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Impact of overexploitation of groundwater along the irrigated perimeter of Tadla, Oum Errabia Basin, Morocco

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ABSTRACT

Groundwater is one of the most important natural resources used for many reasons among which we can cite first and foremost drinking, industry, and agriculture. Understanding spatial and temporal variations in groundwater levels throughout an aquifer is essential for sustainable development and management of groundwater resources. The objective of the present study is to analyze the spatial and temporal variations of groundwater levels in an irrigated perimeter of basin Oum Errabia in Morocco. The present environmental impact of over-exploitation on groundwater manifests as drops in groundwater level, reduction in or cessation of spring discharge, saltwater intrusion, and overall deterioration of water quality. The socio-economic impacts are the result of reduced water quality and quantity. The results obtained in this study show that the problem of low piezometric levels in the water table is the direct consequence of overexploitation, the types of techniques used for irrigation, and faulty operation of the management system, which has led to serious impacts in soil and environment. Analysis of variations in piezometric levels showed a significant reduction over time, down to a depth of 4 m, and that the most exploited zones are those far from the river about 10 km. As soon as one moves away from the river, the exploitation of groundwater intensifies.

Keywords: Groundwater; Overexploitation; Impact; Pollution; Management

1. Introduction

The ministry of equipment, transport, logistics, and water of Morocco has made the development of the water sector a priority and a paramount strategic choice. This sector, which constitutes major support of economic and social development, faces two essential challenges. The first challenge is the depletion of water resources due to the rising demand for water, and the second challenge is the degradation of these resources by anthropic activities [1].

The preservation of water resources has become one of the fundamental issues of our time since drought; overharvest and pollution due to population growth and economic development increasingly threaten the quantity and quality of this vital resource. The growth in population and the development of urban agglomerations, industrial units, and cultivated land have resulted in a deterioration in the quality of groundwater and a significant decrease in water reserves, which are sometimes the only resource available to feed the population.

With approximately 107,000 ha irrigated of the perimeter, the irrigated perimeter of Tadla is one of most important perimeters in Morocco [2]. Its first set up in water dates back to 1936, and remarkably fertile soil, and prolific water resources have encouraged the installation of hydraulic equipment (dams, canals). However, the hydraulic infrastructure within this perimeter has modified the balance of the groundwater in zones of irrigation [3]. The total number

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of farms in the irrigated zone is 27.916, the majority of which are family-type farms (1994 census) [4].

The Béni Moussa zone in the south receives 69,500 ha of water for irrigation from Bin-El-Ouidane Dam which is regulated. The Béni Amir zone in the north receives about 35,000 ha of irrigation water from a diversion structure erected on the Oum Errabia River in Kasba Tadla. The waters of Oum Errabia are currently regulated by the Mohamed El-Hansali Dam completed in 2001.

In a context marked by water shortage due to recurring dryness [5], groundwater has become a limiting factor for agriculture, industry and human consumption, leading to over-pumping and misuse. Overexploitation has caused deterioration of water quality and a decrease in piezometric levels. This study evaluated the impact of this perilous situation on the quality of both groundwater and soil using piezometric measurements in order to inform management on how to the status of this essential resource. Several studies have looked at the evolution of groundwater exploitation within the irrigated area of Tadla [2]. One such study characterized the pumping of groundwater in Tadla [5], another highlighted the exploitation of groundwater resources used to irrigate the perimeter of Tadla [6].

2. Study area

The Tadla plain (Fig. 1) is in Béni Mellal Province about 200 km south-east of Casablanca. It covers about 3,600 km^2 of the Oum Errabia basin, between the High Atlas in the south and the phosphates plateau in the north. Tadla plain is crossed by the Oum Errabia River about 160 km from east to west, which divides it into two large hydraulically-independent irrigated perimeters: the Béni Amir perimeter

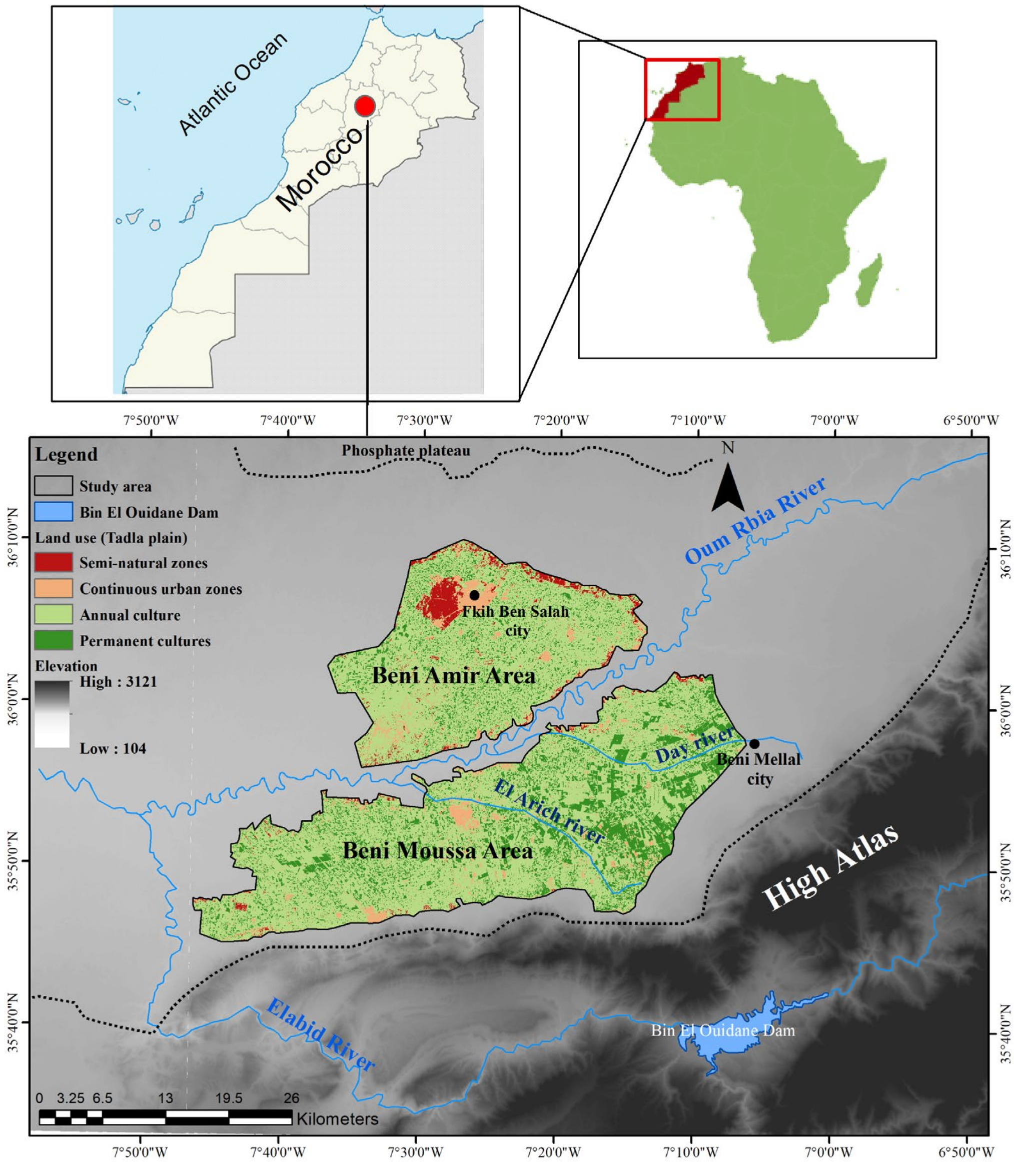

Fig. 1. Irrigated perimeter of Tadla.

in the north and the Béni Moussa perimeter in the south of the Oum Errabia River.

The perimeter of Béni Amir is irrigated from the waters of Oum Errabia (Kasba-Zibania diversion dam) and the perimeter of Béni Moussa from the waters of Oued El Abid (Bin el Ouidane dam). The total area irrigated is about 124,000 ha [3], this irrigation system was created as a solution to frequent and extended droughts and over-exploitation of the water table through human use [7].

The Tadla plain (study area) extends 125 km long and 40 km wide. It is bound on the north by the phosphate plateau (edge of the Cretaceous plateau of Oued Zem), on the south by the Middle Atlas, and between the provinces of Béni Mellal on the east and Azilal on the west. In the east, the basin narrows between the Oued Zem plateau and the Atlas Mountains. In the west, Oued El Abid constitutes the regional limit with Bahira (Province of Kalaa Srarhna).

2.1. Hydrology and hydrological setting

Tadla hydrographic network is characterized by the Oum Errabia River to which the tributaries of Oued Derna and Oued El Abid are added. The Oum Errabia River takes its source from the high limestone plateau of the Middle Atlas, 26 km in the north-east of Khenifra where 40 vauclusian sources comprise its origin. The Srou River, the main tributary of the higher course drains a catchment area, whereas the Oued El Abid River, which is located on the left bank of Oum Errabia, pours its water on the plain. At the entry to the plain, the medium flow of the Oum Errabia River is 10 m^3/s in the summer period. The Oued El Abid River has an annual medium flow of 32 m^3/s. The Water of this affluence is regulated by Bin El Ouidane dams with a total capacity of 1.5 billion m^3 of water [8]. Oum Errabia extends over 160 km in length and divides the plain into two smaller basins that are hydraulically independent.

The aquifer complex of the Tadla plain takes the form of a superposition of several layers which are from bottom to top: the primary water table, the Cenomanian aquifer, the Turonian aquifer, the Senonian aquifer, Eocene aquifers and the Mio-Plio-Quaternary (Béni Moussa and Béni Amir) water tables. In the Tadla plain, as a rule, each aquifer occupies a different geological layer. The hydrogeological system is therefore a multi-aquifer system, with a set of water tables in the Plio-Quaternary fluvio-lacustrine deposits that fill the bottom of the plain of Tadla and Tessaout Aval. An alternation of pre-Quaternary formations, mainly limestone, and marl-limestone which outcrop to the north of the plain and plunge southward below the Plio-Quaternary aquifer deposits. These Middle Cretaceous to Eocene formations overlie bedrock composed of schist and quartzite [9].

The hydrogeological study showed a series of permeable lacustrine limestone lenses set within a marly and impervious matrix. These limestone lenses are separated from each other by real dams under marl soils where the marly facies follows the limestone ones. The sheet drained by the limestone has no way out, and it is put in charge at the downstream of the lens tending to outcrop giving the origin of several existing wetlands even before the impoundment of the Tadla perimeter [4,8]. The Tadla water table is below a sedimentary layer with low permeability. Its wall is located at the top of an Eocene phosphatic formation at a depth of 90 m, corresponding to dolomitic clays. Its thickness increases from north to south. It lies between 50 and 100 m of depth on the major part of its extent. The mobilizable volume of this water table is approximately 190 million m^3 [10].

The groundwater of Béni Moussa occupies an area of 885 km^2 and the aquifer consists of Mio-Plio-Quaternary formations similar to deposits in the plain of Béni Amir. The thickness of these continental formations varies from 150 m to more than 600 m. The mobilizable volume of the water table is 250 million m^3 [10].

The Béni Moussa and Béni Amir water tables are naturally fed by rainfall, infiltration of surface water, and lateral input, and artificially, by the percolation of irrigation water which constitutes the bulk of the recharge in the two aquifers [11].

2.2. Pedology

There are many types of soil in the basin of the Tadla plain. One can easily note sesquioxides soil, calcimagniforms, vertisols, and hydromorphic soil [12].

Under conditions of deterioration, some of the eroded material accumulates near the mountains at the bottom of the valleys, giving some developed soils. This is the case of the soils existing on the low terraces of the Oum Errabia River in recent alluvial zones at the base of the Middle Atlas [11].

The isohumic soil (generally brown grounds and subtropical brown) are the most widespread, and they have the capacity to support the majority of cultures. However, soils with sesquioxides which support only thin cultures are mainly spread over the perimeters of the plain north-west of the town of Fquih Ben Saleh and in the north of Kasba Tadla, in addition to some weak surfaces in the east-north-east and west-south-west of Béni Mellal. Nevertheless, they are calcimagniforms are located along the Oum Errabia River and Derna River.

East of Ouled Jabri area, Ouled Mbark area and in the northern part of Ihrem El Alam area, the soils are characterized by tirsification and support vegetation (vertisols). Between these two zones we found isohumic soils and soil not very developed, resting on conglomerates of alluvial cones. Soils of the hydromorphic type were found in the bottom of valleys or in old poorly-drained marshes (Oued Day, marshes of El Arich) [11].

2.3. Climatological data

The study area has a Mediterranean climate that is arid and semi-arid; the average annual rainfall is less than 350 mm. Variations in spatial distribution of precipitation was noted within the perimeter. In general, precipitation decreases in the west and in the Atlas toward the plain (they are of 560 mm in Béni Mellal). The average annual temperature in the region is 19°C, and annual evapotranspiration is approximately 1,800 mm [4,5].

2.4. Impact of climate change

North African countries face many environmental challenges related mainly to water scarcity, with major economic sectors, notably agriculture, being extremely vulnerable to current climate sensitivity [13–15]. Among the impacts of climate change in the countries of north Africa is the gradual decrease in precipitation from the Atlas chain (north) to the Sahara Desert, the platform of the "Great Erg of north Africa" (south) [16,17].

The southern Mediterranean region faces an increasing demand for water for agriculture, industry, and population growth. And climate change predictions foresee an increase in temperatures, a decrease in rainfall and an increase in the number of severities of extreme events.

The contours of the Mediterranean basin, and particularly north Africa, are vulnerable to flooding. The typical example is the region of Bousalem in north-western Tunisia and Morocco [18–20], and the Majerda Basin (transboundary basin between Algeria and Tunisia). The effect of climate on surface waters in the Tabarka region and in particular in the Sidi El Barrak Dam, the quantity of water from the dam has decreased and is of poor quality. On the other hand, the quantity of sediment has become very siltation of dam. The same phenomenon is observed in Algerian and Moroccan territory [14,21]. In southern Tunisia, another phenomenon is developing stagnation of surface water at collinear dams and lakes due to high evaporation.

The impact of climate change on groundwater in southern Mediterranean countries is widespread and serious. Sensitive areas are directly related to the exploitation of underground water reservoirs. Thus, the combined effects of arid conditions and climate change, leading to increased deterioration of groundwater resources, have been widely observed in many areas of the southern Mediterranean. In addition to the increasing salinity problems in the northern Sahara Basin, water resources in these areas have experienced serious deterioration in quality.

Pollution is another major threat to water resources in these regions, where climate variability and human activities increase the spread of pollution which threaten to increase potential risks to human health. Climatic and environmental variations can influence the development and dynamics of disease and epidemics. Likewise, the continuous exploitation of continental aquifers is not renewable, especially in southwestern Tunisia, Algeria, and Morocco (a subregion in southern Morocco and the region of the Oum Errabia Basin) and causes leakage and interference problems between different aquifer layers. The problem of deterioration and depletion of water resources is not limited to Tunisia, it is also exists in Morocco, Algeria, Libya, Egypt, Jordan, Saudi Arabia, and the United States [16,17,22–30].

In the early 1980s, Morocco suffered long droughts which highlighted the fragility of its water resources. These dry periods had harmful effects on water satisfaction of the socio-economic sectors, in particular agriculture, and on the safeguarding of the terrestrial and watery ecosystems [31].

Climate change is likely to cause a reduction in rainfall and an increase in temperature and frequency and duration of seriously extreme climatic events. These effects are manifested, normally by a hydrous stress emphasis, reducing the volume of mobilizable water, exhausting water underground reserves and deteriorating water quality, among other critical things.

Higher temperatures increase the demand for irrigation water in agriculture, and accelerate snow melt, which consequently leads to the concentration of water flows in winter time and the degradation of water quality by rapid infiltration of irrigation water into the permeable zone [32,33].

Along the Tadla perimeter, climate change has an impact on water resources. After a period of rainfall between the date of impoundment and 1980, the irrigated perimeter of Tadla, like other semi-arid perimeters in Morocco, has made a water scarcity. Also, the drought that took place between 1981 and 1984 was the first in a series of water table years in the irrigated perimeter of Tadla. Indeed, if one considers the volume of the water resources reserved for Tadla by the master line of installation [34], which is about 1 billion m^3/y, it is easy to deduce that in 1981, 1984, 1993, and 2004, the average deficit reached 36%.

3. Groundwater exploitation

The notion of overexploitation of aquifers is at the center of a scientific debate which flourished in the 1970s. This concept was applied primarily in arid and semi-arid climatic states; and particularly in areas where there is irrigation with large scales of developed cultivations of crops. Thus, several authors strongly believe that overexploitation occurs when the exploitations are large or close to the average recharge. However, both harvesting and recharge are difficult terms to define, especially in countries with arid and semi-arid climates [35]. The problem of overexploitation of groundwater is mostly a phenomenon localized in regions that have no other source of supply. We cannot talk about a generalized phenomenon because the rate of exploitation is different from one country to another and from one region to another [36].

Heavy pressure on water resources in some parts of the world results in overexploitation of groundwater. An irreversible exhaustion of the resource requires an abstraction level lower than the recharge volume of the aquifer. Therefore, the level of the aquifer decreases continuously. This is the case in Mediterranean countries, which experience arid to semi-arid climates.

4. Materials and methods

In this work, we used piezometric level data from 2014 to 2017 and the data history of four wells in the Tadla perimeter. These data were mainly collected from the Oum Errabia River and the agency of the hydraulic basin of Oum Errabia (ABHOER), then converted into maps using the geographic information system (GIS) (Fig. 2) to visualize the change in level of the irrigated perimeter of Tadla and to graph these changes over time to get a clearer picture of the exploitation of groundwater. Finally, we discuss the impact of overexploitation on different components of the environment, with a view to provide solutions and criteria for permanent and sustainable management of groundwater resources in light of human demand and climate change.

5. Results and discussion

The Béni Amir water table has been exploited in a rather disorderly way since the substantial volumes pumped by nearly 30,000 farmers are practically uncontrolled. Only the

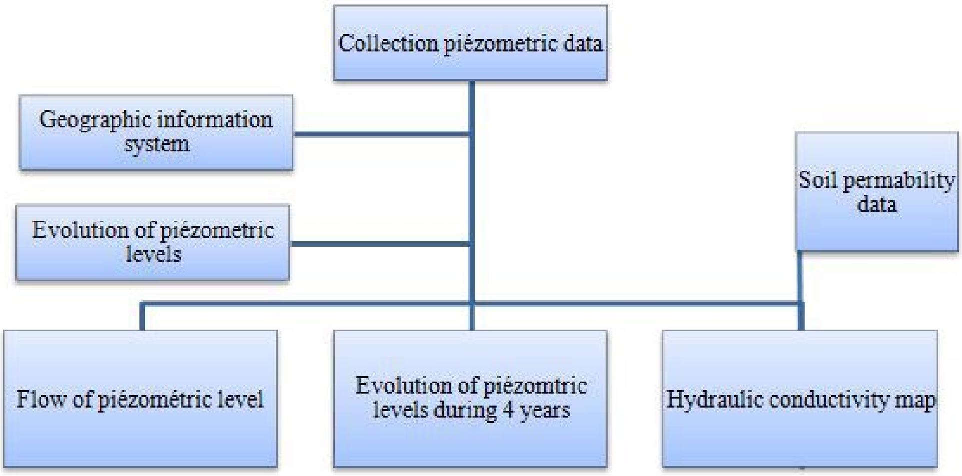

Fig. 2. Flow chart of methodology, 165 mm × 88 mm (96 × 96 DPI).

industrial pumping activity for the Sherif Phosphate Office (OCP) in the Fkih-Ben-Salah region, which will be discussed in detail, has provided new data on the behavior of the water table over a fairly large area and allowed us to total calculate the storage coefficient.

Such intensive pumping reduces the water table piezometric level and consequently decreases evaporation, salinity, and potential danger of pollution due to a sudden increase in rainfall. In addition, the water exumed by the OCP is not recycled, unlike that pumped for agricultural needs; instead, it is exported out of Tadla.

Exploitation of groundwater water resources does not follow strict rules, thus mismanagement and overuse can lead to significant lowering of the piezometric surface in critical areas. In the near future, only in the east regular pumping will be intensified since the irrigation of this zone is mixed. (Bine-El-Ouidane Dam and aquifers of Tadla). Moreover, in this sector, the effect of intensive summer is visible and the piezometric level reaches its minimum at the end of summer.

Nevertheless, a rational exploitation of the water table by pumping, locally under the gravitation of the drains, will have many advantages such as reducing or even suppressing evaporation. Lowering of the piezometric level will prevent crops from untimely rising during rainfall. But the more the area of crops increases, the more the demand for water increases, which makes the transfer of water from Béni Moussa to the perimeter of Béni-Amir or to Bahira [11].

The flow of groundwater generally follows the topography of the study area during four seasons (2014, 2015, 2016, and 2017). According to the piezometric maps in (Fig. 3), it was deduced that groundwater levels change from 1 y to the next because of the overexploitation of certain wells in the region. The map analysis shows that the exploitation of water increased over the years because of the prevailing drought observed in the area of research over the last few years as well as in the areas where there is strong exploitation of groundwater, especially those that are very far from the Oum Errabia River.

After the piezometric level lines, the strong exploitation is clearly noticed in the north, south-east, and south-west and as shown in (Fig. 4). The water table of Béni Moussa indicates the direction of flow of underground water, and that of Béni Amir indicates that the flow is generally south and north. The essential information here is that any type of pollution, regardless of its origin, will contaminate the two layers, as portrayed in the Fig. 4. As far as the direction of the flow is concerned, it was observed that there is a supply from the Oum Errabia River drainage in both layers, so that any contamination along the river will certainly diffuse toward the two water layers.

Fig. 5 showed that the period between 2016 and 2017 experienced strong exploitation in comparison with 2014 and 2015. This remarkable discrepancy is mainly attributable to the lack of rainfall which caused the piezometric level to lower by 4 m. This is clear proof of the intense hydrous deficit that struck the area in previous years.

Four wells were selected on the perimeter, two in the Béni Moussa aquifer and two in Béni Amir (Fig. 6). Well 42/36 is located near the Oum Errabia River and well 695/36 is north of the perimeter far from the river of the Béni Amir aquifer. Well 153/36 is located in the center of the Béni Moussa water table, and well 1618/37 is situated in the south of the perimeter far from the Oum Errabia River.

Originally, the piezometric characteristics of the Béni Amir and Béni Moussa water table were a reflection of natural recharge conditions caused by rainfall. Analysis of piezometric levels showed that well 153 had a stable period (1956–1982) with a slight increase, oscillating between 3 and 5 m until 1998. After this date, there was a remarkable decrease in the piezometric level which dropped 15 m due to excessive exploitation. This decrease, which was reinforced by successive drops in rainfall, finally stabilized around 10 m. As for well 1618 which belongs to the same water table but in the extreme south of the perimeter, piezometric levels maintained stability between 1968 and 1976 and did not exceed 12 m, after a continuous fall by strong exploitation which the level continues to drop, oscillating at a depth of ~20 m.

The analysis of the piezometric evolution of Béni Amir water table showed well 42, which is located south of the water table near of the Oum Errabia River, with a curve that

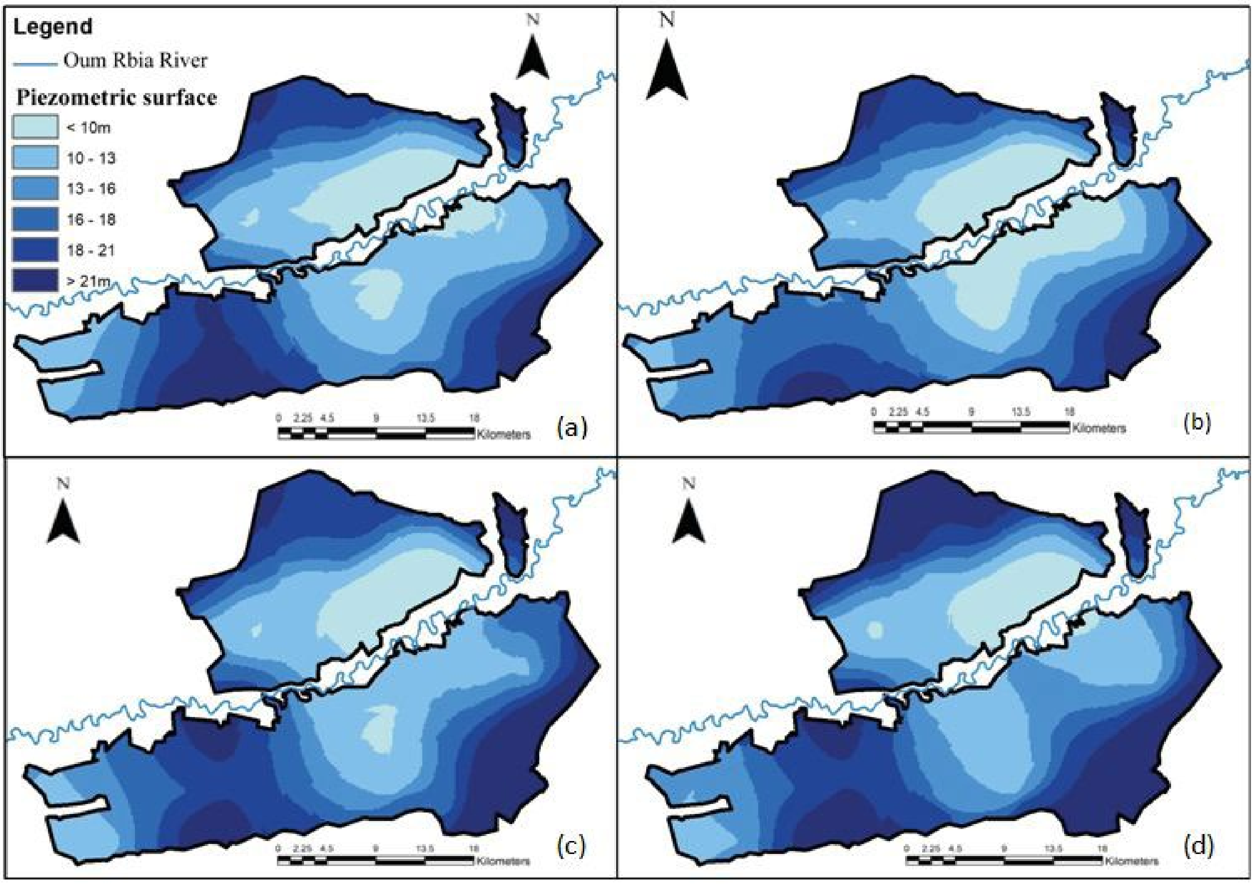

Fig. 3. Piezometric levels map (a) 2014, (b) 2015, (c) 2016, and (d) 2017, 200 mm × 140 mm (96 × 96 DPI).

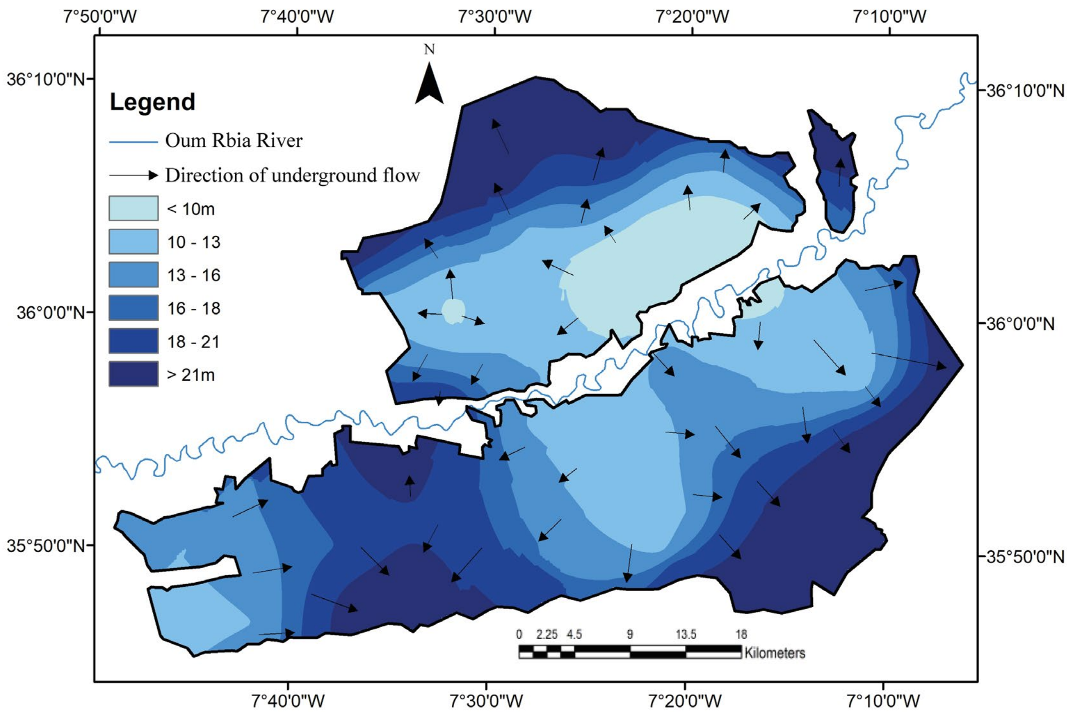

Fig. 4. Groundwater direction flow in the perimeter of Tadla.

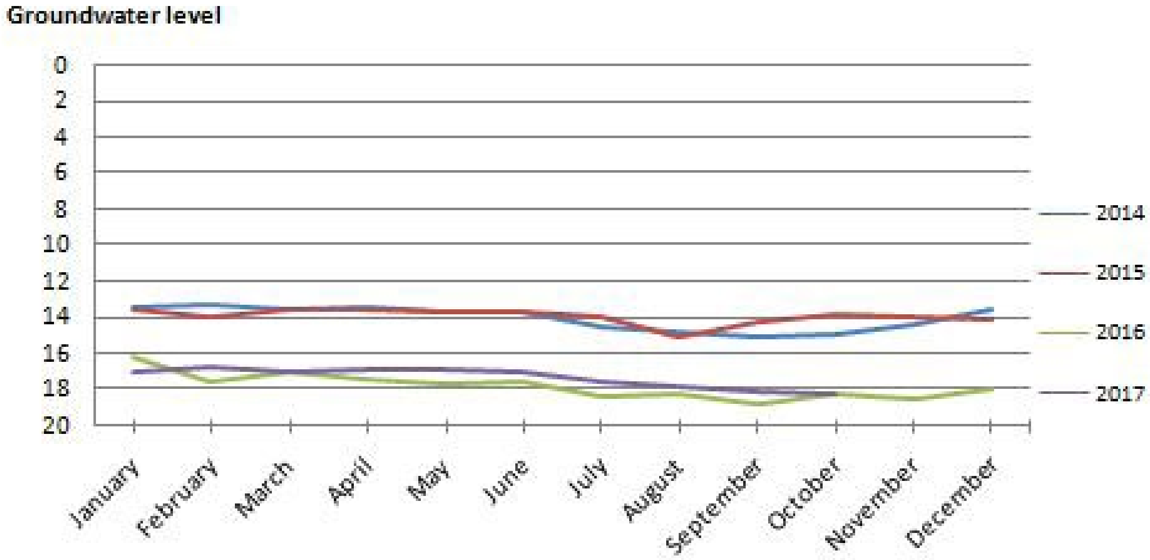

Fig. 5. Comparison of the water table depths during 4 y, 134 mm × 64 mm (96 × 96 DPI).

showed an average decline in the level of water (at least 4 m in some places), and with more than 5 m in other places, especially at the beginning of 1984.

The evolution of the piezometric surface was marked by stability, oscillating only slightly which led us to conclude that that there is the drainage phenomenon from the Oum Errabia River to the well next to it, except in 2009 when the well-experienced a lot of pumping due to a water deficit which extended until 2011. Therefore, the water table provided by the Oum Errabia River explains the slow evolution of the piezometric level even in the years of drought between 1979 and 1984.

Well 695, located at the extreme north of the Béni Amir aquifer, is characterized by a gradual increase in the piezometric level over the years, with a slight increase estimated at 3 m until 1991. After this date and due to heavy exploitation, the piezometric level continued to drop until reaching 20 m depth in 2007. In 2009, as seen in well 42, overexploitation led to a drop in level to more than 25 m depth. Since then, it has oscillated between 15 and 20 m deep.

The years 1959–1983 were marked by an overall decline then stabilization of piezometric levels of the Béni Amir and Béni Moussa water tables, despite the fact that these years were relatively rainy. Good rainfall has reduced the need for irrigation water by about 34 million m^3/y, thus contributing to replenishment of the aquifers of Béni Amir and Béni Moussa.

5.1. Impact of overexploitation

Overexploitation of aquifers occurs when the harvest rate exceeds that of long-term recharge. In practice, however, overexploitation is still mostly related to the consequences of intensive groundwater harvesting. Theoretically, the exploitation of groundwater has the effect of modifying the state of the aquifer and its dynamics, in a more-or-less extensive space. It also modifies the parameters of the aquifer. Indeed, intensive extraction of groundwater is a global problem concerning water resources [37], causing serious environmental issues [38–41], such as a decline in groundwater levels [42–44], seawater intrusion [45,46], land subsidence [47,48], and deterioration of water quality [49–51]. All of the problems caused by intensive extraction of groundwater have a significant impact on the quality of human life, and many solutions to these problems have been proposed and implemented [43,52,53]. Increased deficits in surface water have led farmers to resort to groundwater through the establishment of private wells and boreholes. During the drought of the early 1980s, the average annual rainfall was below 100 mm causing a deficit in water volume in the Bin El Ouidane Dam reaching 70%, as a result, the case subsidized the digging of more than 7,000 wells and the installation of pumping stations. There has been intensive development of pumping in the aquifer due to government encouragement through subsidies. After 1992, drought became a usual phenomenon pushing farmers to find more efficient means of pumping such as drilling rather than digging wells [5].

The quality of water in the aquifer of the plain of Tadla is being degraded by various sources of pollution (domestic, industrial, agricultural), and the Béni Amir aquifer is the saltiest it has been in the last 10 y, saltier than the Béni Moussa aquifer [11].

5.1.1. Decline in piezometric levels

Indeed, if water table recharge is done by rainfall, the lowering of the water is a slow process unlike surface water. When the wells and boreholes pump water from these aquifers, the water level table near the boreholes or wells falls in the form of a depression cone. Depression cones appear only in free aquifers, which are hydraulic flow aquifers with atmospheric recharge [54]. Long-term pumping at high rates will cause an irreversible decline in the water table, reducing discharge to surface water bodies.

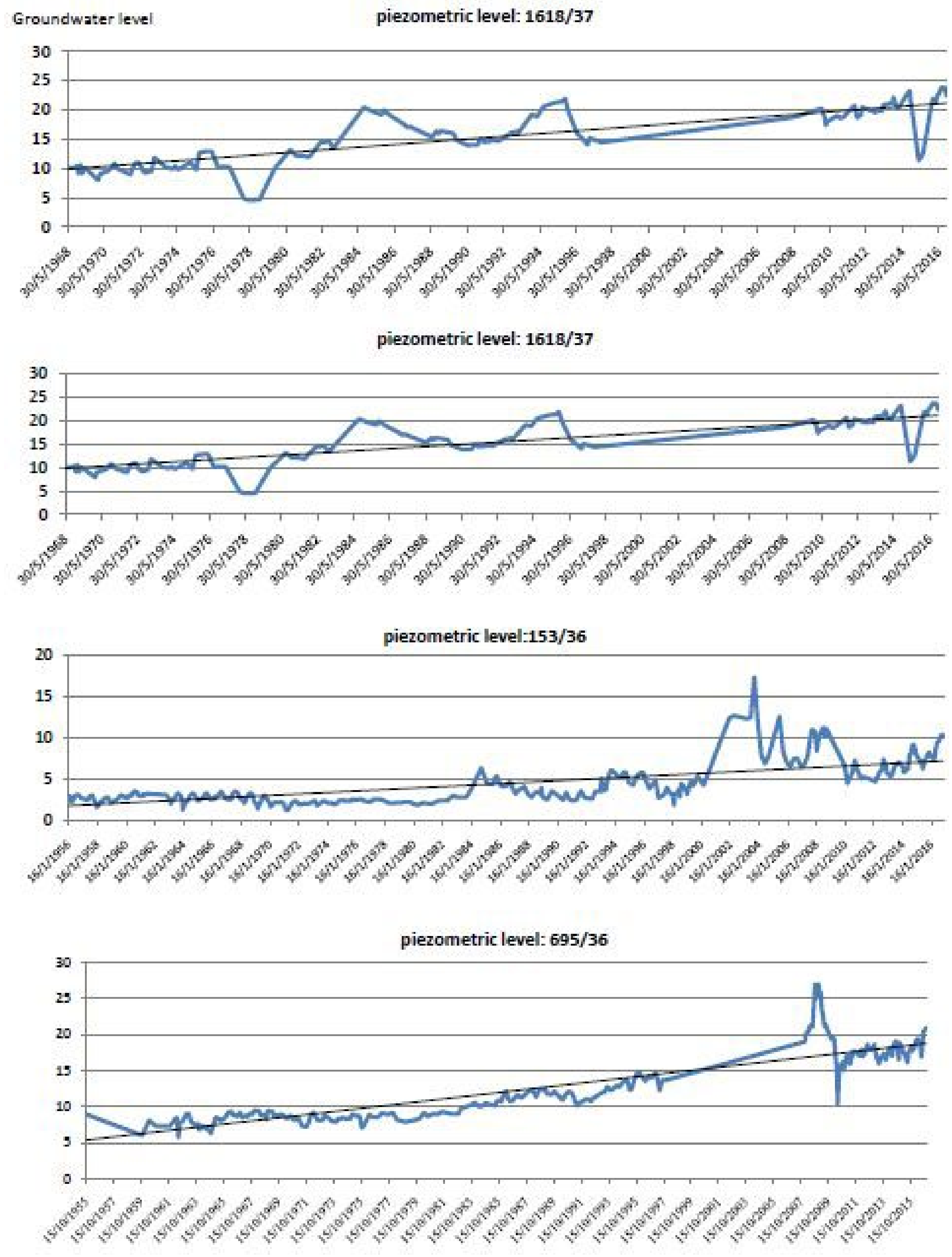

Fig. 6. Evolution of the piezometric levels at wells of Tadla perimeter, 130 × 169 mm (96 × 96 DPI).

5.1.2. Reduction of discharge of water table sources

The water table of Tadla is fed by sources from Dir (Ain Asserdoun, Ain Zawit Chekh, etc.). Due to overexploitation, there has been a significant reduction in groundwater discharge. When groundwater is pumped excessively, surface discharge, such as springs, base flows, and emergences, has the ability to discharge and degrade water-dependent ecosystems underground.

5.1.3. Soil subsidence

The loss of hydraulic pressure due to the depletion of groundwater has caused the spread of the water cone in part of the irrigated perimeter of Tadla, which has led to many problems with the water table. The area under study has long suffered from this problem because of high exploitation as well as natural and artificial drainage. Soil subsidence occurs when excessive amounts of groundwater have been removed from a porous aquifer. Consequently, porous aquifer materials compact and bust, causing a lowering of the soil surface in the area [55].

5.1.4. Salinisation, rapid infiltration of pollutants, and degradation of groundwater quality

Pumping groundwater by taking water at a rate higher than the natural recharge rate can lead to water scarcity that the reverse phenomenon could not restore, even after several years of feeding. Contamination of subterranean water is difficult and sometimes impossible to clean. The salinity of the ground water and its impact vary around the perimeter:

- In Béni Amir, the minimum value of electrical conductivity measured in December 1999 was 1.15 mS/cm and the average conductivity was around 5.5 mS/cm. The surface of the aquifer affected by very high salinity represents 90% of the total surface area.
- In east Béni Moussa, the average conductivity of water was 1.25 mS/cm, the minimum value was 0.75 mS/cm and the maximum was 3.15 mS/cm.
- In west Béni Moussa, the conductivity of water varies between 1.30 and 6.45 mS/cm, and the average value was 3.15 mS/cm, on the whole, an inadequate value for irrigation, but of less concern than that of Béni Amir.

Overall, the problem of water salinity is worrisome in Béni Amir, and to a lesser extent in west Béni Moussa. In east Béni Moussa, the waters of the water table fluctuate between average salinity and high salinity [56].

To identify regions likely to be infected or contaminated by anthropogenic activities, the piezometric level map and the hydraulic conductivity map were superimposed. Hydraulic conductivity is the capacity of aquifer materials to transmit water, which in turn controls the rate of groundwater flow under a given hydraulic gradient. Hydraulic conductivity was determined using data from (Table 1) [57], which was based on studies by other researchers [58]. This study gives the hydraulic conductivity for each type of soil (Table 1). We used these data concerning the granulometric composition of each type of soil in the plain on the basis of those studies [12].

Table 1
Hydraulic conductivity for each soil type [38]

Soil type	Hydraulic conductivity
Sand	5.83×10^{-5}
Loamy sand	1.69×10^{-5}
Sandy loam	7.22×10^{-6}
Loam	3.61×10^{-6}
Silt loam	1.89×10^{-6}
Sandy clay loam	1.19×10^{-6}
Clay loam	6.39×10^{-7}
Silty clay loam	4.17×10^{-7}
Sandy clay	3.33×10^{-7}
Silty clay	2.50×10^{-7}
Clay	1.67×10^{-7}

The map produced has values ranging between 1.67×10^{-7} and 5.83×10^{-5} m/s. As shown in Fig. 7, the highest value of hydraulic conductivity was at the Béni Moussa water table along the left bank of the Oum Errabia River and in the western region extending to the far west. The lowest value covered almost the entire region of Béni Amir and the southern area of the Béni Moussa region.

The result of the combination between the piezometric level and the hydraulic conductivity; the regions where there is a low piezometric level (between 10 and 14 m) very close to the surface showed a high degree of hydraulic conductivity. This explains why these regions have a high rate of contamination, such as in the case of the Béni Moussa water table in the south. On the other hand, the Béni Amir aquifer in the north has a piezometric level between 8 and 20 m with a low hydraulic conductivity.

5.1.5. Socio-economic impact of groundwater exploitation

The socio-economic impact of groundwater exploitation were evaluated in terms of the mobilization of the necessary resources (human, mechanical, and financial) for the construction of the structure (wells, boreholes) and the evaluation of the cost needed to execute and operate the project. Compared to surface water, whose cost remains affordable and related to the water network supply, private pumping, has the advantage of more autonomy and independent use. The cost of a cubic meter of pumped water is two to three times higher than that of farm-scale water. This higher cost includes the expenses of acquisition and operation of the pumping device, as well as maintenance and preparation costs and expenses related to damping [4].

5.2. Management of underground water resources

For groundwater, management is applied at a resource system scale as a common good offered and determined by natural conditions in according to the situation between the exploitation objectives and the objectives of allocation and conservation of the resource for the general population. In general, three major constraints affect water resources in Morocco: scarcity of resources, irregularity in time, and irregularity in space [1]. As the groundwater is interdependent of

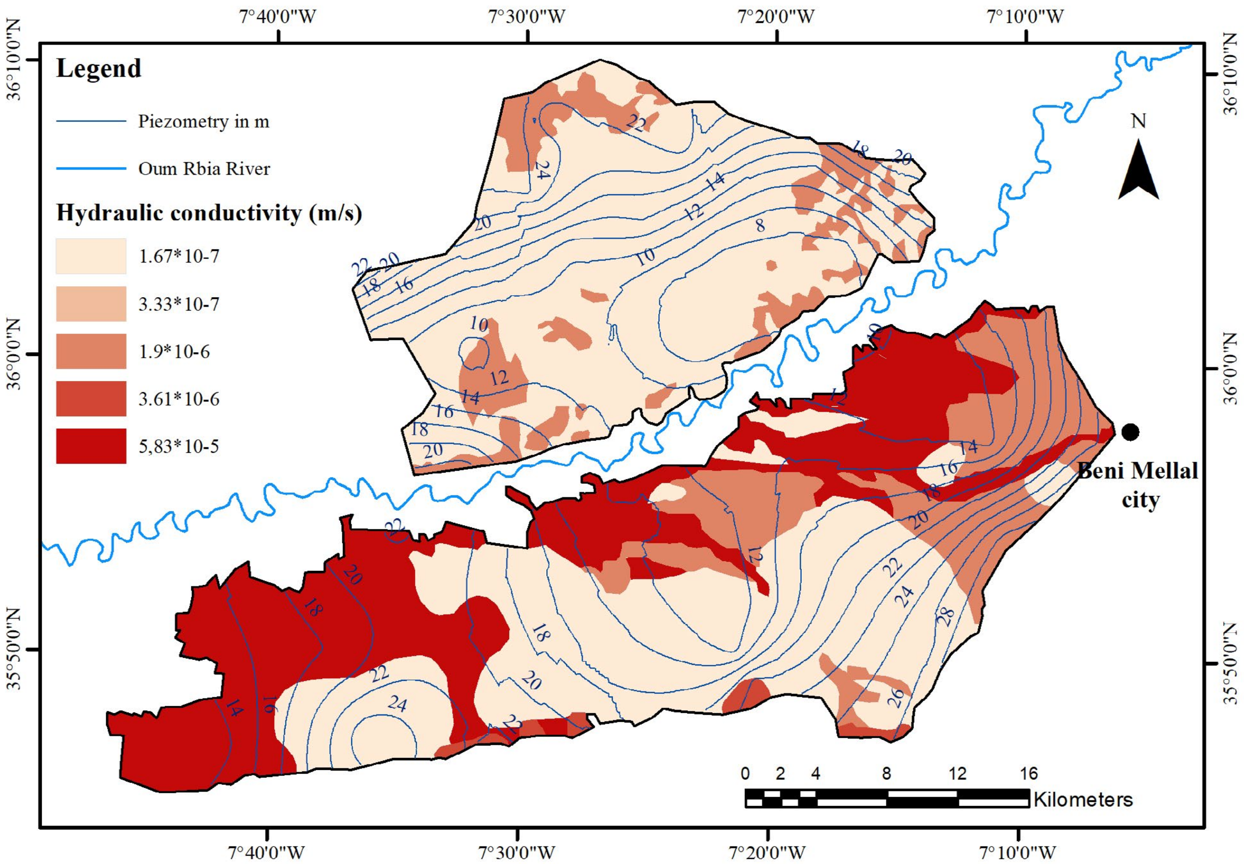

Fig. 7. Layering cards (piezometric maps and hydraulic conductivity).

surface water, its management is integrated with the management of water as a whole with respect to objectives, involvement, and infrastructure.

In parallel with the mobilization of surface water, uninterrupted efforts to explore groundwater resources enabled mobilization of almost all of them to the extent that the majority of water tables are overexploited. Up to 80% of them have already been mobilized. This is an important mobilization rate, predicting that the cost of water will rapidly escalate if we continue to exploit mobilized water resources in excessive and irrational ways.

All these problems invite us to turn to the definition formulated by the International Association of Hydrogeologists (IAH), which proposed a set of criteria that contribute to the sustainable management of groundwater. The following criteria were proposed [59]:

- Sustainable management of groundwater should not be exploited beyond the limits of its renewal over the long term. In the short term, overexploitation of renewable resources can be an economical and acceptable method for the use of water in certain specific cases. Protection of the environment must be recognized as a legitimate use for underground water, and the conservation of this ecosystem places new constraints on management.
- Sustainable management of groundwater on a qualitative level. The only real sustainable methods of groundwater quality management are those based on the concept of prevention of pollution.
- Management must be integrated in terms of quantity and quality and take into account the source of the supply.
- Groundwater users need to be informed and educated about the use of groundwater and its need for protection.

These criteria seem to be the best solutions to address issues of groundwater governance because they highlight the necessary conditions in a pragmatic order, despite the problems of evaluation of the quantities taken, and take it into consideration.

At the national level, effective management of the water potentialities should be a priority in the national water policy. The need to control the demand for water has been strongly felt during droughts that have affected the country since the end of the 1970's, leading to a number of challenges that mainly concern:

- The need for users to review and justify the terms of their water demand,
- The need to undertake and management programs on water conservation and how to protect and maintain its quality,
- The means to move toward a more efficient use of water, both at the level of the operating organization and the end user, and
- The need for equitable distribution of the shortage over all sector users, including drinking water [60].

6. Conclusion

Overexploitation of an aquifer completely disturbs the arrangement of the piezometric surface. The lowering of the surface level of water is represented by large cones of depression accentuated by hydraulic gradients and the reversal of the direction of flow. The uncontrolled exploitation of this resource has weakened its natural recharge possibilities.

But years of heavy rain and good precipitation have reinforced the water table and raised the piezometric level. The effect of these precipitations is immense as they recharge the table water and restore some balance. However, the phenomenon of irreversible degradation is feared. Wells are getting deeper which increases the cost of pumping more than that of the water network.

A number of actions are taking place to fight groundwater pollution in the perimeter of Tadla. We can point to the reduction of the nitrate fertilizers and the sensitizing of farmers to cultivation methods that respect the quality of groundwater resources.

The exploitation of the underground water resources in the region of Tadla leads to some serious consequences which might be listed as follows: the fall of the underground water level, the reduction inside or the suspension of spring discharge, and the deterioration of water quality. These impacts have serious socio-economic implications like the result of reduced water quality and quantity, which negatively affects public health, decreases agricultural productivity because of the high salinity of groundwater, and the availability of natural resources for future generations. In order to address such problems, the following recommendations are useful:

- It is necessary to move toward the use of wastewater and desalination of seawater, especially for the industrial sector, and the good management of surface water must be taken into consideration,
- Establishing continental mechanisms to combat the effects of climate, drought, and desertification,
- Protecting vulnerable areas in the area of study,
- Strengthening the capacity of construction mechanisms for surface and groundwater,
- Going toward smart agriculture, renewable energy, construction of green dams, and the transfer of water from dams to prevent the loss of rainwater at sea, the reforestation by plants that can support salinity and adapt to the dryness of the arid environment [14].

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References

[1] M. Bahir, A. Mennani, Problem of groundwater management in Morocco, Estudios Geol., 58 (2002) 103–108.
[2] A. Hammani, M. Kuper, A. Debbarh, S. Bouarfa, M. Badraoui, A. Bellouti, Evolution of the Exploitation of Groundwater in the Irrigated Perimeter of Tadla, Seminar on the Modernization of Irrigated Agriculture, HAL Cirad., 2004.
[3] M. Faouzi, A. Larabi, Problems of the rise, salinity and pollution by nitrates of the waters of the Beni-Amir water table (Tadla, Morocco), Archive Ouverte. Fr, 27 (2001) 23–36.
[4] A. Hammani, M. Kuper, A. Debbarh, La Modernisation de l’agriculture irriguée (Modernization of Irrigated Agriculture), Proceedings of the Euro-Mediterranean Seminar, 2004.
[5] A. Hammani, M. Kuper, Y. Bekkar, H. Zaz, Exploitation of Groundwater in the Irrigated Perimeter of Tadla (Morocco) Current Situation and Elements of Methodology to Contribute to a Reflection on an Integrated and Sustainable Management of Groundwater and Surface Water, Water Savings in Irrigated Systems in the Maghreb, Second Regional Workshop of the Sirma Project, HAL Cirad., 2006.
[6] M. Saaf, Exploitation of groundwater resources irrigated perimeter of Tadla, Rev. HTE, 140 (2008) 71–73.
[7] K. Del Vecchio, S. Barone, Has Morocco’s groundwater policy changed? Lessons from the institutional approach, Water Altern., 11 (2018) 638–662.
[8] A.B.H.O.E.R., Modeling Study of the Tadla Deep Aquifers, Mission I: Hydrogeological Synthesis and Updating of Data Relating to the Tadla Deep Aquifers, 2007.
[9] C. Archambault, Piezometry of the aquifers of the phosphate plateau and the Tadla plain, Direction Hydraul., (1972) 20.
[10] N. Aghzar, H. Berdai, A. Bellouti, B. Soudi, Groundwater nitrate pollution in Tadla (Morocco), J. Water Sci., 15 (2002) 459–492.
[11] H. Etienne, D. Guessab, C. Archambault, The Tadla plain, 231 (1975) 299–364.
[12] C. Massoni, G. Missante, The plain of Tadla, 24 (1967) 343–345.
[13] L. Radhouane, Climate change impacts on north African countries and on some Tunisian economic sectors, J. Agric. Environ. Int. Dev., 107 (2013) 101–113.
[14] Y. Hamed, R. Hadji, B. Redhaounia, K. Zighmi, F. Bâali, A. El Gayar, Climate impact on surface and groundwater in north Africa: a global synthesis of findings and recommendations, Euro Mediterr. J. Environ. Integr., 3 (2018) 25.
[15] Y. Hamed, B. Redhaounia, A. Ben Sâad, R. Hadji, F. Zahri, Groundwater inrush caused by the fault reactivation and the climate impact in the mining Gafsa basin (southwestern Tunisia), J. Tethys, 5 (2017) 154–164.
[16] N. Mokadem, A. Demdoum, Y. Hamed, S. Bouri, R. Hadji, A. Boyce, A. Sâad, Hydrogeochemical and stable isotope data of groundwater of a multi-aquifer system: northern Gafsa basin–Central Tunisia, J. Afr. Earth Sci., 114 (2016) 174–191.
[17] A. El Gayar, Y. Hamed. Climate Change and Water Resources Management in Arab Countries, In: Euro-Mediterranean Conference for Environmental Integration, Springer, Cham, 2007.
[18] E. Reynard, M. Lasri, G. Werren, K. Obda, M. Amyay, A. Taous, Map of flood phenomena in the Fez and Beni Mellal basins, 25 (2011) 71–81.
[19] D. El Hafid, Z. Zerrouqi, B. Akdim, Study of drought sequences in the isly basin (eastern Morocco), Larhyss J. Res. Lab, Subterranean Surf. Hydraul., 31 (2017) 83–94.
[20] Z. El Abidine Triqui, R. Moussadek, Impact of climate change on water resources in (Morocco) case of the region of Khenifra, upstream of watershed of Bouregreg, Eur. J. Sci. Res., 150 (2018) 420–439.
[21] B. Abdellaoui, A. Merzouk, M. Aberkan, J. Albergel, Hydrological balance and siltation of the Saboun dam (Morocco), J. Water Sci., 15 (2002) 737–748.
[22] J.W. Lloyd, A changing approach to arid-zone groundwater resources in developing countries. Gambling with groundwater: physical, chemical and biological aspects of aquifer–stream relations, Int. Assoc. Hydrogeol., Las Vegas, (1998) 7–12.
[23] J. Margat, The Overexploitation of Aquifers, Vol. 3, In: Selected Papers on Aquifer Overexploitation, International Association of Hydro-geologists, Heise, Hannover, 1992, pp. 29–40.
[24] S.S.D. Foster, Unsustainable Development and Irrational Exploitation of Groundwater Resources in Developing Nations: An Overview, Vol. 3, Simmers, Ed., Selected Papers on Overexploitation, International Association of Hydrogeologists, Heise, Hannover, 1992, pp. 321–36.
[25] J. Margat, K.F. Saad, Concepts for the Utilization of Non-renewable Groundwater Resources in Regional Development, Natural Resources Forum, United Nations, New York, NY, 1983.

[26] S. Bouri, J. Makni, H. Ben Dhia, A synthetic approach integrating surface and subsurface data for prospecting deep aquifers: the southeast Tunisia, Environ. Geol., 54 (2008) 1473–1484.
[27] Y. Hamed, M. Zairi, W. Ali, H.B. Dhia, Estimation of residence times and recharge area of groundwater in the Moulares mining basin by using carbon and oxygen isotopes (south western Tunisia), J. Environ. Prot., 1 (2010) 466–474.
[28] R. Hadji, Y. Achour, Y. Hamed, Using GIS and RS for Slope Movement Susceptibility Mapping: Comparing AHP, LI and LR Methods for the Oued Mellah Basin, NE Algeria, In: Euro-Mediterranean Conference for Environmental Integration, Springer, Cham, 2017.
[29] H. Besser, N. Mokadem, B. Redhaounia, R. Hadji, A. Hamad, Y. Hamed, Groundwater mixing and geochemical assessment of low-enthalpy resources in the geothermal field of southwestern Tunisia, Euro Mediterr. J. Environ. Integr., 3 (2018) 16.
[30] H. Besser, N. Mokadem, B. Redhouania, N. Rhimi, F. Khlifi, Y. Ayadi, Y. Hamed, GIS-based evaluation of groundwater quality and estimation of soil salinization and land degradation risks in an arid Mediterranean site (SW Tunisia), Arabian J. Geosci., 10 (2017) 350.
[31] M.D. El Jihad, Seasonal droughts in the upper Oum Errabia basin (central Morocco): aspects and frequencies, John Libbey EUROTEXT, 14 (2003) 157–167.
[32] J. Guillaume, Influence of Agricultural Activities on Nitric Pollution of Groundwater. Analysis by Modeling of the Impacts of Arable Farming Systems on Nitrate Leaks in the Alluvial Plains, Doctoral Thesis, University of Toulouse, University of Toulouse III-Paul Sabatier, 2008.
[33] A. Khattabi, A. Chriyaa, A. Hammani, B. Moudoud, Climate Vulnerabilities and Development Strategies: Synthesis and Strategic Recommendations for Taking Climate Risk into Account in Sectoral Policies and Strategies, 7 (2014).
[34] P.D.A.I.R.E, Water Resources Management Plan Béni Mellal city, 1992.
[35] N. Hernandez-Mora, R. Llamas, L.M. Cortina, Misconceptions in Aquifer Over-Exploitation: Implications for Water Policy in southern Europe, Vol. 17, C. Dosi, Ed., Agricultural Use of Groundwater, Fondazione Eni Enrico Mattei (FEEM) Series on Economics, Energy and Environment, Springer, Dordrecht, 2001, pp. 107–126.
[36] B.L. Morris, A.R.L. Lawrence, P.J.C. Chilton, B. Adams, R.C. Calow, B.A. Klinck, Groundwater and Its Susceptibility to Degradation: A Global Assessment of the Problem and Options for Management, Vol. 3, United Nations Environment Programme, Eary Warning and Assessment Report Series, 03-3, 2003.
[37] E. Custodio, Aquifer overexploitation: what does it mean?, Hydrogeol. J., 10 (2002) 254–277.
[38] S. Zektser, H.A. Loáiciga, J.T. Wolf, Environmental impacts of groundwater overdraft: selected case studies in the southwestern United States, Environ. Geol., 47 (2005) 396–404.
[39] B.T. Ong'or, S. Long-cang, Groundwater overdraft vulnerability and environmental impact assessment in Arusha, Environ. Geol., 51 (2007) 1171–1176.
[40] J. Wu, P. Li, H. Qian, Hydrochemical characterization of drinking groundwater with special reference to fluoride in an arid area of China and the control of aquifer leakage on its concentrations, Environ. Earth Sci., 73 (2015) 8575–8588.
[41] F. Jafari, S. Javadi, G. Golmohammadi, N. Karimi, K. Mohammadi, Numerical simulation of groundwater flow and aquifer-system compaction using simulation and InSAR technique: Saveh basin, Iran, Environ. Earth Sci., 75 (2016) 833.
[42] J. Qian, H. Zhan, Y. Wu, F. Li, J. Wang, Fractured-karst spring-flow protections: a case study in Jinan, China, Hydrogeol. J., 14 (2006) 1192.
[43] S. Du, X. Su, W. Zhang, Effective storage rates analysis of groundwater reservoir with surplus local and transferred water used in Shijiazhuang city, China, Water Environ. J., 27 (2013) 157–169.
[44] J.R. Campos-Gaytan, T. Kretzschmar, C.S. Herrera-Oliva, Future groundwater extraction scenarios for an aquifer in a semiarid environment: case study of Guadalupe Valley Aquifer, Baja California, northwest Mexico, Environ. Monit. Assess., 186 (2014) 7961–7985.
[45] A. Vandenbohede, E. Van Houtte, L. Lebbe, Sustainable groundwater extraction in coastal areas: a Belgian example, Environ. Geol., 57 (2009) 735–747.
[46] D. Werner, A.M. Bakker, V.E. Post, A. Vandenbohede, C. Lu, B. Ataie-Ashtiani, D.A. Barry, Seawater intrusion processes, investigation and management: recent advances and future challenges, Adv. Water Resour., 51 (2013) 3–26.
[47] D.L. Galloway, T.J. Burbey, Regional land subsidence accompanying groundwater extraction, Hydrogeol. J., 19 (2011) 1459–1486.
[48] W. Zhang, L. Gao, X. Jiao, J. Yu, X. Su, S. Du, Occurrence assessment of earth fissure based on genetic algorithms and artificial neural networks in Su-Xi-Chang land subsidence area, China, Geosci. J., 18 (2014) 485–493.
[49] K. Kruawal, F. Sacher, A. Werner, J. Müller, T.P. Knepper, Chemical water quality in Thailand and its impacts on the drinking water production in Thailand, Sci. Total Environ., 340 (2005) 57–70.
[50] Y. Zhai, J. Wang, H. Huan, J. Zhou, W. Wei, Characterizing the groundwater renewability and evolution of the strongly exploited aquifers of the north China Plain by major ions and environmental tracers, J. Radioanal. Nucl. Chem., 296 (2013) 1263–1274.
[51] A.M. Pophare, B.R. Lamsoge, Y.B. Katpatal, V.P. Nawale, Impact of over-exploitation on groundwater quality: a case study from WR-2 Watershed, India, J. Earth Syst. Sci., 123 (2014) 1541–1566.
[52] H. Bouwer, Artificial recharge of groundwater: hydrogeology and engineering, Hydrogeol. J., 10 (2002) 121–142.
[53] S.M. Gorelick, C. Zheng, Global change and the groundwater management challenge, Water Resour. Res., 51 (2015) 3031–3051.
[54] G.D.E.S.D., Needs Assessment and Groundwater Management Framework in Transboundary Basin Organizations in Africa, 2015.
[55] Available at: www.sjr.net
[56] B. Bouazzama, A. Current Situation of Soil and Groundwater Quality in the Tadla Irrigated Area, Graduate Thesis, IAV Hassan II, Department of Rural Engineering and Soil Sciences, Rabat, Morocco, 2000.
[57] B.K. Ferguson, Stormwater Infiltration, CRC Press, Boca Raton, FL, 1994.
[58] W.J. Rawls, D.L. Brakensiek, K.E. Saxtonn, Estimation of soil water properties, Trans. ASAE, 25 (1982) 1316–1320.
[59] F. Villarroya, Regulatory Issues Mainly About Aquifer Over-exploitation Within the Scope of Sustainable Development, Future Groundwater Resources at Risk (Proceedings of the Helsinki Conference), Hydrologie.org.: IAHS Publication, 1994, pp. 389–389.
[60] M. Jellali, Development of water resources in Morocco, Mediterr. Semin., (1997) 51–68.