass balance analysis of chlorides. This mixing rate can be estimated employing Eq. (2) as presented by Abou Zakhem and Hafez in 2007:

$$F(\%) = \frac{[Cl_{\text{sample}}] - [Cl_{\text{fresh}}]}{[Cl_{\text{sea}}] - [Cl_{\text{fresh}}]} \times 100 \quad (2)$$

With:

F corresponds to the seawater fraction.

Cl_{sample} corresponds to the concentration of chlorides in the water sampled.

Cl_{fresh} corresponds to the concentration of chlorides in fresh groundwater. For our case, the average chloride concentrations of wells with electrical conductivity values less than 1000 $\mu\text{s}/\text{cm}$ were used as Cl concentrations. Cl_{sea} corresponds to the concentration of chlorides in seawater.

The calculated mixing rates exhibit a range between 0% and 15.9% (as illustrated in Fig. 14). The most substantial values are observed in specific samples, such as 11/51 with a rate of 15.9%, 45/51 at 14.5%, 149/51 at 13.2%, O114 at 13.3%, and O94 at 12.8%. In contrast, the remaining samples depict mixing rates varying from 0% to 6.5%.

The elevated values are distributed primarily along the coastline, indicative of the seawater intrusion extending into the aquifer. The average width of this intrusion is estimated to be approximately 2 km. This contamination is likely attributed to a decline in the piezometric level due to decreased precipitation patterns observed over the previous decades within the study area (Ouhamdouch et al. 2018), as well as the impact of rising sea levels induced by global warming (IPCC, 2013).

4 Conclusion

The integration of findings derived from both the hydrogeochemical and isotopic approaches, encompassing parameters such as (Na, Cl), (Ca, Mg), (Br, Cl), ($\delta^2\text{H}$, $\delta^{18}\text{O}$), and ($\delta^{18}\text{O}$, Cl), offers a more comprehensive understanding of the origins of groundwater salinization within the study area.

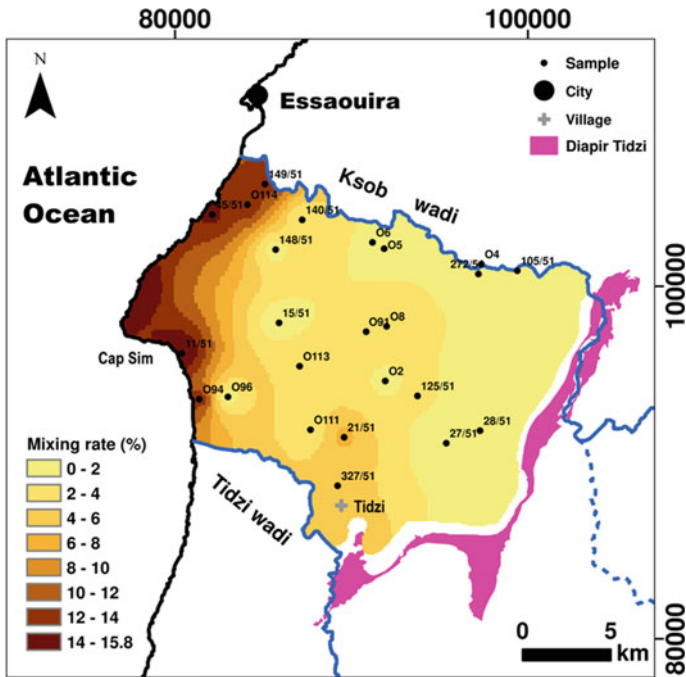


Fig. 14 Seawater fraction of analysed samples. *Source* Developed by the author

Ionic ratios such as Br/Cl approximating 1.5 to 1.7‰, Na/Cl approaching 0.86, as well as the presence of weak Mg/Ca and SO₄/Cl ratios collectively indicate the incursion of seawater into the fresh groundwater of the Plio-Quaternary aquifer in the Essaouira basin. This intrusion, supported by ionic ratios, is further substantiated by stable isotopes. The joint application of oxygen-18 content and chloride levels reveal a mixing rate of 15.9% at well 11/51, 14.5% at sample 45/51, 13.2% at well 149/51, 13.3% at point O114, and 12.8% at well O94. These elevated rates are distributed along the coastline, signifying the advancement of the saline front by approximately 2 km. The principal drivers behind this intrusion likely include a decline in the piezometric level due to reduced precipitation over recent decades in the study area and the impact of rising sea levels associated with climate change.

The case of the Essaouira region, located on Morocco’s Atlantic coast, serves as an illustrative example of the multifaceted challenges encountered in semi-arid zones. Beyond its regional significance in water resource management, the methodology employed can be readily adapted and applied to other regions grappling with analogous climatic and anthropogenic constraints:

- Implementation of hill dams to mitigate wadi bed erosion and combat siltation by enhancing the longevity and mobilization of water resources via the dams.
- Establishment of artificial recharge mechanisms in areas characterized by deficits and vulnerability, especially those susceptible to seawater intrusion.

- Incorporation of desalinated seawater into available water resources to enhance their quality.
- Adoption of purified wastewater for irrigation purposes in cases where conditions permit, including golf courses, green spaces, and agriculture.
- Transition from aquifer overexploitation to surface water withdrawals, as a means to address water resource sustainability concerns.

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