

Evolution of Groundwater in the Cheliff and Mitidja Aquifers (North Algeria) in Qualitative and Quantitative Terms



Faiza Hallouz and Mohamed Meddi

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Abstract Due to rapid population growth over time, the importance of freshwater is increasing, and the availability of this vital resource is becoming progressively more challenging. Consequently, the exploitation of untapped water sources becomes a necessity. With industrial development, groundwater is increasingly exposed to various contaminants by infiltrating polluted discharges. Water resources in Algeria, especially in the Cheliff and Mitidja plains, are limited, vulnerable, and unevenly

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distributed spatially. This precarious situation inevitably calls for new measures to be taken to utilize these resources sustainably. Natural factors, such as drought or geological constraints, affect the supply and distribution of drinking water. Therefore, it is imperative to quantify and analyze the quantity and quality of water supplies, and to devise methods for managing this resource to ensure its long-term viability. The water quality in these regions has significantly deteriorated in recent years due to unregulated urban discharges, intensive use of chemical fertilizers, and poorly managed farms. These factors alter the chemical composition of water, rendering it unsuitable for intended purposes. This chapter offers a scientific overview of the current groundwater status in the Cheliff and Mitidja regions, focusing on both qualitative and quantitative aspects.

Keywords Algeria, Cheliff and Mitidja, Chemism of water, Groundwater pollution, Groundwater quality, North Africa

1 Introduction

Water is an essential element for the survival of humans, animals, and plants, which stands as a cornerstone of life itself. Ensuring water security is paramount for the continuation of human existence. Worldwide, the importance of water scarcity and the increasing demand for this essential resource have become more prominent. Groundwater, well known for its reliable availability and acceptable quality, plays a crucial role in numerous industrial and agricultural processes, especially in areas where rivers and lakes are in short supply. Across the globe, nations face the challenge of ensuring groundwater resources' quality and long-term sustainability. Recent studies by Zhang et al. [1] and Bose et al. [2] underline the pressing need for comprehensive strategies to prevent contamination, thereby averting potential ecological disasters and safeguarding public health. The ramifications extend beyond environmental concerns, intertwining with economic growth and societal well-being. Stretching vast distances, this ancient underground water source has enabled human settlement and agricultural pursuits in an unforgiving landscape. Here, the careful management of groundwater is emblematic of sustainability and a testament to human ingenuity [3].

In arid and semi-arid regions, the looming specter of drought further underscores the criticality of effective groundwater management [4]. The global scenario underscores the importance of safeguarding groundwater quality and availability. The exploitation of groundwater beyond its natural replenishment rate has been observed in places such as California in the United States, where agricultural demands have outpaced the available supply [5]. The Punjab region in northern India, for instance, relies extensively on groundwater for its agricultural output, a practice that demands vigilant monitoring to counterbalance the risk of over-extraction and subsequent land subsidence [6]. In Australia, the Great Artesian Basin stands as a testament to

the enduring importance of groundwater in arid regions. In recent years, several regions of North Africa have grappled with alarming declines in groundwater levels, leading to concerns about long-term sustainability especially in Algeria [7].

Algeria is a country located in North Africa that faces several significant challenges. Among these challenges, we can cite drought, particularly during the 1940s and 1970s [8–16]. Drivers such as rapid population growth, urbanization, and climate change are significant factors that have profoundly impacted the region's economic and environmental stability. These problems have serious consequences on the economy and the quality of life of the Algerian population.

The Cheliff and Mitidja regions are two important regions in Algeria, known for their agricultural production and water resources. The Cheliff river stretches over 700 km and flows through several regions, including the Atlas Mountains. The Mitidja is a coastal plain that extends 80 km along the Mediterranean coast. These two regions are important for cities' agriculture, fishing, industry, and water supply. Both regions are important in Algeria which is rich in various natural resources, including water, fertile land, and minerals. However, these regions also have environmental problems, including freshwater pollution, land degradation, and biodiversity loss. These problems can adversely affect both the economy and the inhabitants' quality of life.

The groundwater resources in these two regions are estimated to be more than 2 billion m³, with over 90% of these resources already exploited [17]. This over-exploitation has raised concerns about the sustainability of the water resources. One of the major concerns in the Cheliff and Mitidja regions is groundwater pollution due to the unscientific and excessive use of fertilizers in agriculture and certain industrial activities. Urbanization and demographic growth also contribute to pollution. The Cheliff and Mitidja plains are widely regarded as one of Algeria's most productive agricultural areas. They possess a large reservoir of groundwater, which serves as a vital source of irrigation and drinking water. Unfortunately, this valuable resource has experienced a significant reduction in natural recharge, leading to a substantial drop in water levels in certain regions. The primary causes of this reduction are the decrease in rainfall, amounting to about 20% since 1975 [8, 11, 16, 18–20], and continuous over-exploitation of groundwater [21].

The study addressed a research gap in understanding the long-term effects of pollution on the aquifers of the Cheliff and Mitidja plains in Algeria. Despite recognizing the effects of agricultural and industrial pollution, the specifics of pollutants and their long-term impacts are unexplored. To bridge this gap partially, this study's overall aim is to preserve water quality for drinking and irrigation in both plains. Therefore, it is essential to (1) monitor the groundwater resources and develop strategies for sustainable groundwater resource management, ensuring their availability for future generations, (2) understand the dynamics of the Cheliff and Mitidja aquifers in terms of both quality and quantity, and (3) have insights into the factors influencing groundwater evolution, including human activities and natural processes. Thus, the objective of this study was to investigate the evolution of groundwater in the Mitidja and Cheliff plains.

2 Methodology

The research focuses on the Cheliff and Mitidja aquifers situated in Northern Algeria, forming the geographical scope of the study. These aquifers hold immense significance as they are vital in supplying essential groundwater resources for agricultural and residential purposes. The selection of these aquifers as the study's focal point was influenced by their pivotal role in the local water supply and the existence of previous research efforts.

The methodology outlines a detailed approach in studying the evolution of groundwater in the Cheliff and Mitidja aquifers and is presented in Fig. 1. It involves reviewing the existing literature, collecting and analyzing data (such as climate, hydrology, and hydrography), comparing previous studies, conducting both quantitative and qualitative analyses, drawing conclusions, and providing

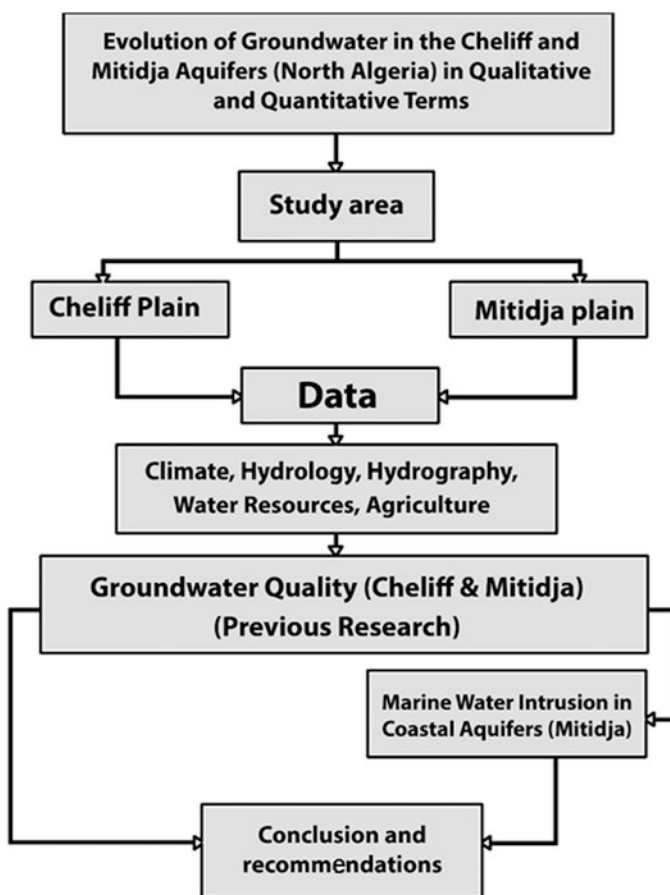


Fig. 1 Flowchart of the procedural stages devised in the research

recommendations for future research and groundwater management practices. Specific outcomes include:

- Quantitative understanding of groundwater flow patterns and trends over time
- Qualitative assessment of groundwater quality changes
- Identification of potential sources of contamination or deterioration in groundwater quality

3 Study Area

This study was conducted in two regions in Algeria: the Cheliff plain in the northwest and the Mitidja plain in the north (Fig. 2). These regions have distinct climatic and geomorphological contexts and are polluted due to excessive use of fertilizers in their agricultural plains. The Mitidja plain, particularly its eastern part (including the Rouiba and Réghaia regions), is affected by polluting industries, impacting the main aquifers studied in this research. The Cheliff River is distinguished from other wadis in Algeria due to its unique characteristics, originating from the highlands and draining a portion of these elevated areas. Its notable length and significant flow rates further differentiate it. The flow rates are notably influenced by the underlying geological structure of the regions it traverses [22]. The Mitidja plain, located in the northern region of Algeria, forms potential aquifers serving as the primary source of potable water for the central part of the country [23]. The study is important for safeguarding the quality of these waters, which are intended for drinking water supply and irrigation purposes.

3.1 Mitidja Plain

The Mitidja plain is the most significant sub-littoral plain in Algeria. It is situated in the hinterland of Algiers, the capital of Algeria, extending across the territories of Algiers, Boumerdès, Tipaza, and Blida. Encompassing an area of approximately 1,450 km² from Boumerdès in the east to Tipaza in the west (Fig. 2), it stretches over a length of 100 km with a width that varies from 8 to 18 km. This expansive plain is a part of the Algiers coastal basins, designated with code 02 by the National Agency for Hydraulic Resources (ANRH). It gently slopes toward the Sahel and the sea, with an average elevation of 100 m [24].

Geomorphologically, the Mitidja plain is divided into four sub-basins. Surface water outlets are located along the Mediterranean coast (Table 1 and Fig. 2), draining the main river valleys of the area, which belong to the Algerian coastal basin (code 02). Table 1 describes the main characteristics of the four sub-basins, with the largest ones being the Nador and Mazafran sub-basins [25].

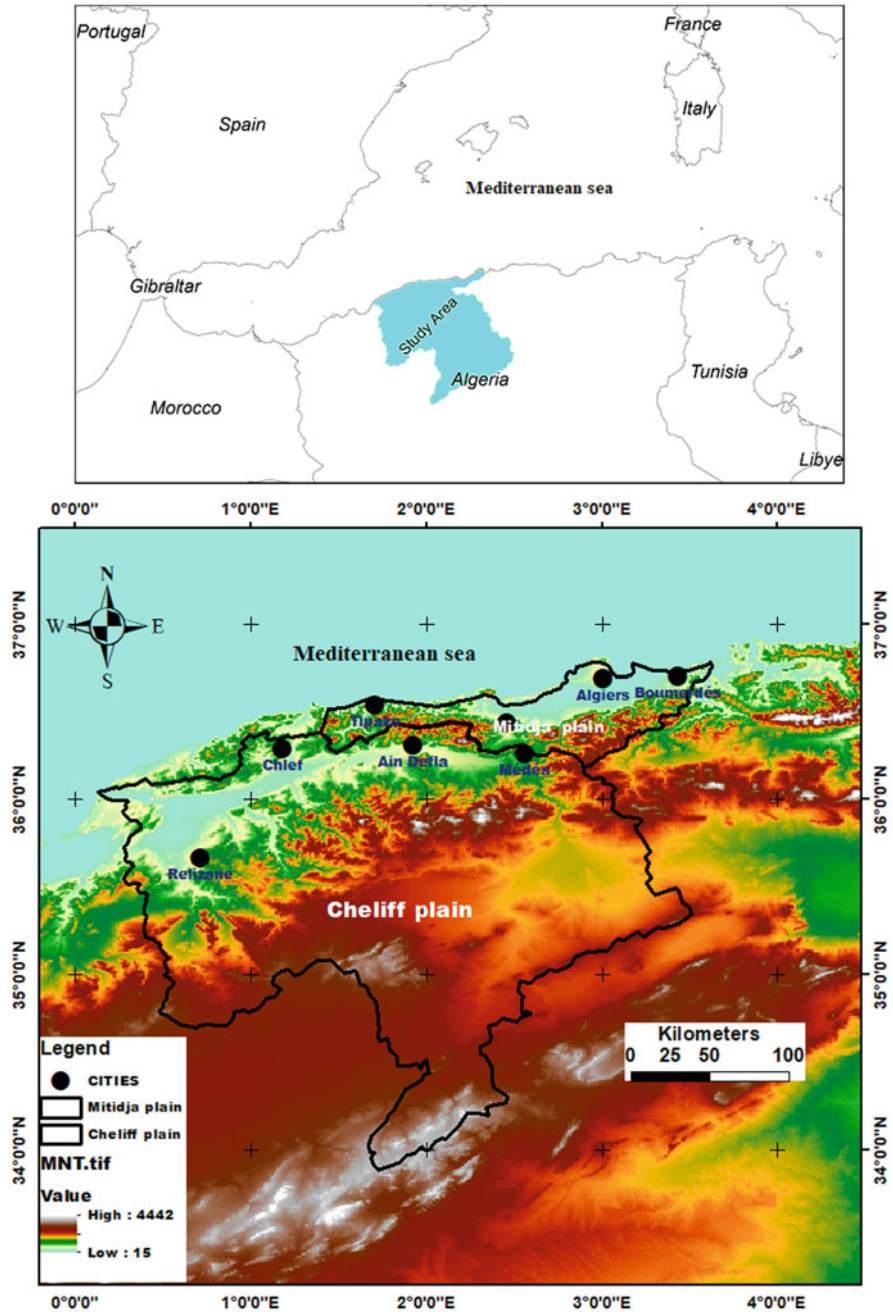


Fig. 2 Geographical location of the study plains (Cheliff and Mitidja)

Table 1 Sub-basins of the Mitidja plain [25]

Basin name	Area (km ²)	Description
Wadi Nador	230	Wadi Nador is the result of the confluence of several secondary wadis
Wadi Mazafran	1,860	About 60% of the basin area is mountainous. Wadi Mazafran is the result of the confluence of wadis Djer, Bouroumi, and Chiffa
Wadi El Harrach	1,270	Wadi El Harrach originates in the mountains of Tablat before emptying into the sea
Wadi Hamiz	380	Wadi Hamiz drains the basin with one of the Réghaia wadi

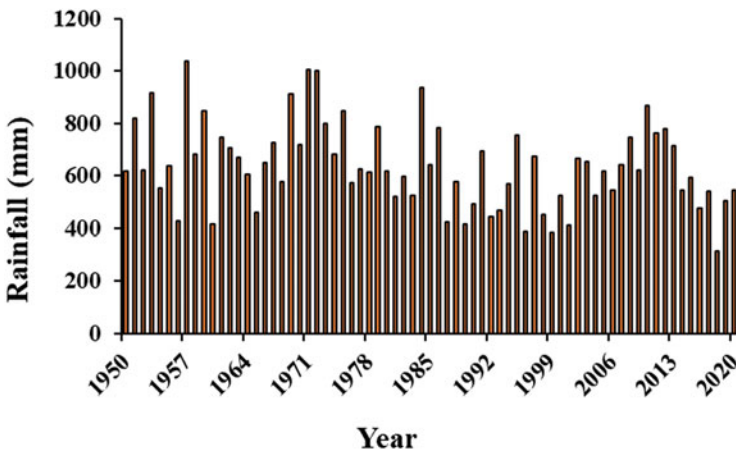


Fig. 3 Evolution of rainfall in Mitidja (1950–2020)

3.1.1 Climate

Between 1950 and 2020, precipitation in the Mitidja plain in northern Algeria exhibited interannual variability. It had a wet season before 1971 lasting nearly 4 years, followed by a prolonged drought period in the region (Fig. 3). Precipitation in the region has significantly declined (see Fig. 3). The Boufarik station recorded 1,006.97 mm of rainfall during the wet season. Typically, resource recovery takes place in November when rainfall exceeds evapotranspiration. Evapotranspiration accounts for approximately 80.13% of the total precipitation for the entire watershed. The Mitidja plain is influenced by the sub-humid Mediterranean climatic regime with continental influences, characterized by rainy and mild winters and hot summers. The study area receives about 640 mm rainfall per year on an average [26].

3.1.2 Hydrography

Hydrologically, the Mitidja plain is traversed by six major wadis that ensure the drainage of the mountainous watersheds of the Atlas Mountains [24, 27]. From east to west, these wadis are Hamiz, Djemaa, El Harrach, Chiffa, Bouroumi, and Djer. Downstream of the Mitidja plain, Wadi Bouroumi and Wadi Chiffa converge to form Wadi Mazafran. Wadi Harrach intersects with Wadi Djemaa near Baba Ali. To the east of Wadi Hamiz flows Wadi Réghaia, which is considered secondary. The wadis mentioned above are largely in hydraulic connection with the Mitidja aquifer, as their water can either infiltrate the aquifer or drain from it. The plain is divided into four river basins: Wadi Nador, Wadi Mazafran, Wadi Harrach, and Wadi Hamiz (Table 1). These wadis originate in the foothills of the Blidean Atlas. The rivers, particularly in their downstream reaches, contribute to the renewal of the alluvial aquifer of the Mitidja before flowing into the Mediterranean Sea.

The piezometric level in the Mitidja aquifer shows an alarming decline between 1990 and the early 2000s. In Mitidja East, a maximum fall of 18.6 m is recorded during low water and 15.9 m during high water, according to National Agency for Water Resources (ANRH) data. Moreover, during this period of groundwater regression, the Mitidja experienced rapid demographic change.

The number of inhabitants nearly doubled between 1987 and 2007, resulting in considerable demand for water [8]. In 2010, the volume of water mobilized exceeded 329 Mm³, with surface water representing 53% and groundwater 28% [8].

The Mitidja region possesses a substantial hydrogeological potential, with access to a vast aquifer system estimated to contain around 500 million cubic meters of water resources. This aquifer is composed of two main segments: the Astian and the Quaternary alluvium. Notably, the Quaternary alluvium, the larger of the two, contributes a significant portion, supplying 295 million cubic meters annually, which accounts for 60% of the total available volume [24, 28].

3.1.3 Water Resources

The groundwater of the Mitidja aquifer supplies drinking water to many localities in the capital as well as several cities in the four wilayas – Algiers, Blida, Boumerdès, and Tipaza – located across large parts of the plain (Fig. 4). They also irrigate tens of thousands of hectares of agricultural land and supply almost to all industrial units.

According to the Hydrographic Basin Agency of Algiers [29], the groundwater resource of the Mitidja is estimated at 328 million m³. This includes the main fields from which the aquifer is tapped: Mazafran I and II, Chebli, Barraki, Haouch Felit, and Hamiz [24].

Alongside the over-exploitation of the aquifer, exacerbated by prolonged drought, the piezometric level of the Mitidja aquifer has shown a continuous decline since 1980. Between 1980 and 2000, there was a significant and continuous drop in groundwater levels, with some areas experiencing declines of up to 30 m in their

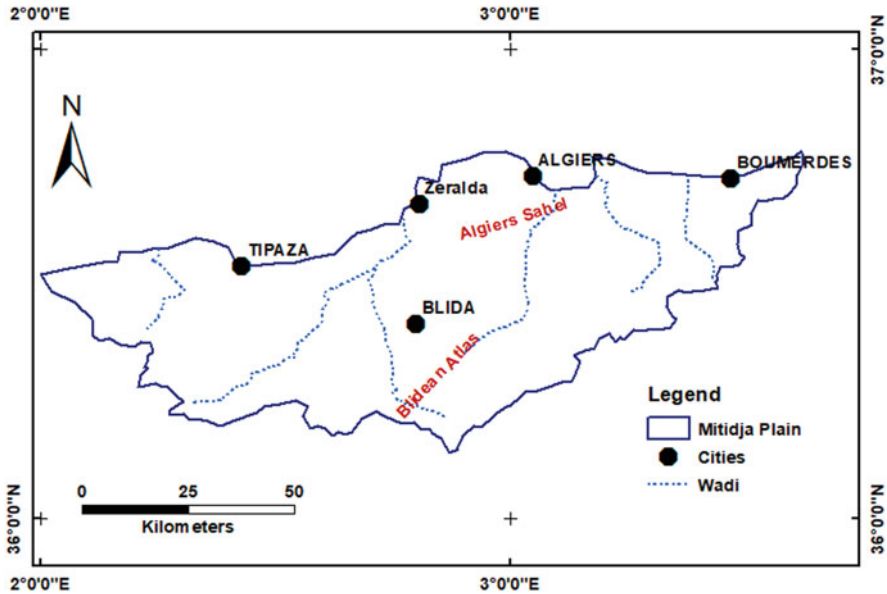


Fig. 4 Mitidja hydrographic region

aquifers. However, from 2000 to 2012, a stabilization of groundwater levels was also observed and reported by Meddi et al. [24]. Several factors may have contributed to this stabilization, including improved water management practices, initiatives to enhance groundwater recharge, potential changes in precipitation and drought conditions, increased awareness of groundwater conservation, technological advances, desalination adoption, research and monitoring efforts, and community engagement. Local geological and hydrological factors also play a crucial role in groundwater dynamics. Understanding these factors is crucial for sustainable groundwater management.

Moreover, the decline in water levels has facilitated the intrusion of saltwater into the eastern part of the Mitidja aquifer [30]. The aquifer of the plain of Wadi Nador in Tipaza serves as a stark example for several reasons: all boreholes tapping this aquifer (sixteen in total) have now been abandoned due to saltwater intrusion affecting the aquifer over a distance of more than 1.5 km from the coast [31].

3.1.4 Mitidja Agriculture

Soils in Mitidja are characterized by low organic matter content, with averages ranging between 0 and 3.5%. In Mitidja, fertilization rates vary widely depending on the type of crop, as detailed in Table 2 [25].

Table 2 Distribution quantities of ammonium nitrate with respect to types of culture in Mitidja ([25]; Open access)

Crop types	Applied amounts (kg/ha)
Vegetable crops	400
Dried vegetables	200
Citrus fruit	1,000
Trees	500
Vineyard	300
Cereals	200
Fillings	100

The total agrarian area (TAA: refers to the total agricultural land area within the plain of Mitidja), which includes both useful agricultural area (UAA) and unproductive land such as uncultivable terrains and structures, is approximately 164,000 ha. The useful agricultural area (UAA) totals around 100,000 ha; 60% of this is irrigated for intensive crops requiring significant water and fertilizer inputs [25]. The remaining land is covered by dry vegetation, where water delivery is solely dependent on rainfall.

3.2 *Cheliff Plain*

The Cheliff plain is located in west-central northern Algeria. The Cheliff-Zahrez hydrographic region (Fig. 2) consists of three river basins: the Cheliff, the Zahrez, and the coastal Dahra. Extending over 43,750 km², the Cheliff basin is the largest hydrographic basin in northern Algeria. This basin is subdivided into three watersheds: the upstream Cheliff basin ending at the Boughzoul dam, the Upper and Middle Cheliff basins, and the Lower Cheliff and Mina basins. The Cheliff valley, which is traversed by the Wadi Cheliff, is situated in the northern part of the Cheliff watershed and occupies 22% of the area in northern Algeria.

3.2.1 *Climate*

The climate of the Cheliff is characterized by hot, dry summers with occasional storms and mild, humid winters. This climate can be categorized as a semi-arid Mediterranean type [32] (Fig. 5). Existing climatic conditions play a crucial role in the hydrological and hydrogeological behavior of the basin. As shown in the data from 1950 to 2020 (Fig. 5), interannual rainfall in the Cheliff basin decreased from the early 1970s to the mid-2000s. Drought conditions reemerged starting in 2019.

The interannual rainfall map for the Cheliff basin illustrates the distribution of rainfall. Specifically, rainfall decreases as one moves inland from the sea, due to the gradual depletion of water vapor in the atmosphere. This happens as air currents lose their moisture while crossing over the mountain ranges [33]. Unusually, the Cheliff plains exhibit a semi-arid continental climate despite their proximity to the sea, being only about 50 km away on average [34]. The climate is notably harsh and has even

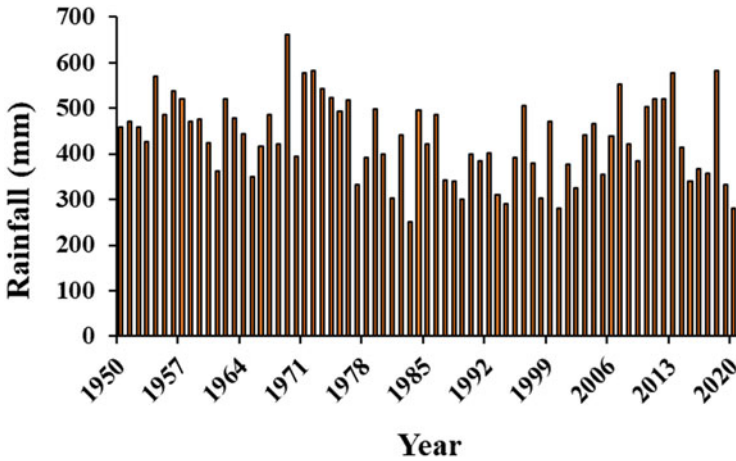


Fig. 5 Rainfall pattern in Cheliff (1950–2020)

been described as a “meteorological curiosity” for its unusual characteristics [35]. The area is called “Four du tell” or “portion of the Sahara lost in the tell.” The temperature in the Cheliff region is significantly higher than in neighboring regions due to several factors, which can include its geographic location, local topography, and prevailing wind patterns. Often situated away from coastal or mountainous areas that typically have more moderate temperatures, the Cheliff may experience a more continental climate characterized by more significant temperature fluctuations.

In general, the average annual rainfall decreases from north to south and east to west. The annual rainfall is marked by strong temporal variability [36]. In the Upper and Middle Cheliff basins (Fig. 6) and the Dahra Mountains, the average annual rainfall exceeds 500 mm. The average rainfall varies between 300 and 500 mm/year in the Upper and Middle Cheliff plains, and between 350 and 400 mm/year in the Lower Cheliff and the Mina basins. The southern basin (Boughzoul) is extremely dry, with an average annual rainfall ranging between 170 and 260 mm/year [36].

3.2.2 Hydrographic Network

The hydrographic network of the Cheliff basin consists of a dense and intricate stream network, primarily composed of temporary watercourses (Fig. 7). The Wadi Cheliff is considered one of the major North African wadis. It is formed by the confluence of two large rivers: Wadi Touil and Nahr Ouassel. It has both the longest course and the highest flow in the region [37].

The Cheliff Wadi flows through a valley that runs parallel to the sea, featuring several meanders. Waters from Ebda and Ras Ouahrane flow into its right bank,

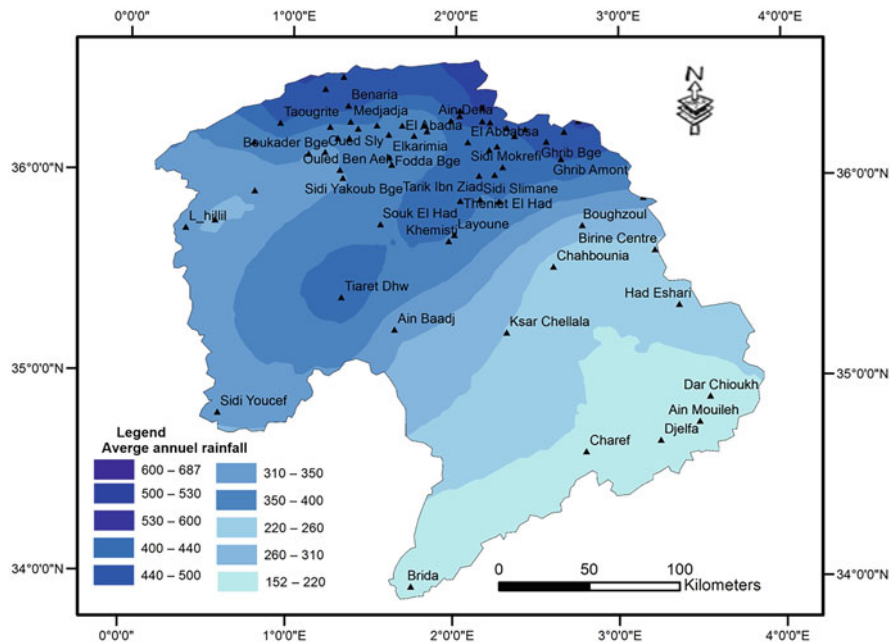


Fig. 6 Spatial distribution of average annual rainfall ([36]; Open access)

while Deurdeur, Harreza, Rouina Zeddine, Fodda, Sly, Rhiou, and Djediouia contribute to its left bank. The important tributary Wadi Mina also joins it further to the west [38]. The layout of the hydrographic network has been shaped by the structural elements that have influenced the region over geological time, particularly during the Quaternary period. The intricate hydrographic network was established due to major geological events that impacted the area and has been modified and reoriented over time due to tectonic evolution.

3.2.3 Groundwater Resources in the Catchment Area (Cheliff)

The Cheliff-Zahrez watershed comprises two distinct regions. In the northern part, it is characterized by the Cheliff valley, which is flanked by the imposing Tellian mountain ranges the Mount of Dahra to the north and the Ouarsenis massif to the south. These majestic mountain chains define the northern boundary of the watershed, showcasing the natural beauty of the region. In contrast, the southern section of the watershed encompasses the Zahrez basin, adding diversity to the landscape. This geographical diversity within the Cheliff-Zahrez watershed creates a unique and captivating environment, showcasing both the rugged charm of the mountains and the allure of the basin.

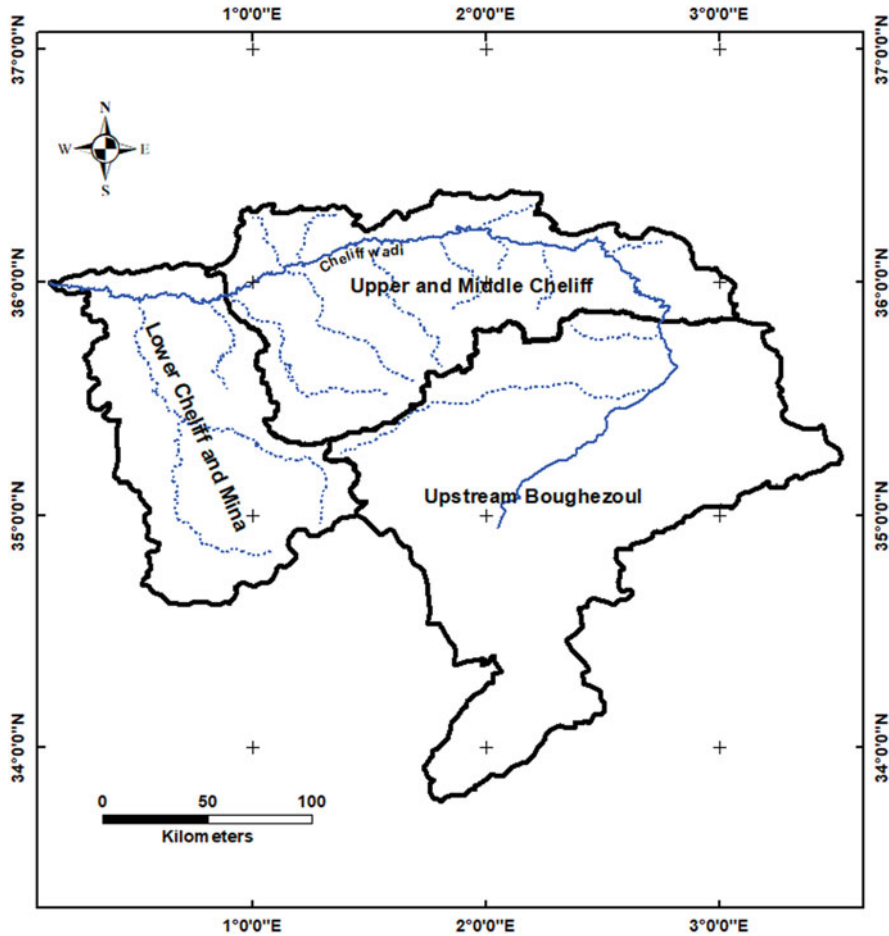


Fig. 7 Chelif hydrographic region

Many geological formations in the area contain groundwater; the oldest of these are attributed to the Jurassic period, while the most recent correspond to Quaternary alluvium. In the northern zone, the two Tellian chains offer limited and unfeasible water resources found in limestone and sandstone formations. These formations are generally underdeveloped and are encased in larger, less permeable geological structures. The Chelif-Zahrez region is home to 42 aquifers, boasting a water supply potential of 225 million cubic meters per year [17].

On the left bank, the groundwater levels are shallow. They vary between 3 and 60 m below ground in the plains and can reach depths of up to 80 m, particularly in the areas of Ain Soltane, Wadi Sly, and Boukadir. The aquifers are also shallow throughout the valley, with an average depth ranging from 10 to 30 m. This confirms that the groundwater accessed by these points originates from Quaternary alluvium

[39]. Water level alone does not indicate groundwater's origin, but it is part of a combination of tools used to determine its source.

Furthermore, the depth-to-water-level map of the alluvial aquifers in the Upper and Middle Cheliff displays a wide range of depths, ranging from 3 to 280 m, as illustrated in Fig. 9. The right bank features areas with deeper aquifers, such as Arib, located north of Khemis-Miliana and extending toward Ain Soltane in the Upper Cheliff aquifer. Additionally, the depths extend to the east toward El Amra in the alluvial aquifer of the Middle Eastern Cheliff. On the other hand, the left bank has shallow aquifer levels, ranging from 3 to 60 m in the plains. Measurements taken from multiple points show that the average depth of aquifers in the shallow valley ranges between 10 and 30 m. The water level or depth range, when studied alongside geological examinations of soil and rock samples, can provide insights into the origin of groundwater. If the depth range of the groundwater aligns with layers identified as Quaternary alluvium through geological studies, it suggests that the groundwater in those depths originates from that period. Essentially, the combination of the depth and the geological composition of that depth helps in identifying the age and origin of the groundwater source.

Madene et al. [39] confirmed these observations. The researcher added that in the area to the west of El Abadia (Fig. 8), depths exceed 80 m. Meanwhile, the maximum depth of 280 m is found in the northeastern part of the alluvial aquifer of Middle Cheliff, near the cities of Ouled Fares and Chattia.

It should also be noted that the groundwater resources in the Chlef region (wilaya) are primarily found in Quaternary alluvium, specifically Pliocene Astian sands, and in sedimentary rocks such as lithothamnium limestone. According to the Directorate of Water Resources, the volume of water extracted and used in the Middle Cheliff plain in 2014 from wells, boreholes, and other sources totaled 25.08 million cubic meters [41].

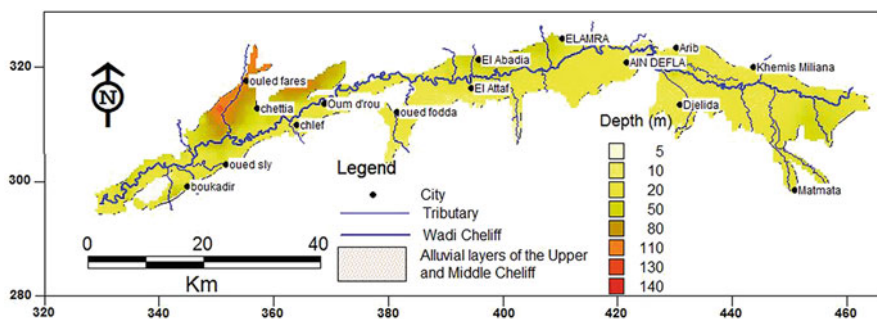


Fig. 8 Depth-to-water-level map of alluvial aquifers in Upper and Middle Cheliff ([39]; Open access)

4 Groundwater Quality and Quantity in the Cheliff and Mitidja Plains

Groundwater is the most heavily used resource in terms of volume. Between the years 1975 and 2000, Algeria experienced an intense and sustained drought, characterized by a 30% deficit in rainfall. This drought negatively impacted the flow patterns of rivers, the water levels in dam reservoirs, and groundwater recharge rates. These effects had serious repercussions on all socio-economic activities in the country. The main aquifers in the northern part of the country are currently being over-exploited, resulting in a decrease in the static water level, a reduction in available resources, and, most concerning, a deterioration in water quality that renders them unusable. Significant drawdowns in piezometric levels, exceeding 1 m per year in some cases, have been observed in numerous wells. Additionally, water quality has deteriorated in certain aquifers, particularly those located along the coast, such as the Mitidja and Annaba aquifers, due to marine intrusion [16, 42, 43]. Groundwater drawdowns have also been observed in the neighboring country of Morocco, where Del Vecchio and Kuper [44] have reported similar findings.

The renewal of this resource depends on aquifer recharge, which in turn is influenced by rainfall and evapotranspiration [44, 45]. An increase in evaporation and evapotranspiration, attributable to rising temperatures, could lead to decreased aquifer recharge and directly impact both the level and quality of the aquifers [46, 47].

Several recent studies have shown that climate trends correlate well with variations in groundwater levels [48, 49]. For example, in several regions of Algeria, groundwater levels have fallen by more than 30 m since 1975 due to drought and over-exploitation [24, 33, 42, 50, 51].

In Algeria, urban and industrial effluents are frequently discharged into the environment without appropriate treatment. These effluents are primary sources of water quality degradation, affecting both surface and groundwater. Agriculture also contributes to this degradation through the excessive use of pesticides, herbicides, and fertilizers, leading to groundwater pollution by nitrates [21, 25, 27, 39, 40, 42, 52–54].

Indeed, the Hydrographic Basin Agency, along with the Water Resources Directorate, Agricultural Services Directorate, and Directorate of Mines and Industry of the Departments of Ain Defla and Chlef, has identified potential sources of water pollution. They found that the plains of the Upper and Middle Cheliff, which include the aquifers of the same regions, have a population of about 817,227 inhabitants. These residents produce approximately 3,827,074 m³ per day of domestic wastewater. This wastewater is treated by two plants located in the Ain Defla and Chlef municipalities, which have a combined treatment capacity of roughly 48,000 m³ per day, or 4.38 million m³ per year. Notably, the discharge point for these plants is the Wadi Cheliff. Nevertheless, because treatment facilities are lacking in other localities, it is estimated that roughly 2,983 tons of nitrogen are discharged annually through domestic wastewater. This poses a significant threat of groundwater

pollution, as indicated by Madene et al. [39]. In addition, more than 616 tons of household waste are deposited daily at two Technical Landfill Centers (TLC) located in the municipalities of Ain Defla and Chlef. These centers are particularly intended for municipal solid waste from the city of Ain Defla. Waste is also deposited at other unregulated sites. While the number of landfill sites is relatively limited and the volume of waste is fairly average, there still exists a risk of pollution. This is because the waste contains high concentrations of organic matter.

It has been estimated that agri-food activities generate the largest pollutant load in this region, measured at 12,191,796 inhabitant-equivalent. This is followed by industrial manufacturing activities, which contribute a load of 1,564,975 inhabitant-equivalent. Breeding is generally a practice reserved for private individuals in this area. Farmers commonly use livestock discharges as fertilizers, producing approximately 611 tons of nitrogen annually. This results in a significant pollutant load, particularly in the municipalities of Chlef, Ouled Fares (Middle Cheliff), and Djelida (Upper Cheliff). Other affected areas include Djendel, Bir Ouled Khelifa, Ain Soltane, and Ain Defla (Upper Cheliff) [39].

4.1 Cheliff Plain

The Cheliff plain predominantly relies on groundwater from the alluvial aquifer for irrigation purposes. This has led to a high demand for water and a consequent significant decline in groundwater quantity and quality [55]. Excessive mineralization of this water often results in soil salinization, which severely limits crop yields as the water does not always meet irrigation standards (Fig. 9).

According to a study by Abdelbaki et al. [56] on the application of GIS in evaluating groundwater quality in the Lower Cheliff plain, they discovered several key findings. First, the coarse alluvium of the Lower Cheliff plain constitutes a significant aquifer, which is accessed through multiple boreholes. Second, while the aquifers contain fresh water, the surface layers of very fine formations – such as clays and silts – contain salty water at shallow depths. Lastly, they revealed that the groundwater in the Lower Cheliff plain is largely non-drinkable. The composition of this water is influenced primarily by the geological features of the region. Additionally, agricultural and industrial activities and wastewater discharged directly into the wadis contribute significantly to the chemical composition of the groundwater in this area.

In a study examining the evolution of hydrochemical quality of groundwater in the Upper Cheliff plain of Algeria, Achour et al. [57] discovered that nitrate concentrations range from 0 mg/l to 245 mg/l. These levels are significantly higher than the World Health Organization [58] standards, which are set at 50 mg/l.

The increase in nitrate concentrations has been progressive from the end of 1993 to the beginning of 2003, mainly affecting the front and center of the plain. Starting in the latter part of the year 2008, however, the nitrate contamination became more

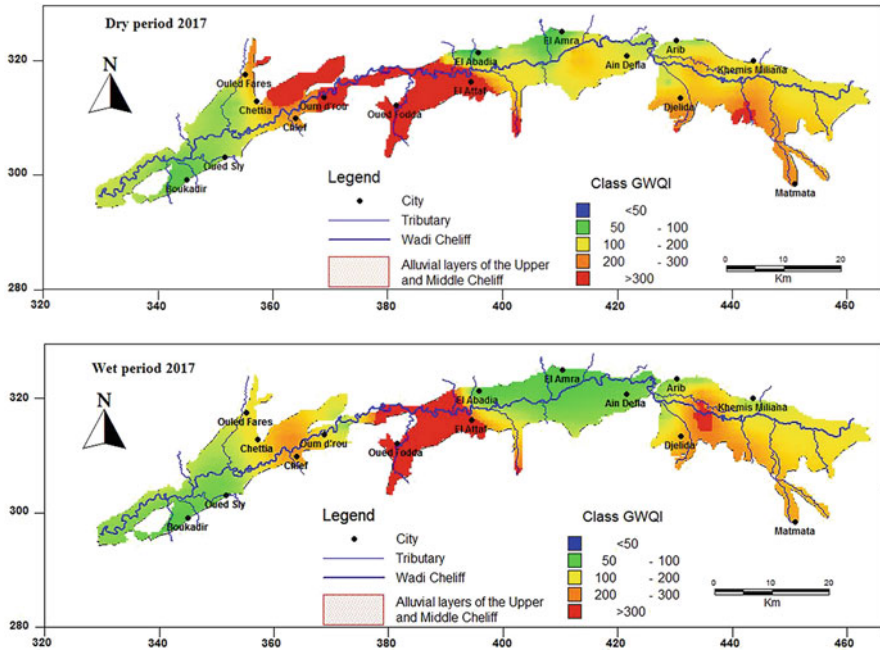


Fig. 9 Index map of the groundwater quality (GWQI) in the Upper and Middle Cheliff alluvial aquifers in 2017 ([40]; Open access)

significant and spread across the entire plain. Several factors could contribute to this excess. These may include the nitrification of organic nitrogen, leaching of nitrates from affected soils, use of chemical fertilizers, or discharges from local communities.

Bouchenouk [55] demonstrated that the chemical quality of water in the Boukadir alluvial aquifer, located in the western part of the Middle Cheliff basin, was of poor quality. This is primarily due to high salinity, which is influenced by both the existing lithology of the aquifer and prevailing climatic conditions. It is also noted that the evolution of nitrate concentrations for the period 1990–2010 of the alluvial aquifer of the Boukadir plain reflects a progressive temporal degradation of the quality of this water intended for consumption and/or irrigation. Regarding the environmental aspect, investigations into pollution sources in the Boukadir plain have revealed high levels of nitrate contamination, which are primarily of agricultural origin.

In a study on the geochemical characteristics of groundwater used for irrigation in the Cheliff plains, Bouzada [59] found that over 50% of the boreholes in all three plains had an electrical conductivity (EC) exceeding 2.25 dS/m, making them unsuitable for irrigation. However, only five boreholes – three in Lower Cheliff, one in Middle Cheliff, and one in Upper Cheliff – had sodium adsorption ratios

(SAR) that exceeded the threshold of 15 meq/l. Water in the Cheliff region tends to precipitate as calcite-gypsum, affecting the calcium ion levels and subsequently increasing SAR. When the waters from the Middle and Upper Cheliff are diluted, instead of making them safer, they can become more problematic. This is because of the potential increase in residual alkalinity. If these waters accumulate in the soil, they can be harmful. In contrast, Lower Cheliff waters present the highest risk, particularly in terms of SAR values. Understanding the geochemical evolution of these irrigation waters is crucial for predicting their impact on soil quality.

Gharbi [60] conducted a study assessing and mapping groundwater quality in the Upper Cheliff plain. He found that most of the study area is characterized by poor to medium quality water. A significant decline in water quality was observed, attributed to the gradual increase in levels of chlorides, nitrates, and sulfates. Gharbi's results also highlighted that groundwater quality deteriorates from the north to the south of the plain. However, the western part of the area exhibits relatively good water quality.

Meddi et al. [24] conducted a study on the impact of reduced rainfall on groundwater resources in the Cheliff-Zahrez basin. Meddi et al. [24] found that over the last four decades, diminished rainfall has led to a decrease in the volume of water stored in dams. Consequently, this has resulted in the over-exploitation of groundwater resources, particularly for agricultural purposes. This shows that climate variability and groundwater levels are closely interconnected, mainly due to fluctuations in precipitation. These variations have had a negative impact on the management of groundwater resources and have led to declining groundwater levels globally.

A study by Touhari et al. [61] investigated the evolution of nitrate ions from 2002 to 2008 in the Upper Cheliff aquifer. The study found that nitrate levels were consistently higher during the high-water season compared to the low water season. Notably, a spike in nitrate levels was observed during heavy rainfall in April, which is likely due to leaching from agricultural lands. The campaign in 2004 recorded maximum nitrate levels of 280 and 260 mg/l, significantly exceeding both WHO and Algerian standards of 50 mg/l. The researchers concluded that the high levels of nitrate pollution in the groundwater can primarily be attributed to various sources, including agriculture, livestock, and urban practices like the disposal of domestic and industrial waste.

Bouderbala [62] evaluated the suitability of groundwater for drinking and agricultural uses in the plain of Upper Cheliff. The study found that the concentration of most chemical constituents exceeds WHO standards, largely due to various sources of pollution. As a result, the groundwater is severely contaminated and deemed unsuitable for drinking purposes. However, the study indicates that groundwater is generally suitable for irrigation in most parts of the plain. Factors affecting the water's mineralization include the lithology of the aquifer, anthropogenic influences such as urban sewage discharge and fertilizer use, and natural processes like evaporation due to the semi-arid climate.

Further, Madene et al. [40] conducted a study to evaluate the groundwater quality in the plains of Upper and Middle Cheliff, located in Northwestern Algeria, and its suitability for both irrigation and consumption. The study found that the water quality poses a health hazard for humans, necessitating appropriate treatment before use. However, the water was generally found to be safe for irrigation, with exceptions for a few sensitive crops such as garlic, onions, beans, and strawberries.

4.2 *Mitidja Plain*

The alluvial aquifer of the Mitidja in Northern Algeria is a critically important underground reservoir that has experienced significant deterioration in recent years in terms of quantity and quality. Mimouni et al. [63] highlighted the pollution of this aquifer by nitrates. This pollution has been confirmed by subsequent studies conducted afterward by Hadjoudj [54], Ait Ouali [64], Yahiaoui [65], and Djoudar-Hallal [66]. Additionally, Khouli and Djabri [67] conducted an in-depth study over several years, attributing the presence of nitrates in the waters of the alluvial aquifer of the Mitidja to the excessive use of nitrogen fertilizers in agriculture [68].

In addition, Hadjoudj et al. [54] conducted a study on the physico-chemical characterization of groundwater in the Mitidja plain for the period from 2004 to 2007. They found that the concentrations of most physico-chemical characteristics met Algerian water consumption standards. However, nitrate concentrations were significantly higher than the threshold (50 mg/l). Based on these findings, they identified three potential sources of nitrate contamination:

1. **Agricultural origin:** The Mitidja is primarily an agricultural region. In its western area, the fertilization rate has reached nearly 400 kg of nitrogen per hectare.
2. **Urban origin:** Urban discharges channeled by the public sewerage system are not fully treated. Consequently, they are released into the wadis that traverse the plain. Since the aquifers in the Mitidja are alluvial, part of this polluted water infiltrates the underlying aquifers.
3. **Industrial origin:** The eastern region of the Mitidja has substantial industrial activity. Industrial effluents are discharged directly into the wadis without prior treatment. This has led to high levels of nitrate pollution, with concentrations averaging 120 mg/l. This is largely due to the intense socio-economic pressure exerted on this part of the Mitidja by industrial, agricultural, and urban activities.

Sengouga et al. [69] found that groundwater pollution and its spatial distribution in the Mitidja aquifer coincided with agricultural zones in most contaminated areas. The research indicates that nitrate levels in the aquifer have risen due to the intensification of agriculture in the region. Without preventive measures, this could lead to further deterioration in groundwater quality and results in environmental consequences. According to the final report from the Deutsche Gesellschaft

für Internationale Zusammenarbeit (GIZ), or the German Agency for International Cooperation, published in 2016, an assessment of groundwater quality revealed an enrichment of nitrates in some regions, including the Mitidja aquifer. The main causes are the leaching of nitrates from soils, which originate from organic and mineral fertilizers not utilized by plants.

Furthermore, Zamiche et al. [70] demonstrated that the groundwater in the Mitidja plain exhibits high salinity. This can be explained by the EC values, which remain below the threshold of 3 dS/m, and the average SAR value, which stays below 5 meq/l. Overall, the high salinity is primarily due to the dissolution of geological formations and the evaporation of the groundwater. A variable influence of marine invasion is also noted, particularly in eastern Mitidja.

In summary, several studies have highlighted the critical issues facing the Mitidja aquifer in North Algeria:

Nitrate contamination: Zamiche et al. [68] found that intensive fertilizer use and poor soil retention have made the central part of the Mitidja aquifer highly vulnerable to nitrate contamination. This contamination has exceeded safety guidelines set by the World Health Organization.

Hydro-geochemical factors: Zamiche et al. [23] identified seawater intrusion and nitrate contamination as key factors affecting the aquifer's hydrochemical evolution, indicating a combination of natural processes and human activities contributing to groundwater degradation.

Groundwater depletion: Bouderbala [71] reported a significant drop in groundwater levels between 1974 and 2010, primarily attributed to reduced rainfall and over-exploitation. Coastal areas also suffer from high salinity due to seawater intrusion. Also, there are elevated nitrate concentrations attributed to agriculture and urban pollution.

Widespread nitrate pollution: Khouli et al. [25] noted disparities in nitrate levels across the entire aquifer. Nitrate concentrations rise during recharge and irrigation periods due to leaching from agricultural soils and the use of nitrogenous fertilizers, particularly in market gardening.

Growing threats: Algérie Presse Service [72] reported that the Mitidja aquifer faces severe threats from pollution and increased water withdrawals, driven by demographic and economic growth. Over-exploitation, especially for agriculture and drinking water supply, has led to surface aquifer drawdowns and marine intrusion in certain areas.

Pollution sources: Integrated Water Resources Management (AGIRE) found that nitrate concentrations in the groundwater significantly exceed standard limits and are primarily attributed to agricultural activities, urban discharges, and industrial activity. The eastern Mitidja region is particularly affected, with direct effluent discharges into wadis without treatment.

Quantitative and qualitative pressures: AGIRE's analysis highlighted that the aquifer faces both quantitative and qualitative pressures. Water withdrawals for various purposes are lowering the aquifer level, leading to marine intrusion, which jeopardizes water quality for drinking and irrigation.

It is evident that the Mitidja aquifer faces a complex set of challenges, including pollution, over-extraction, and seawater intrusion, which collectively threaten the region's groundwater quality and availability. Addressing these issues will require a comprehensive approach involving regulation, sustainable agricultural practices, and improved wastewater management to safeguard this vital resource.

4.2.1 Marine Water Intrusion in Coastal Aquifers (Mitidja Plain)

Over the past two decades in Algeria, there has been a marked increase in saltwater intrusion from the sea, predominantly due to the prolonged droughts plaguing the north. This led to excessive and unchecked water extraction to cater to rising demands. At present, every region spanning Algeria's extensive 1,200 km coastline faces the threat of this saline invasion. Multiple sites along the coast have reported groundwater contamination, with the central areas, including the plains of Wadi Nador, Wadi Mazafran, and the Bord El Bahri region, being significantly impacted [73].

Research conducted by Mania et al. [74] between 1981 and 1984 revealed a concerning trend of marine saltwater intrusion into the aquifer. This issue was attributed to the large-scale pumping primarily set up to address the water requirements of Algiers East. This included fulfilling the potable water needs of its residents and catering to several smaller industries. In addition, the aquifer was tapped to irrigate surrounding horticultural and tree-farming areas. Their findings indicated polluted regions at the Hamiz wadi mouth (Stambul) and around Bordj-El-Kiffan-Verte Rive. The saline spread could stretch up to 1 km inland, fluctuating with the aquifer's hydrodynamic conditions, notably during water-scarce periods.

Several hydraulic issues could be mitigated through the use of artificial groundwater recharge. Over-exploitation has dangerously lowered the water level of the Mitidja aquifer, even causing several instances of land subsidence in the region. Moreover, intensive pumping has led to the intrusion of saltwater into the coastal aquifers of the Wadi Nador plain, causing the saltwater wedge to continually expand within the aquifer. Now is a relevant time for Algeria to start using this water storage method, especially since it does not require significant material resources. Artificial groundwater replenishment could serve as an alternative solution to harness the billions of cubic meters of water that currently flow into the sea and cannot be captured through dam construction. This approach could also mitigate the drawdown of groundwater levels, which occurs due to the insufficient mobilization of surface resources.

Bouderbala et al. [75] conducted a study to understand the salinity levels of groundwater in the Nador coastal aquifer in Algeria. By analyzing high and low groundwater samples from 2013, they aimed to track the changes in groundwater hydrochemistry from the point of recharge to the coastal area. Their findings corroborated that the increased salinity stemmed from marine intrusion into the aquifer, extending approximately 2 km inland.

The findings by Khoualed and Remili [30] and Bechkit et al. [76] regarding marine intrusion along Algeria's coast are alarming. The evidence of lowering water tables, shifts in groundwater flow, and increasing mineralization toward the sea highlights a significant threat to the region's coastal aquifers. Bechkit et al. [76] discovery of clay's protective role against saltwater intrusion is intriguing and could inform future strategies for managing this issue.

The overall situation of coastal groundwater reserves in Algeria is deeply concerning. The existing shortfalls in water supply compared to demand are likely to worsen due to saltwater intrusion and pollution from various human activities. Despite dam construction and desalination efforts, the projected 1 billion cubic meter water shortfall by 2025 is alarming, especially for regions like Chelif-Zahrez and Algiers-Soummam-Hodna.

Certainly, urgent and comprehensive measures are needed to address these challenges. This includes improving water resource management, reducing pollution, and exploring innovative solutions to mitigate the impact of marine intrusion on Algeria's coastal aquifers. Solving these issues is crucial for ensuring a sustainable water supply and protecting the environment and the livelihoods of those dependent on these vital water resources.

Finally, even if in the medium term, demand seems to be satisfied, the fact remains that a rigorous demand management policy is necessary. This can be achieved through several key measures:

1. **Construction of wastewater treatment plants and adherence to discharge standards:** To safeguard water quality, investing in the construction of wastewater treatment plants is imperative. Strict adherence to standards for the discharge of treated water into the receiving environment is essential. This ensures that the water returned to natural sources is safe and clean. Moreover, regulating agricultural activity in the vicinity of boreholes intended for human consumption is crucial to prevent contamination.
2. **Artificial groundwater recharge:** Utilizing artificial groundwater recharge can address various hydraulic problems. This approach offers a sustainable alternative to prevent the loss of billions of cubic meters of water that currently flows into the sea. By recharging groundwater artificially, we can bolster water resources and reduce wastage.
3. **Immediate closure of heavily contaminated boreholes and wells:** Boreholes and heavily contaminated wells should be promptly shut down to prevent further groundwater pollution. This action is critical for protecting the health of those dependent on these water sources.
4. **Cessation of operations in vulnerable areas:** Ceasing water extraction operations in areas vulnerable to intrusion, such as regions susceptible to saltwater intrusion, is essential. This proactive step helps maintain the integrity of freshwater aquifers.
5. **Promotion of micro-irrigation:** The widespread adoption of micro-irrigation techniques can significantly reduce water consumption in agriculture. This efficient method optimizes water use while sustaining crop yields.

6. **Piezometric measurement campaigns:** Regular piezometric measurement campaigns are essential to monitor groundwater level fluctuations. These measurements provide valuable data for assessing the health of aquifers and the impact of water extraction.
7. **Chemical and geophysical analyses:** Conducting chemical and geophysical analyses is vital for monitoring and locating the freshwater–saltwater interface within aquifers. This information guides effective management strategies to combat saltwater intrusion.
8. **Study and modeling of saltwater intrusion:** In-depth studies and modeling efforts are necessary to understand and predict the spread of saltwater intrusion into freshwater aquifers. This knowledge enables the development of targeted strategies to mitigate this critical issue.

In summary, a comprehensive approach that encompasses these measures is imperative for sustainable groundwater management. By implementing these strategies, we can ensure the availability of clean and secure groundwater resources for future generations while addressing the challenges posed by increasing demand and environmental pressures.

5 Conclusion

The water deficit of the last few decades has negatively affected agricultural production as well as surface and groundwater resources in the Cheliff and the Mitidja plains of Algeria. The alluvial aquifers of the Mitidja and Cheliff are very important groundwater reservoirs in the country that have suffered a great deal of deterioration in recent years both quantitatively and qualitatively.

Furthermore, it has been observed that nitrate concentrations consistently exceed established norms. This pollution primarily arises from agricultural activities and urban discharges channeled through the public sewage system and ultimately discharged into the wadis traversing the plain. At the same time, the eastern region of the Mitidja has a very high level of industrial activity whose effluents are discharged directly into the wadis without prior treatment, stressing that this region is the most affected by pollution where nitrate concentrations reach an average 120 mg/l.

Furthermore, the Cheliff plain, primarily dedicated to agriculture, heavily depends on groundwater for irrigating a diverse range of crops, including market gardening, orchards, and even supplementary irrigation for cereals. Besides the challenge of ensuring an adequate water supply, the quality of this groundwater does not consistently meet irrigation standards. Excessive mineralization of the water frequently results in soil salinity issues, significantly hampering crop yields.

6 Recommendations

To address the challenges of water resources in Algeria, a multifaceted approach is needed:

- **Water resource management:** Implementing sustainable water resource management practices is essential. This includes efficient use of available water resources, adopting modern irrigation techniques, and regulating groundwater extraction to avoid further depletion.
- **Pollution control:** Stringent measures should be taken to control pollution sources, particularly agricultural runoff and untreated industrial discharges. Implementing proper wastewater treatment before discharge is crucial.
- **Agricultural best practices:** Encouraging sustainable and eco-friendly agricultural practices can play a pivotal role in diminishing the influx of pollutants into the water system. This encompasses judicious application of fertilizers and chemicals, effective irrigation management, and the adoption of soil conservation techniques.
- **Water quality monitoring:** Regular monitoring of water quality is essential to track changes and trends. This information can guide decision-making and help identify areas where intervention is most urgently needed.
- **Public awareness:** Raising awareness among the public, industries, and agricultural communities about the importance of water conservation and pollution prevention can encourage everyone to take responsible actions.
- **Legislation and enforcement:** Enforcing water quality regulations and holding industries and individuals accountable for pollution is crucial. This may involve setting and enforcing limits on pollutants in water sources and imposing penalties for non-compliance.
- **Research and innovation:** Investing in research and innovative technologies for water treatment, pollution prevention, and efficient water use can contribute to more sustainable water management solutions.

Addressing these challenges requires collaboration between government agencies, industries, agricultural sectors, researchers, and communities to ensure the long-term health of the Cheliff and Mitidja plains' water resources and agricultural productivity.

Additionally, to bridge the whole research gap in the topic, the future research should focus on:

1. Identify the specific pollutants in the aquifers
2. Determine the sources of these pollutants
3. Track the temporal trends of pollutant concentrations
4. Assess the health and environmental risks posed by the polluted aquifers
5. Propose and test pollution mitigation strategies
6. Evaluate the sustainability of water management considering population and industrial growth
7. Engage local communities for better insights and sustainable practices

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