Recharge and Hydro-geochemical Evolution Groundwater in Semi-Arid Zone (Essaouira Basin, Morocco)

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Abstract
Arid and semi-arid areas are threatened by desertification, and thus the degradation due to various factors, including drought, of course, but also the exploitation of resources. They are, in fact, already in a state of stress (resources less than 500 m^3 per year per capita) with important disorders induced by climate change. These make an impact on the hydrological cycle, with longer droughts and increased flooding. These disorders will strengthen the already observed degradation of ecosystems, which are often overexploited. Essaouira synclinal area is part of the semi-arid areas of Morocco that are subject to the impact of climatic and human pressures. In the case of this coastal area, which includes two main aquifers superimposed; the Plio-Quaternary and Turonian, the resulting vulnerability is compounded by the risk of infiltration navy. The Rainfall in the area does not exceed 300 mm $year^{-1}$, the average temperature hovers around 20 °C, the piezometric map of Essaouira synclinal basin was made, different water samples have been collected from October 2009 after exceptional rainfall, all waters are sodium-chloride facies, interpretation of mineralization indicates power by the Ksob Wadi in the northeast and increasing levels of chlorides in the central part generated by the Essaouira diaper hidden. Excessive levels of nitrates have been identified, as well as chlorides after rains of winter 2009. The electrical conductivity and concentrations of ^{18}O and ^{2}H were measured, a local meteoric water line was determined according to the Atlantic origin of precipitation.
However, the water Turonian, characterized by significant resources, demonstrates a very low charging current; its vulnerability would be more related to human pressure than changes in climatic conditions.
The Essaouira Basin is more vulnerable to drought because its climate is entirely dependent on recharge meteoric waters.
Keywords : Basin of Essaouira; Aquifer; Semi-Arid Regions; Drought; Hydro-geochemistry; Stable Isotopes; Recharge.

1. Introduction

Morocco is typically semi-arid country where water resources are likely to change dramatically under the influence of climatic fluctuations or human actions. (Cudennec et al., 2007) These changes may affect groundwater stocks, rarely rising (Idder et al., 2007), often in significant reduction (Karaouli et al., 2008), but also their quality (Karaouli et al., 2008; Bouhlassa et al., 2008). Apart from a stream aquifer system to another, the natural recharge of groundwater is mainly due to water infiltration wadis at their highest floods. In the Mediterranean region, such a phenomenon is often highly variable in time and space (Lange et al., 1999).
The relative scarcity of water resources in the Essaouira Basin, their fragility and their uneven distribution give rise to a greater risk of shortage that is growing continually cope with demographic pressures and the growing needs of the socio-economic growth. In the Western High Atlas, Essaouira synclinal area is part of the Essaouira Basin, with an area of 300 km2, bounded by the Ksob Wadi in the north, Tidzi Wadi in the south, the Tidzi Diapir in the East and the Atlantic Ocean to the west (Fig. 1). The present position of the study area leads to a degradation of water quality caused by rising salinity and the threat of seawater intrusion due to overexploitation of groundwater.
The prevailing climate is semi-arid with highly variable rainfall averaging 300 mm/year, However the annual rainfall varies from 100-630 mm (Fig. 2a) and precipitation of rain within one year shows two seasons, dry from April to September and wet from November to March (Fig. 2b). The average temperature varies between 20 ° C and 21 ° C, the difference between the coldest month (January) and warmest month (August) can reach 17 ° C (Bahir, 2001).

2. Hydrogeology of the study area

In geological terms, the Essaouira synclinal zone is less rugged, with a lower relief (Fig. 3), characterized by low hills and shaped by a sparse water system. The Plio-Quaternary and Turonian are the main reservoirs of groundwater in the Essaouira Basin. The Plio-Quaternary, with a matrix of sandstone or limestone marine dune has a hydraulic conductivity primary porosity and contains a large free surface whose wall is formed in the synclinal structure, by the Senonian marls, flayed the ante-Pliocene shows that the Plio-Quaternary can be in direct contact with the Triassic and Cretaceous other levels (Laz, 1959; SCP, 1959).

It is operated in rural areas and provides drinking water, domestic needs and a lesser extent irrigate farmland (Bahir et al., 2000). The Turonian, contains a layer quickly captivated by the Senonian marls in the synclinal structure and probably in direct contact with the Pliocene-Quaternary on the edges of this structure to the north to Ksob Wadi, the West's approach of Essaouira diapir hidden in the east and south near the Tidzi diapir.

The Mesozoic age of the growth of the Tidzi structure is based on (Fig. 1) an unconformity separating Triassic from Portlandian (i.e., uppermost Jurassic) strata, a significant increase in the thickness of the Lower Cretaceous from the eastern to the western side of the Tidzi anticline (Fig. 3) and, the sedimentary wedges exposed along the N–S trending flanks of the structures (Fig. 4).

The unconformity at the base of the Portlandian is well exposed along the foot of the relief forming the eastern side of the Tidzi structure (Fig. 4) and is formed by an erosional surface separating sub-vertical Triassic layers from Lower Cretaceous strata, which dip by 40 – 50° to the E. The base of Lower Cretaceous layers is generally parallel to the unconformity surface, showing that the relief formed during pre-Late Jurassic folding had been effectively peneplained and that the entire area experienced regional subsidence during the Early Cretaceous (Fig. 4 a).

Notwithstanding the poor constraints on the initial stages of the Tidzi structure, anticlinal folding was ongoing in the Late Cretaceous causing the formation of the well-known sedimentary wedges seen along sections perpendicular to the fold (Fig.4). The growth of the Tidzi anticline took place during generalized, long wavelength subsidence (Fig. 5b), affecting the entire region W of the Old Marrakech Massif and allowing for continuous sedimentation.

The Tidzi diapir oriented NNE-SSW (20 km) from the Ksob Wadi until the Tidzi Wadi where he takes an east-west direction and anticline Triassic heart of Essaouira in the West masked by recoveries Plio-Quaternary (Fig. 6) and identified by geophysical structures. There is also an intense fracturing with a general direction N10 cutting Cretaceous carbonate formations.

The aquifer is made of dolomitic limestone affected by a Fracturing N 110 °, the same direction as the fault detected by geophysics along the Ksob Wadi (Fekri, 1993). The wall of this layer is constituted by the Cenomanian marls are representative of the study area.

3. Piezometer

The companion measure of the groundwater level Plio-Quaternary conducted in October 2009 allowed us to map the potentiometric (Fig. 8) established for all levels combined to show that the general direction of water flow takes place in South-East to North-West, imposed by the inclination of the bedrock. In the downstream, the waters diverge to circumvent the Essaouira anticline hidden oriented NE-SW. This over, we note the existence of a line of watershed with a SE-NW direction and influences the direction of flow of water. The groundwater is then separated in two compartments, the first in North streamlines directed in a manner identical to the overall flow, the second in the South, with lines of flow directed from East to West. The lake is located upstream to 140 m and 10 m downstream.

The hydraulic gradient showed variations induced by the pelvic structures and lithology of the reservoir in the upstream part of the study area, the gradient is relatively large, about 2% due to the steepness of the wall the aquifer on the rising Tidzi diapir. At the center, this gradient decreases seven-fold to reach a value of 0.3%. In the Downstream, the hydraulic gradient increases again to reach an average of 2%. Differential gauging made during the hydrological cycle 1990-1991 and confirmed in 2004 is used to estimate flows infiltrated from the Ksob Wadi to the Plio-Quaternary aquifer at a rate of 42 L s^{-1} (Fekri, 1993).

The passage of this river in the gorge where the Turonian flow would also result in losses of 64 L s^{-1} the benefit of the Turonian aquifer. The year 2008-2009 is noted as a wet year par excellence, following heavy rainfall as experienced Morocco, something that appear to provide a recovery of groundwater level in the Plio-Quaternary aquifer.

The Agency Tensift basin hydraulics has a network of surveillence to study the problem of groundwater recharge of aquifers Turonian and Plio-Quaternary of the Essaouira basin (Fig. 16).

Piezometers 430/51 and 428/51 for the Plio-Quaternary aquifer and piezometer 093/51 for the Turonian aquifer shows a continuous descent and inexorable during the years 2007 to 2010, reflecting the impact of climate change and overexploitation of water resources (Fig.17). This poses a problem for the management of water resources in the future. the public authorities fear a resource depletion and imbalances hydrochemical and quality degradation as a result of exploitation rates still supported to meet the demand for increasingly important.

4. Hydrochemistry

The study of the chemistry of water is to identify the chemical facies of waters, their qualities and potability, as well as their suitability for irrigation. It can also track the spatial evolution of physicochemical parameters and estimate their origin, correlating with the geology and groundwater level. Almost all points of the aquifer are intended to supply drinking water and more modest for the irrigation of farmland. To be used, the water must meet certain standards that vary depending on the type of use. This study is based on physico-chemical analysis of samples taken from the entire basin in October 2009 (Fig. 9).

The temperature, electrical conductivity and water pH were measured in the field (Tab. 1). In the laboratory, analysis focused on the chemical major anions (HCO^{3-}, Cl^{-}, SO_4^{2-} and NO^{3-}) and cations (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}). The results of major element chemistry laboratories conducted by the National Office of Potable Water (ONEP) and the Office of Regional Development in Agricultural Value Haouz Marrakech (ORMVAH) are presented in (Tab. 2).

4.1 Groundwater Plio-Quaternary

The groundwater Plio-Quaternary is characterized by their hydrochemical variability. Indeed, the recorded conductivity varies from 770 ms cm^{-1} to more than 3,500 ms cm^{-1} (Fig. 10), with an average of 2,000 ms cm^{-1}. Even with this variability, the waters of the groundwater are grouped in one family and are characterized by the sodium-chloride facies (Fig. 11, 12). The analysis of maps of the spatial distribution of sodium (Fig. 13), chlorides (Fig. 14) and electrical conductivity show that there is a good correlation between the concentrations of chloride and sodium and that the distribution of these two factors correlate well with the electrical conductivity. Examination of the spatial distribution map of mineralization of water (Fig. 10) shows some chemical zonation mainly due to the lithological nature of land crossed. In the northeast to south of Ksob Wadi, we have the lowest electrical conductivity, they increase fairly steadily to the southwest, with a maximum near the Essaouira diapir hidden in the Southwest. Beyond this structure to the northwest, the observed electrical conductivities are lowered.

The Map of sodium and chloride confirms this evolution, they found a feeding area by the loss of the Ksob Wadi in the northeast with moderate levels of chloride and sodium, these levels increase approximately in the direction of flow until the area where Plio-Quaternary aquifer lies directly on the land evaporitic of Essaouira diaper hidden. As the mineralization of sodium and chloride of water obtained from a contact with the ground detrital aquifer Plio-Quaternary elements torn from the Triassic of landforms and this is a function of time Living, Moreover, in direct contact with the evaporite of Essaouira diaper hidden. The Chlorides correlate well with sodium, suggesting a common origin of both elements by dissolution of halite, and the effect of sea spray aerosols and leached by rain seeping into the aquifer. For nitrate (Fig. 15), the minimum contents are saved to the limits of the Ksob Wadi for the remainder of the study area, there is an increase in these levels towards the southwest, the distribution of nitrate shows also the contribution of the Ksob Wadi in the mineralization of groundwater by dilution near this river.

The main source of nitrates is associated with traditional withdrawal methods that make a significant portion of water flowing around the well, is quasi-permanent pools which are enriched nitrate by cattle dung during watering. Also, indoor air pollution from septic systems and septic loss, lack of protection of wellhead, the lack of prevention and environmental programs for the population seriously threatens groundwater resources and led to poor quality supply water (Galego et al., 2005).

Measurements of nitrate were performed with a liquid chromatograph and complemented by those of other major elements (Ca^{2+}, $Mg2^{+}$, Na^{+}, Cl^{-}, HCO^{3-}, CO_3^{2-}), determined by spectrophotometry and by volume.

The presence in some wells, excessive nitrate concentrations is an indication of pollution, and therefore a risk to the health of infants (less than 6 months). It can cause circulatory disorders: Methemoglobinemia or "blue baby syndrome" (Rajagopal and Graham, 1989), as it can cause cancer of the stomach (Chakrawaty, 1989 in El tayab el seddig, 1993). Nitrates can also cause hypertension and are the precursors of carcinogenic nitrosamines (Magee and Barnes, 1956; Castany, 1982).

Pollution of groundwater by nitrates may have several origins (Faillat, 1986):

- Solution heat from rocks;
- Meteoric;
- Contributions by the soil and plants;
- Fertilizers;
- Contributions by indoor pollutants.

In the case of the coastal area of Essaouira, the last factor seems to be the accused (Table. 2) (Fig. 15).

Regarding safe drinking water and those using the national standards of the Directorate General for Water, we note that the waters of the syncline of Essaouira are medium to poor quality according to the overall mineral content, electrical conductivity and chloride content. Depending on the concentration of nitrates, they are moderate to poor for 70% of wells surveyed and 55% exceed the WHO standard of 50 mg l^{-1}.

4.2 Groundwater Turonian

The small number of water points serving the water Turonian, because of its depth and the high cost operation that demand remains a pickled in understanding the properties of this aquifer. The waters of the Turonian show homogeneous electrical conductivity with a minimum value of 1450 µs cm^{-1} recorded in wells B6 and a maximum value of 2340 µs cm^{-1} at the point (B21) (Tab. 1). The groundwater Turonian have the same chemical profile chloride-sodium like that the Plio-Quaternary water (Fig. 8, 9) and it is difficult to distinguish them only by their mineralization, from shallow or moderately mineralized Plio-Quaternary. The two points studied (B12 = 390-51) and (B14 = 346-51) are the property of the National Office of Potable Water (ONEP) and are intended for the city of Essaouira and around town, showing low levels of nitrate (8.06 mg l^{-1}). In contrast, higher concentrations of chloride and sodium, respectively, 319.5 mg l^{-1} and 184.23 mg l^{-1} for item 390-51 and 270.51 mg l^{-1} and 149.96 for item 346-51 (Tab. 2). From the point of view of the cleanliness, the levels of chloride and sodium wholes points of the Turonian aquifer exceed the recommendations made by the World Health Organization (WHO). For cons, nitrate levels remain well below this standard.

In summary, the degradation of the quality of the water resources in the Essaouira Basin and especially the groundwater pollution by nitrates demonstrate the vulnerability of the studied aquifer, and makes more difficult the water supply with acceptable quality, particularly as the population of the region has only this water for daily consumption

5. Vulnerability and Impact of Climate Change

Natural scarcity of water resources around Mediterranean basin is accentuated by increasing human needs, specially in Northern Africa where annual water availability ranges between 500 and 1 000 of cubic meters per inhabitants.

The salinity of the water has been studied intensively in recent decades, particularly in coastal aquifers, driven by scientific interest as well as social relevance. and this related to the quality of water resources which is an issue more important because of the issue of recharge for countries in arid and semi-arid areas.

Due to the population growth and climate change (causing long periods of drought) in the world, many countries have intensively increased their use of water sources for supplying potable water to population and for their agricultural (irrigation) and industrial development. Due to the scarcity of surface waters, people exploit mainly underground water reservoirs. Hence, it is necessary to study and characterize these water reservoirs to avoid any excess exploitation.

The analysis of changes in temperature and temporal variability in rainfall, has been made in recent decades for several stations by the Directorate of Meteorology of Morocco. It highlights a rise in average temperature of about 2 ° C and a very significant decline of approximately 29% of the total rainfall during 1978-2012 compared to the period 1961-1977. The 1994-1995 season was the driest of the last century in Morocco.

A review of years of drought in Morocco during the twentieth century reveals a higher frequency and greater spatial extension of drought between 1982 and 2012: A total of seven episodes of drought in Morocco during this period as against 11 in the last century.

Overall, the average annual flow of rainfall in the territory is estimated at 150 billion m^3, very unevenly distributed across regions. And 15% of the region receives more than 50% of rainfall input.

If we deduct the losses by evaporation and flow of control of the sea, the water potential mobilized in the current economic conditions and technology is estimated at 20 billion m3, of which 16 billion from surface water and 4 billion in groundwater.

These 20 billion m3 are distributed unequally on nine large basins in Morocco including Essaouira Basin.

The relative scarcity of water resources in the Essaouira Basin, their fragility and their uneven distribution give rise to a greater risk of shortage that is growing continually cope with demographic pressures and the growing needs of the socio-economic growth. In the Western High Atlas, Essaouira synclinal area is part of the Essaouira Basin, with an area of 300 km^2, bounded by the Ksob Wadi in the north, Tidzi Wadi in the south, the Tidzi Diapir in the East and the Atlantic Ocean to the west.

6. Isotopic Composition

In these conditions and to understand better the functioning of these aquifers and therefore despite the contribution of geological studies carried out in the basin, a combined approach between the methods of hydrodynamic and isotope geochemistry has been followed for many years. It is identified the origin of groundwater and to locate areas of natural recharge and the links between groundwater (seepage exchanges), contribution to explaining the origin of the mineralization, especially in sectors the saltier.

In the Essaouira Basin, the hydrodynamic behaviour is strongly influenced by runoff (Chkir et al., 2008). In this context, stable isotopes are a tool performs to determine the origin and history of water recharge areas and relations between the layers. Analyses were performed at the Technological Institute of Lisbon Sacavem Department of Environmental and Analytical Chemistry in the context of the Integrated Action between the universities of Lisbon and Marrakesh and funded jointly; the results of these tests are grouped in Table 3.

In the Essaouira Basin, the isotope content of water Plio-Quaternary is between -3.72 and -4.56 ‰ vs. δ^{18}O SMOW. These waters are the cloth Turonian between -4.17 and -4.55 ‰ vs. δ^{18}O SMOW (Fig 18, Fig 19).

The correlation diagram for deuterium vs. oxygen-18 water in the basin of Essaouira can define a local meteoric right equation: $d = 7.72\ {}^2H\ {}^{18}O + 10.53$ ($n = 15$, $R^2 = 0.82$) bit different from the global meteoric water (GMWL) slope 8 with a deuterium excess around 10. The location of water points for the Plio-Quaternary aquifer, often

near the Ksob wadi is consistent with a recent rapid recharge. It characterizes the precipitation of oceanic origin; the equation of this line was calculated without taking into account the three water points 390-51, 272-51 and Ksob wadi identified as evaporated because they are placed below right meteoric (Fig. 18).
The point marked by 272-51 evaporation Plio-Quaternary aquifer and is in close proximity to the river, which confirms the power of the water in the Ksob wadi already highlighted in a quarter North-eastern sector of the aquifer piezometer. Well 390-51, which captures the Turonian aquifer, it is position on the diagram $^{18}O^{-}$ deuterium indicates complementary evaporated water from the river for part of the low water. The other water analyzed aligned right meteoric which means that the power of the two aquifers, and especially of the Turonian aquifer is rapid evaporation without significant if we exclude the point 390-51.
Tritium analysis was performed for thirteen water points supplied by the different aquifers of the Essaouira coastal zone. Data obtained are shown in Table 5. Tritium values vary from a minimum value smaller than 0.8 UT and a maximum value of 4.2 UT. We notice from results shown in Table 4 that recent waters of the Essaouira coastal zone present tritium concentrations comprised between 2 and 4 UT. It is notably the case of 65/51, 27/51, 327/51 and 386/51 water points, confirmed by higher ^{14}C activities for some of them. Water having tritium concentrations smaller or equal to 2 UT are considered as being ancient such as those belonging to the 21/51, M98/51, 218/51, 361/51, 380/51, 390/5 and Ain Aghbalou points.^{14}C was analysed in some of these waters to confirm or show up the weakness of this hypothesis. Tritium was analysed in May 2004 in water samples belonging to water points supplied by the main aquifers used for supplying potable water to the Essaouira city (Table 6). Measurements were realised at the Sacaven Institute of Technology of Lisbon (Portugal). Tritium concentration varies between a minimum value smaller than 1.1UT and a maximum value of 4.2.UT (Fig 20). It is to be noticed that recent waters of Essaouira coastal zone show tritium concentrations larger than 2 UT. It is the case of water points 272/51 and 386/51 called Idda ou Gourd drillings and the aerodrome drilling which supply water respectively to Essaouira and Idda ou Gourd in agreement with results obtained in 1996. Then, one can say that the 2004 campaign has definitively confirmed the recent recharge of these water points. On the other hand, waters showing tritium concentrations smaller or equal to 2 UT are considered as ancient, such as water points 261/51, 390/51, 6/51 and M98. The Turonian aquifer supplying 50% of potable water to the city of Essaouira, notably drillings of more than 300 m depth (346/51 and 390/51), and the 6/51 source show tritium concentrations smaller or equal to 2UT (Bahir, 2001). One can conclude from data obtained for tritium, for the 2004 campaign, that the recharge is low or non-existing for drillings performed in the Pliocene-Quaternary aquifer, notably the 261/51 one which supplies the city of Essaouira with a flow rate of 6l/s. This is corroborated by its portion from the Ksob river, which when rising supplies the neighbouring water points. The ^{14}C radioisotope was utilized for dating ancient waters with very low tritium concentrations.To assess initial 14C activities of underground waters of the coastal zone of Essaouira many models were tested (Table 7).These different models may take into account of the ^{14}C chemical dilution, isotopic exchanges and isotopic mixtures with isotopic exchange. From the analysis of data given in Table 5, 6 and 7 one can deduce that:
Two water points among those studied presenting significant tritium concentrations and ^{14}C percentage larger than 85% should be considered as recent. Among these two water points one can notice well number 65/51 situated near the Ksob river which supplies potable water to the Essaouira city with a flow rate of 6l/s (5% of the total water supply). This well, supplied by the turonian aquifer, shows an ^{18}O concentration of -4.53 δ‰. This value is intermediate between the isotopic concentration of -4 δ‰ for the Pliocene-Quaternary waters and that of the Turonian ones which is of -5δ‰, indicating a drainage of the Pliocene-Quaternary aquifer. The second water point consists of the 386/51 drilling, impounded by the Turonian aquifer waters and supplying potables waters to the aerodrome of Essaouira. The M98 drilling which has no detectable tritium and has a ^{14}C concentration of 80%, has been supplied before the 1952-1963 nuclear tests and its radiocarbon age does not exceed some hundred years independently of the model utilized. The 390/51 drilling impounded by the Turonian aquifer waters, supplies the Essaouira city with a flow rate 60 l/s representing 50% of the water needs. This drilling has a radiocarbon age of about 6500 years according to the IAEA model, a little lower but still always of several thousand years according to the other models. This means that there exist very ancient waters people are surexploiting. This could present a risk of lack of water to supply the Essaouira city. The 380/51 drilling impounded by the Turonian aquifer which supplies potable water to the Si Ahmad ou Hmad town (5000 inhabitants), is also overexploited. It has a radiocarbon age greater than 20,000 years independently of the model utilized indicating a low recovering rate of the Turonian aquifer. The present ^{14}C activity (around 70%) of the Aghbalou source impounded by the Barremian-Aptian aquifer which supplies water to a population of 10,000 inhabitants and their livestock with a flow rate of 30l/s. This water source presents a tritium concentration smaller than 2 UT. Its supplying was then before the nuclear tests and its radiocarbon age is of some thousand years, independently of the model utilized. The Igounitene source, impounded by the Portlandian - Berrisian aquifer with a flow rate of 0.5l/s, shows a ^{14}C activity around 70% and a tritium concentration smaller than 2UT. Its supplying was then previous to the nuclear tests and its radiocarbon age is of some hundred years.

Conclusion

Geochemical and isotopic approach the waters of the groundwater in the plain Essaouira showed the close relation-wadi water is the main source of groundwater recharge. The diagnosis of the condition of aquifers vulnerability face the stress of anthropogenic pressures and climate. On the one hand, the mineralization and concentrations of chloride in the Plio-Quaternary aquifer has to have the power by the Ksob Wadi and the role of Essaouira diapir hidden in the increase of mineralization chloride waters in the central part. As the excessive levels of nitrates following heavy rainfall in the year 2008-2009, accompanied by elevated chloride, causing degradation of water quality in the region and highlights the vulnerability of abstraction. On the other hand, the inventory levels of stable isotopes of two aquifers has to differentiate where the water of the Plio-Quaternary shows charging current but is threatened by seawater intrusion due to overexploitation of resources. However, the water Turonian, characterized by significant resources, demonstrates a very low charging current; its vulnerability would be more related to human pressure than changes in climatic conditions. The development of a rational exploitation strategy may therefore help to enhance water while protecting its long-term potential.

Faced with this scenario announcing a rise inevitable problem, an alternative scenario is possible, based on the implementation of proactive policies:

- Economical use of water through the implementation of management tools for water demand: technical, economic, regulatory and social.
- Increase the exploitable potential through better conservation of soil and water and increased use of artificial recharge of Plio-Quaternary and Turonian to promote infiltration and storage in the aerated zone of soil and thus reduce evaporation losses.
- As the use of unconventional resources such as desalinated seawater for drinking water or treated wastewater for agriculture must be currently considered as a priority in order to avoid triggering shortages of water.

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Tab. 1 Results of the campaign in October 2009 from the coastal area of Essaouira; aquifers Plio-Quaternary and Turonian.

Sample	X (km)	Y (Km)	Z (m)	N.P/sol (m)	H (m)	PT (m)	c25°C (µs/cm)	T°C	pH	Aquifer
B1=Ksob Wadi	85,5	105,62	22		22		2440	20	7,37	wadi
B2=149-51	85,1	105,8	40	37,2	2,8	33,3	3160	22	6,7	Plio-Quat
B3=138-51	87,85	92,83	109	5	104	26	3520	21	7,31	Plio-Quat
B4=M33	91,15	102,3	78	29	49		2040	20	7,41	Plio-Quat
B5	90,29	102,26	102	48	54	56	2249	19	7,4	Plio-Quat
B6	91,43	102,44	79	22	57	110	1450	21	7,1	Turonian
B7	95,15	104,49	97	27,8	69,2	38	770	20	7,25	Plio-Quat
B8=93-51	92,37	101,9	98	44	54	28,7		21		Plio-Quat
B9	93,41	102,68	114	47	67	50	1763	19	7,41	Plio-Quat
B10=M61	91,2	100,75	90	34	56	40	1720	23	7,5	Plio-Quat
B11=103-51	94,82	102,17	99	22,5	76,5	26,5	1671	21	7,3	Plio-Quat
B12=390-51	96,81	100,93	111		111		1947	23	7,39	Turonian
B13=272-51	97,17	100,76	105,5		105,5	38,4	2180	20	7,15	Plio-Quat
B14=346-51	97,27	100,7	105		105		1969	27	7,17	Turonian
B16=133-51	87,8	98,8	70	38	32	40	2550	22	7,24	Plio-Quat
B17=15-51	86	97,97	70	7	63	8,8	3070	15,5	7,1	Plio-Quat
B18=3-51	81,4	93,4	18	4	14	11	2130	19	7,44	Plio-Quat
B19=M66	90,5	95,5	110	61	49		1911	23,5	7,55	Turonian
B20=21-51	89,4	91,4	89,6	28	61,6	30	3780	20	7	Plio-Quat
B21=380-51	89,35	91,8	135	102	33	184	2340	25	7,69	Turonian
B22=327-51	88,8	88,8	130	24	106	50	2850	21,5	7,3	Plio-Quat
B23=363-51	89,75	88,2	150		150	228	2150	24	7,2	Turonian
B39	84,98	111,08	23	5	18	6	3060	23	7,28	Plio-Quat

Tab. 2 Chemical analysis of groundwater; aquifers Plio-Quaternary and Turonian.

Sample	HCO^{3-}	Cl^-	NO_3^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	K^+	Aquifer
B1= Ksob wadi	146,4	475,7	31	128,64	40	38,64	266,8	5,46	Wadi
B3=138-51	109,8	766,8	89,28	124,8	38	45,96	438,15	10,53	Plio-Quat
B4=M33	207,4	347,9	45,26	104,64	40	30,24	221,95	13,65	Plio-Quat
B5	176,9	390,5	0,62	102,72	42	39,84	207,69	10,53	Plio-Quat
B7	67,1	74,55	100,4	27,36	30	24,12	36,8	3,12	Plio-Quat
B9	219,6	241,4	10,54	121,44	44	35,04	138,69	4,68	Plio-Quat
B10=M61	195,2	255,6	13,64	119,52	46	41,04	127,42	5,46	Plio-Quat
B11=103-51	176,9	217,97	6,82	111,84	38	31,44	135,7	4,68	Plio-Quat
B12=390-51	183	319,5	8,06	111,84	34	35,04	184,23	4,29	Turonian
B13=272-51	189,1	355	27,28	129,6	42	38,64	212,98	4,29	Plio-Quat
B14=346-51	195,2	270,51	8,06	104,64	38	35,04	149,96	5,07	Turonian
B16=133-51	146,4	442,33	50,84	96	40	42,36	236,44	3,9	Plio-Quat
B18=3-51	195,2	344,35	199	44,64	34	30,24	254,38	5,85	Plio-Quat
B19=M66	219,6	264,12	0,62	176,16	34	37,44	167,21	25,35	Turonian
B21=380-51	231,8	420,32	0	133,92	38	30,24	286,35	15,21	Turonian
B39	207,4	372,75	168,6	168,48	66	59,28	219,42	19,5	Plio-Quat

Tab. 3. Piezometric measurement results realized in January 2010

Site	N°IRE	x	y	Date of Measurement	N.P Jan 2010	PH	O2 Dissolves	T °C	conductivity (µs/cm)
Sidi Mokhtar	1601/52	154000	117000	18/01/2010	53,1	8,7	69,5	23,1	1310
Sidi Mokhtar2	1602/52	156200	117200	18/01/2010	62,24	8,74	73	23,5	1160
Sidi Mokhtar1	1603/52	153400	114500	18/01/2010	61,03	8,76	74,6	23,3	1320
Sidi Mokhtar Sidi Mohamed	2095/52	157560	104300	18/01/2010	28,93	8,93	63	23,6	1340
Od.Bou.Sbaa	2096/52	157000	100000	18/01/2010	41,94	9,04	62,4	25	1470
Sidi Mokhtar ouled Azouz	2097/52	154450	109250	18/01/2010	23,54	8,89	62,5	24,9	1420
Ida Ouguerd Douar.Bouzima	0093/51	92375	101875	27/01/2010	29,6	8,35	62,8	19,3	1190
Ida Ouguerd	0428/51	93650	101500	27/01/2010	50,12	8,5	60,4	20,4	990
Adamna	0430/51	93300	104950	28/01/2010	15,63	9,01	56,8	19,6	2130
Meskala	1126/52	118700	99100	22/01/2010	73,35	-	-	22,68	1250
Meskala	1166/52	116150	82900	22/01/2010	7,17	8,81	67	21,8	1140
Kourimat 2	1726/52	132650	101000	26/01/2010	39,7	8,58	58,8	19,7	700
Kourimat 1	1727/52	129000	102350	26/01/2010	26,27	8,58	62,1	20	890

Tab. 3 Contents of stable isotopes ^{18}O and ^{2}H of the waters of Essaouira synclinal (campaign of october 2006)

Sample	**X**	**Y**	**$\delta^{18}O$ (°/₀₀)**	**d^2H**	**Aquifer**
B2=149-51	85,1	105,8	-3.79	-19.2	Plio-Quat
386-51	92	98,65	-4.17	-22.2	Turonian
M98	89	100	-4.56	-24.2	Plio-Quat
B17=15-51	86	97	-3.87	-19.3	Plio-Quat
11-51	80,45	96,45	-3.50	-14.9	Plio-Quat
B20=21-51	89,4	91,4	-4.51	-26.2	Plio-Quat
B21=380-51	89,35	91,8	-4.56	-23.6	Plio-Quat
B23=363-51	89,75	88,2	-4.55	-26.8	Turonian
B22=327-51	88,8	88,8	-4.11	-21.3	Plio-Quat
27-51	95,5	91,3	-4.55	-22.9	Plio-Quat
M24	95	91,5	-4.34	-23.5	Plio-Quat
28-51	97,2	91,8	-4.50	-22.7	Plio-Quat
148-51	85,7	102,05	-3.82	-20.7	Plio-Quat
Ksob Wadi	86	106	-3.57	-19.0	Plio-Quat
93-51	92,37	101,9	-4.33	-22.3	Plio-Quat
B12=390-51	97	100	-4.37	-25.8	Turonian
B13=272-51	97,17	100,76	-3.72	-20.3	Plio-Quat
B14=346-51	97,25	100,7	-4.17	-21.4	Turonian

Table.4. Data obtained for the physical parameters and radioisotope concentrations for the underground waters of the coastal zone of Essaouira.

Simple	**X**	**Y**	**Nature**	**Origin**	**Altitude**	**Depth (m)**	**T (°C)**	**pH**	**Alc. (méq/l)**	**^{3}H (UT)**	**^{14}C pcm**	**^{13}C °/°°**
272/51	97,17	100 ,76	Well	Plio-Quat	105,5	38,4	20,6	7,65	3,3	3,9		
21/51	89,40	91,40	Well	Plio-Quat	135	29	21,7	7,13	2,8	2		
327/51	88,80	88,80	Well	Plio-Quat	130		22,2	7,23	4,03	3,2		
65/51	87,70	105,60	Well	Turon	15	20,3	22,5	7,48	4,64	2,8	88,9 +/-0,5	-9,8
390/51	97,00	100	Drilling	Turon	95	200	26,7	7,35	4,94	2	32,5 +/-0,4	-9,4
386/51	92,00	98,65	Drilling	Turon	105	100	23,2	7,56	4,26	4,2	84,8 +/-0,6	- 10,3
380/51	89,35	91,80	Drilling	Turon	135	194	26,1	7,54	4,67	1	3,0 +/-0,5	-9,0
M98	89,00	100	Drilling	Bar-Apt	90	100	22	7,59	3,55	1,1	79,6 +/-0,6	-9,3
A.Aghbalou	11,51	111	Drilling	Bar-Apt	80		23,1	7,5	3,58	1	72,0 +/-0,4	- 10,0
216/51	100,65	96,00	Source	Por-Ber	160		23,1	7,28	4,53	1		
218/51	82,55	68,25	Source	Por-Ber	308		22,5	7,29	4,24	1	68,5 +/-0,6	-9,9
361/51	86,45	70,30	Drilling	Lias	382	90	23,5	7,22	4,45	2		
203/51	78,90	64,35	Drilling	Callov	14	50	22,7	7,11	4,26	3,8		
346/51	97,27	100,70	Drilling	Turonien	105					1,5		
363/51	89,75	88,20	Drilling	Turonien	150					1,2		
149/51	85,10	105,80	Drilling	Turonien	40					0,2		

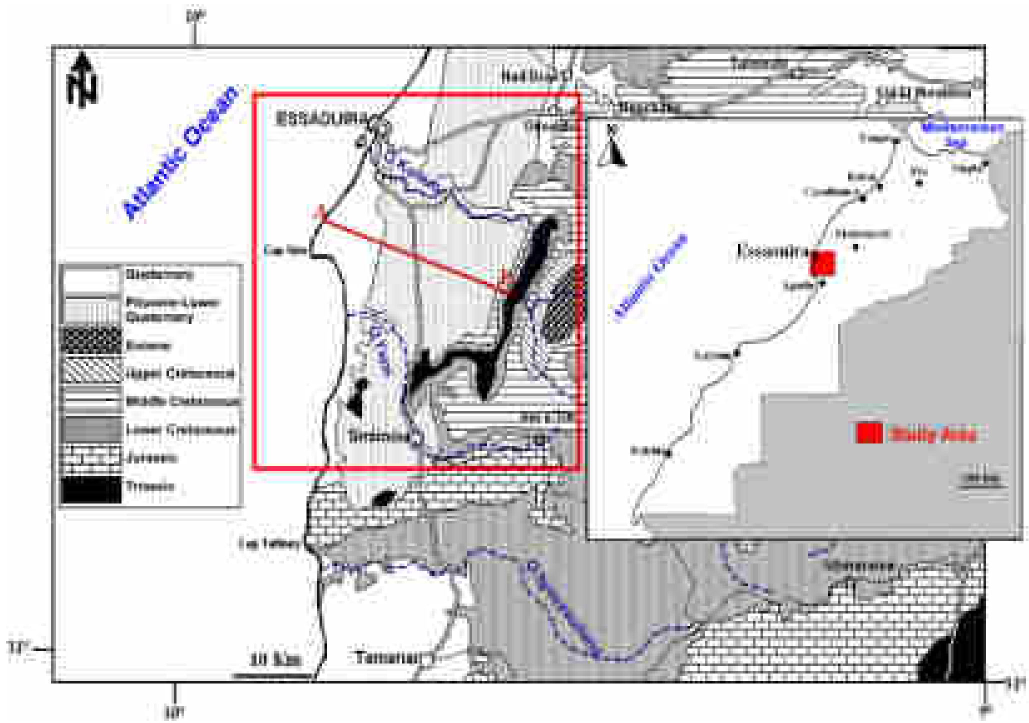


Fig. 1 Geological map (adapted from geological map of Morocco 1 / 1000000. 1985). A–B represents the cross-section location of Fig. 4.

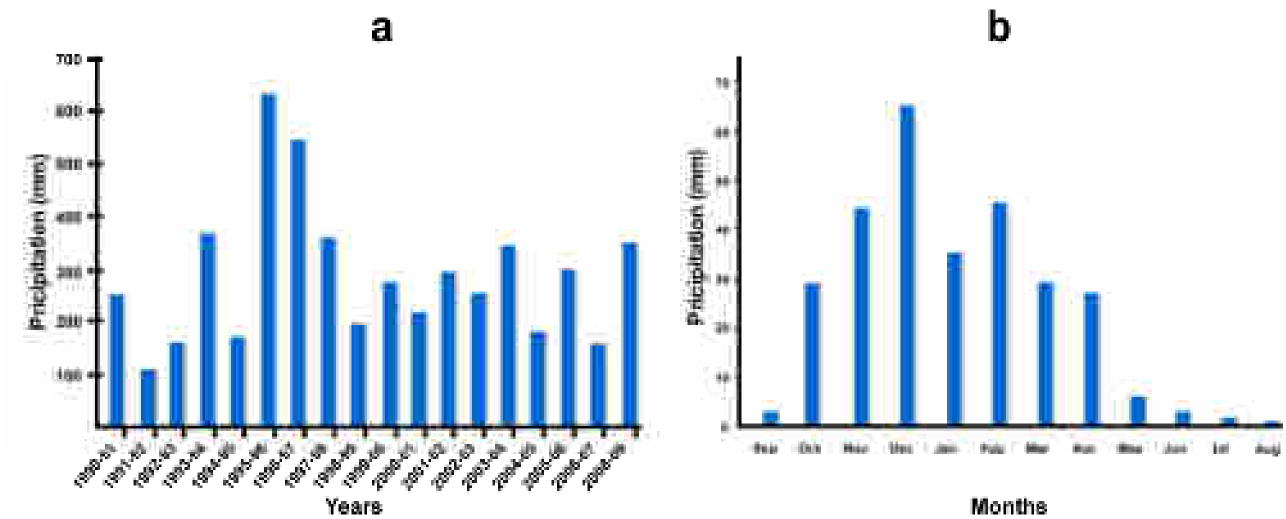


Fig. 2 Precipitation (a) annual values and (b) monthly mean values at Essaouira Station (1990-91 to 2008-09).

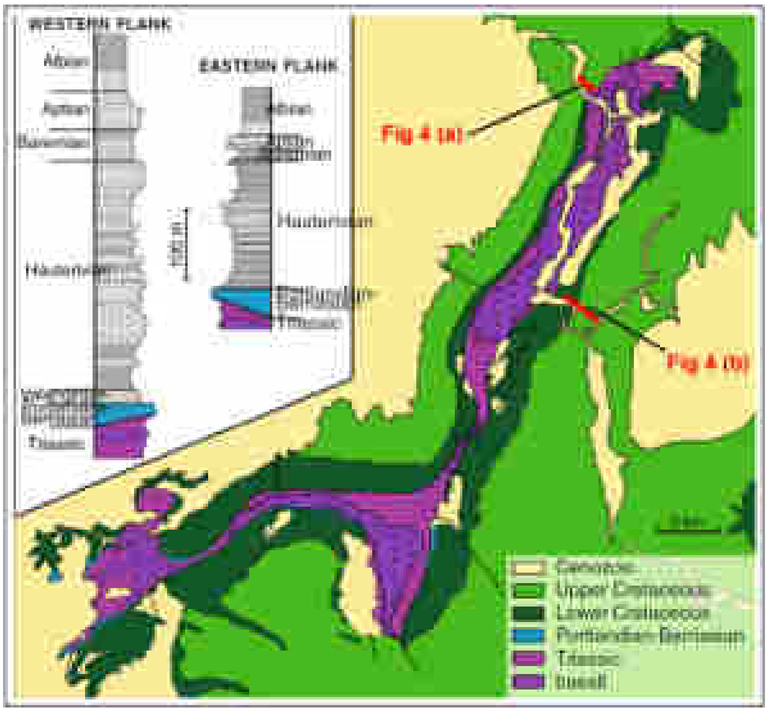
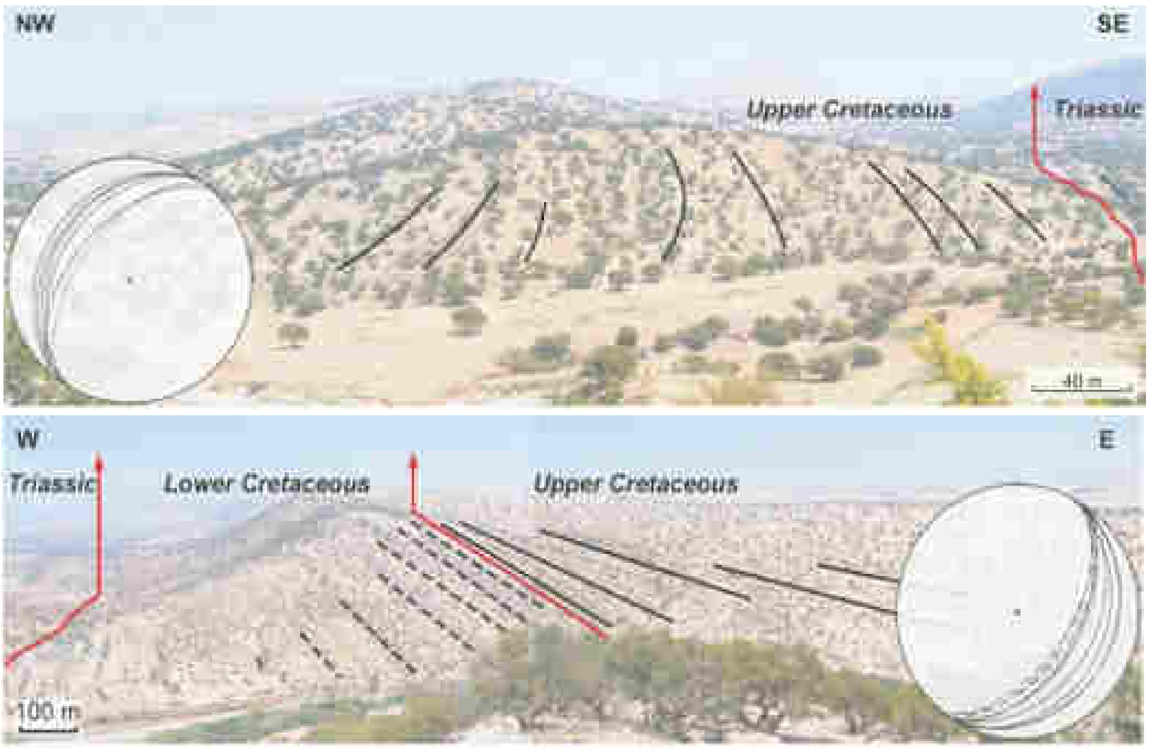


Fig. 3. Map of the Tidzi anticline. Representative stratigraphic columns for the western and eastern sides of the structure are shown in the insets, after the 1:100,000 geological map of Morocco (Tamanar sheet)



(a)

(b)

Fig. 4 Syn-sedimentary wedges along the N–S trending flanks of the Tidzi anticline.
See **Fig.**3 for location.

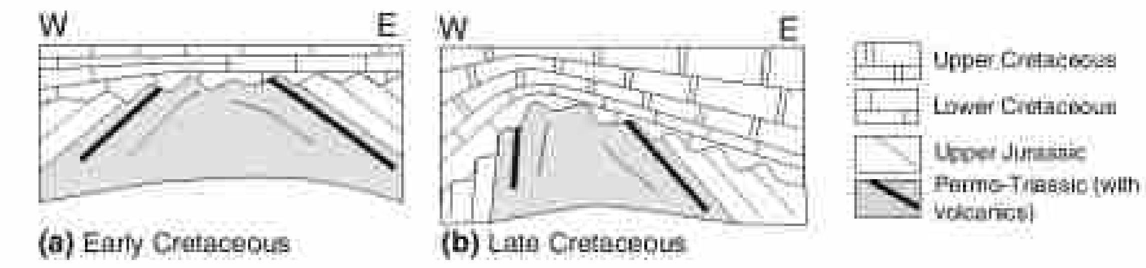


Fig. 5 Evolutionary scheme of the Tidzi anticline in pre-Alpine times

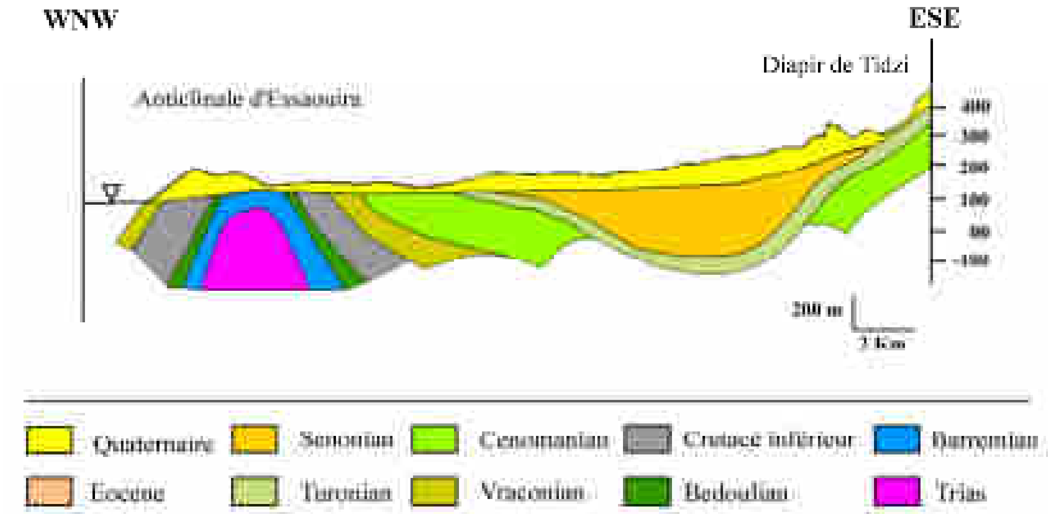


Fig. 6 Geological section of the syncline of Essaouira (After Fekri 1993, modified). For location, see Fig. 1, section AB.

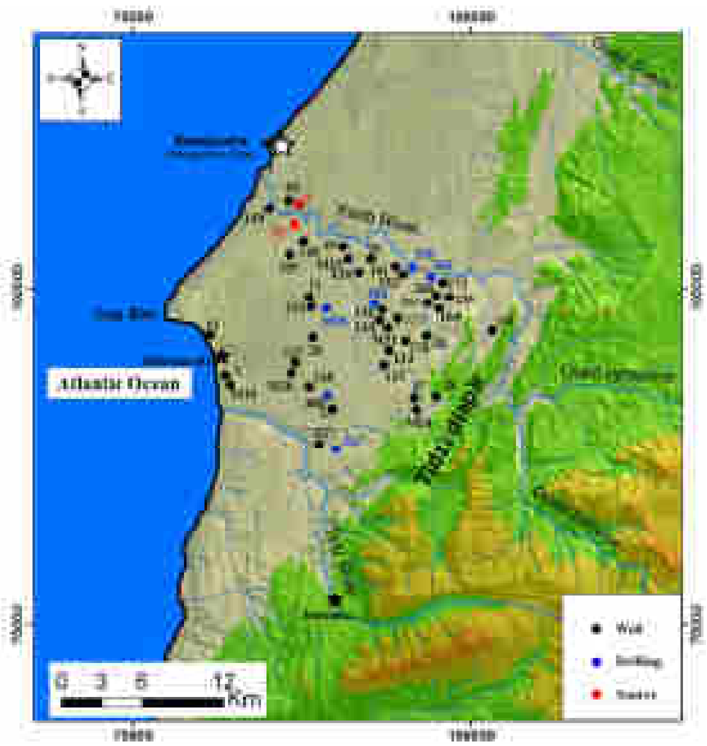


Fig. 7 Map showing the water points of the Essaouira basin

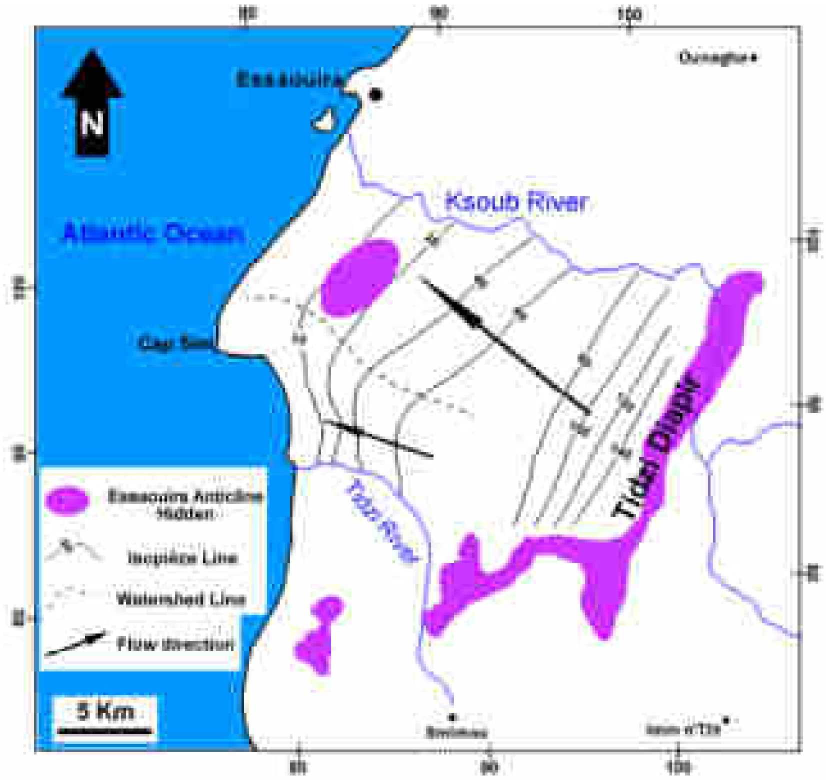


Fig. 8 Essaouira basin piezometric map in October 2009.

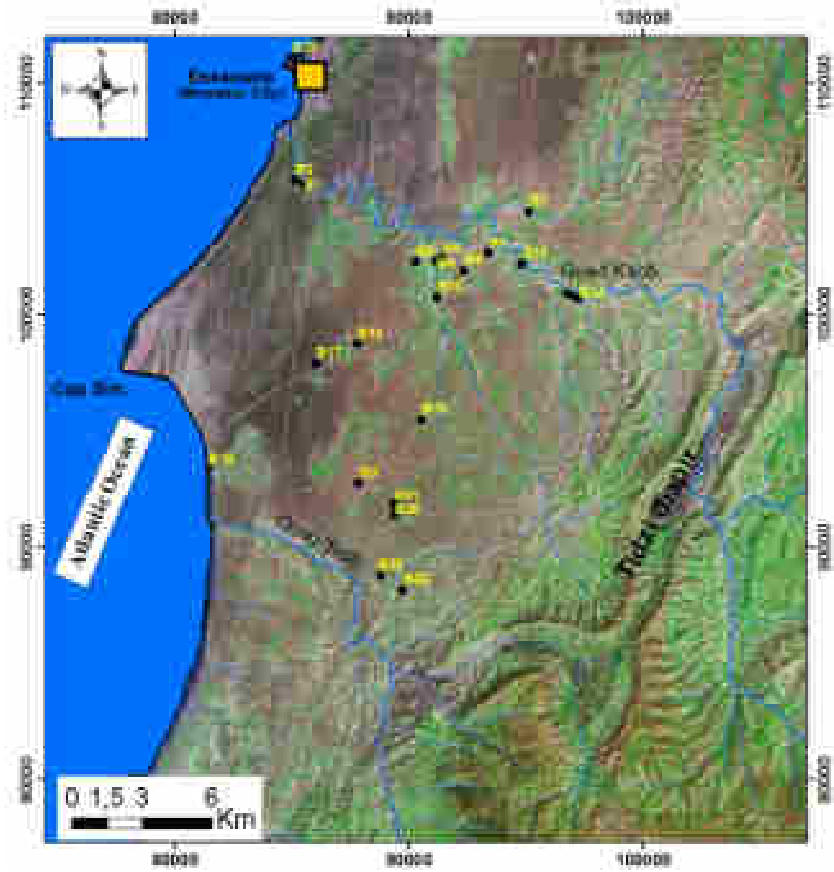


Fig. 9 Distribution of sampled water points in the study area.

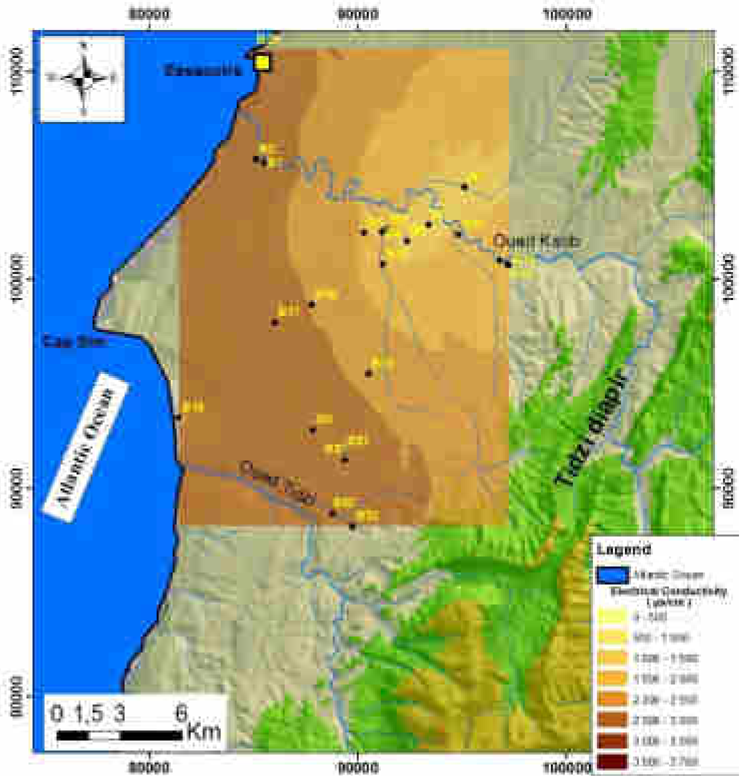


Fig. 10 Spatial distribution of Electrical Conductivity in the Essaouira Basin.

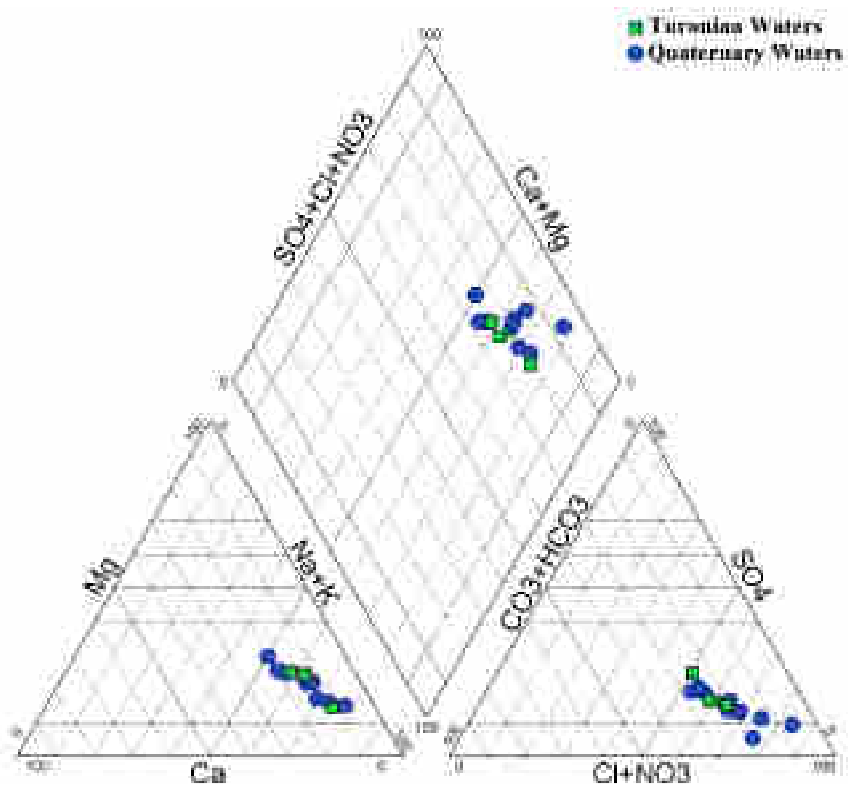


Fig. 11 Piper diagram of Plio-Quaternary water and Turonian water.

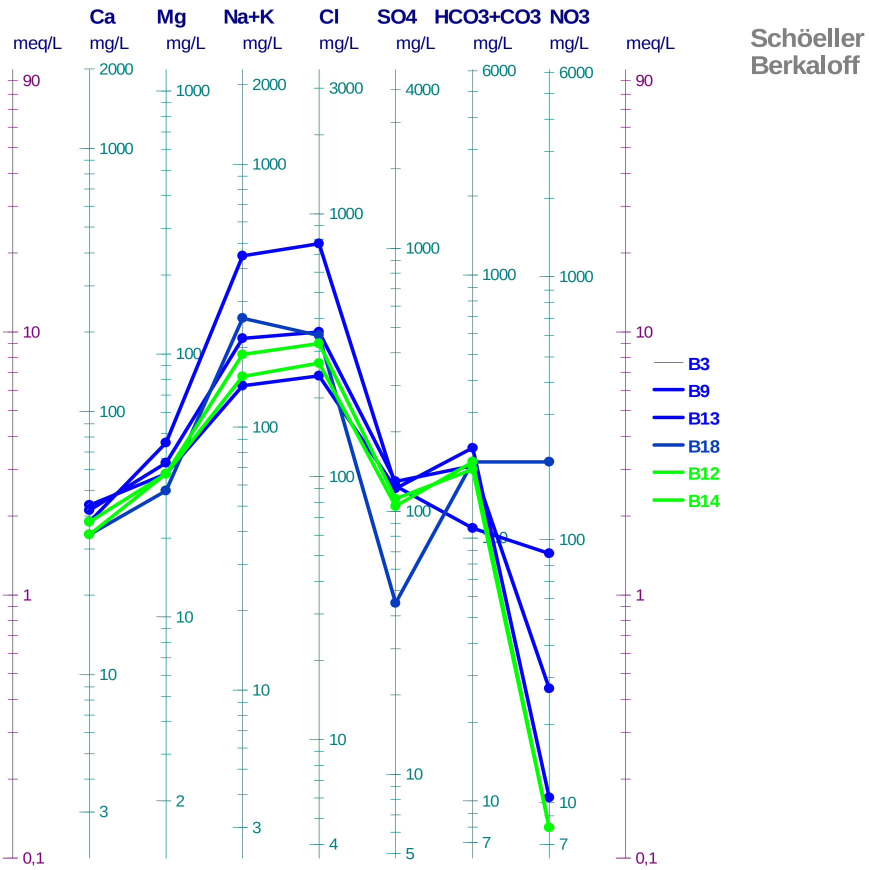


Fig. 12 Facies chemical wastewater Plio-Quaternary (B3, B9, B18 B13et) and Turonian (B12 and B14).

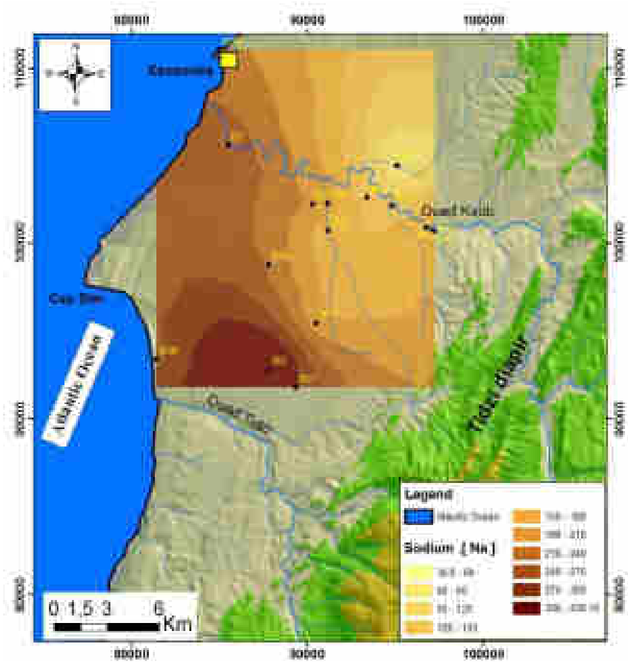


Fig. 13 Spatial distribution of sodium in the Essaouira Basin Syncline.

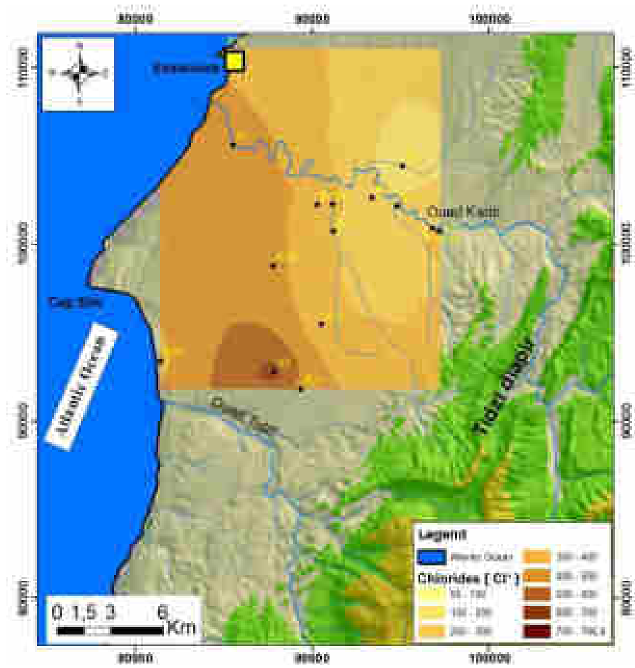


Fig. 14 Spatial distribution of in the Essaouira Basin Syncline.

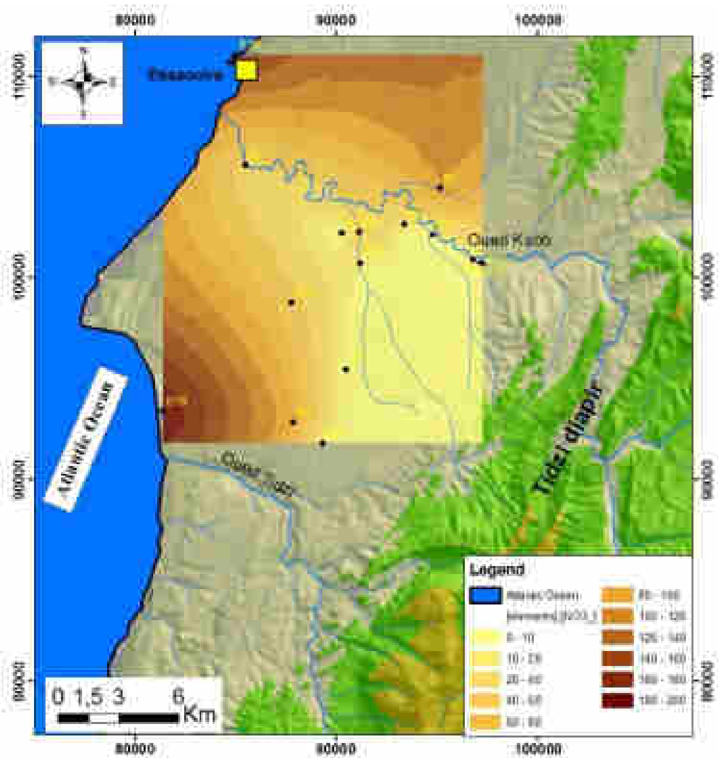
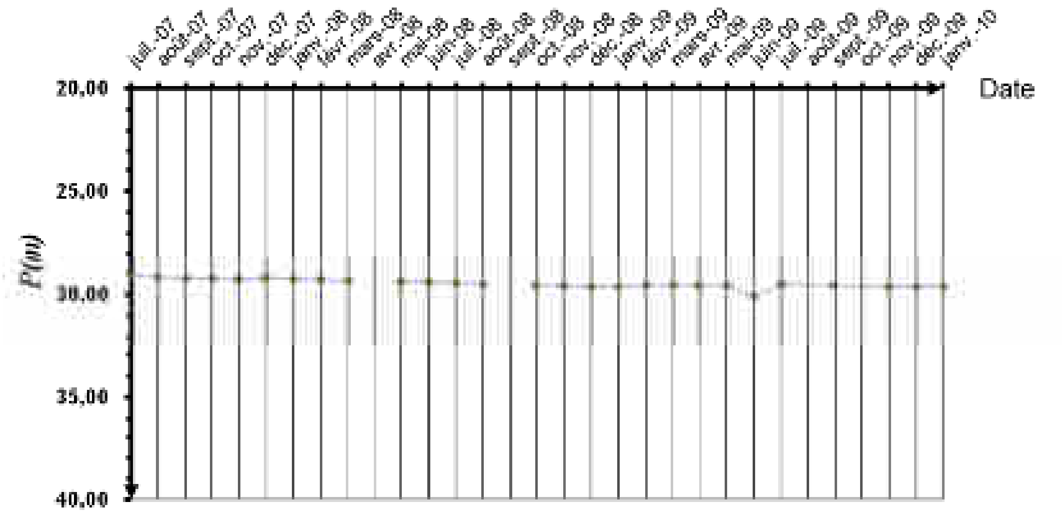
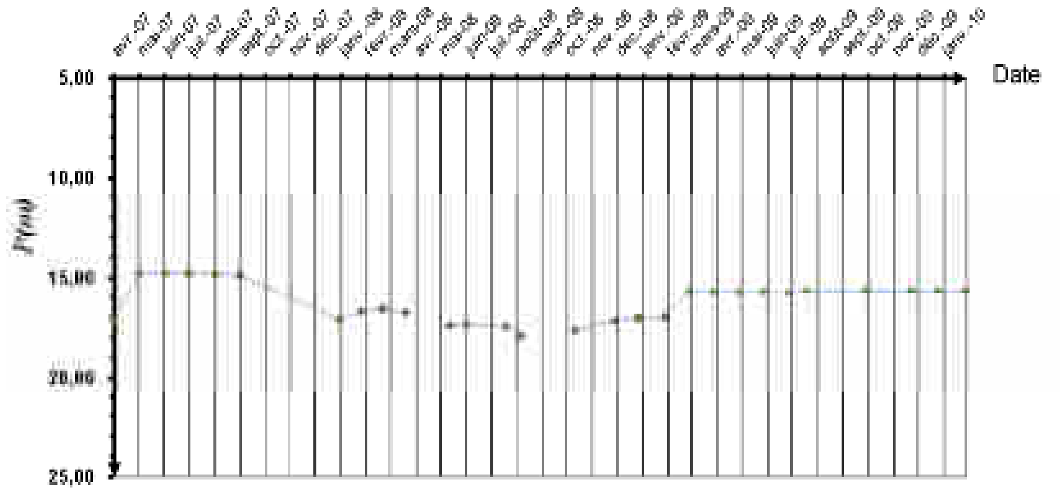


Fig. 15 Spatial distribution of nitrates in the Essaouira Basin Syncline.

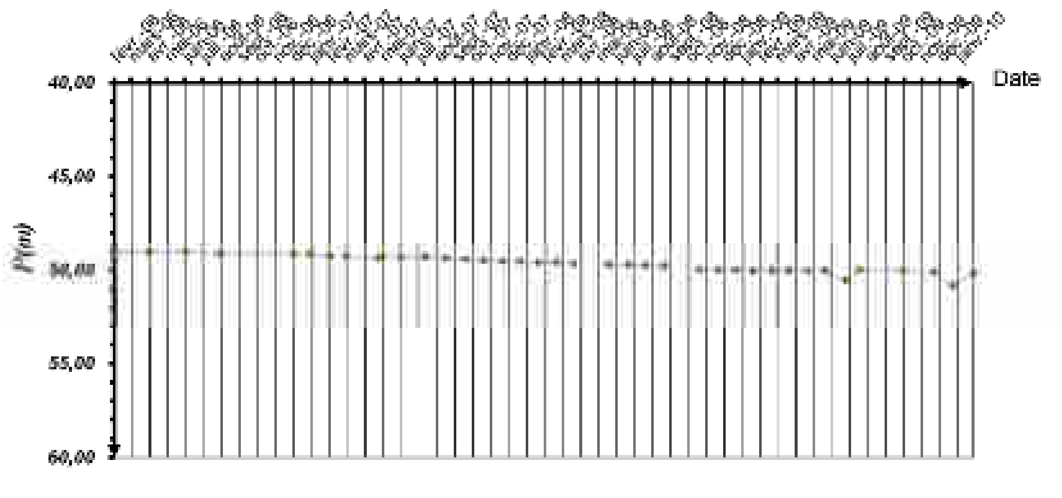
Fig. 16. Location of stations piezometric measurements over the basin of Essaouira.



(a)



(b)



(c)

Fig. 17 (a) Evolution of the piezometric level at the station Ida Ouguerd Douar. Bouzima 93/5, **(b)** Evolution of the piezometric level at the station Adamna **c** Evolution of the piezometric level at the station Ouguer, **(c)** Evolution of the piezometric level at the station Ouguer

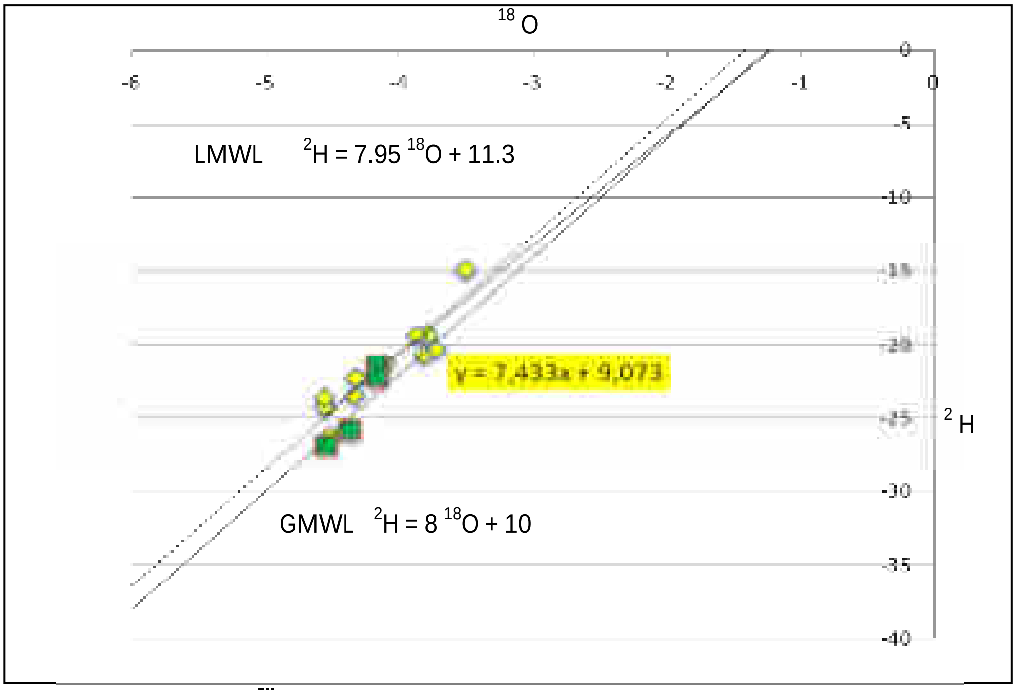


Fig.18 Relationship (^{18}O / Deuterium) the groundwater in the area of Essaouira synclinal.

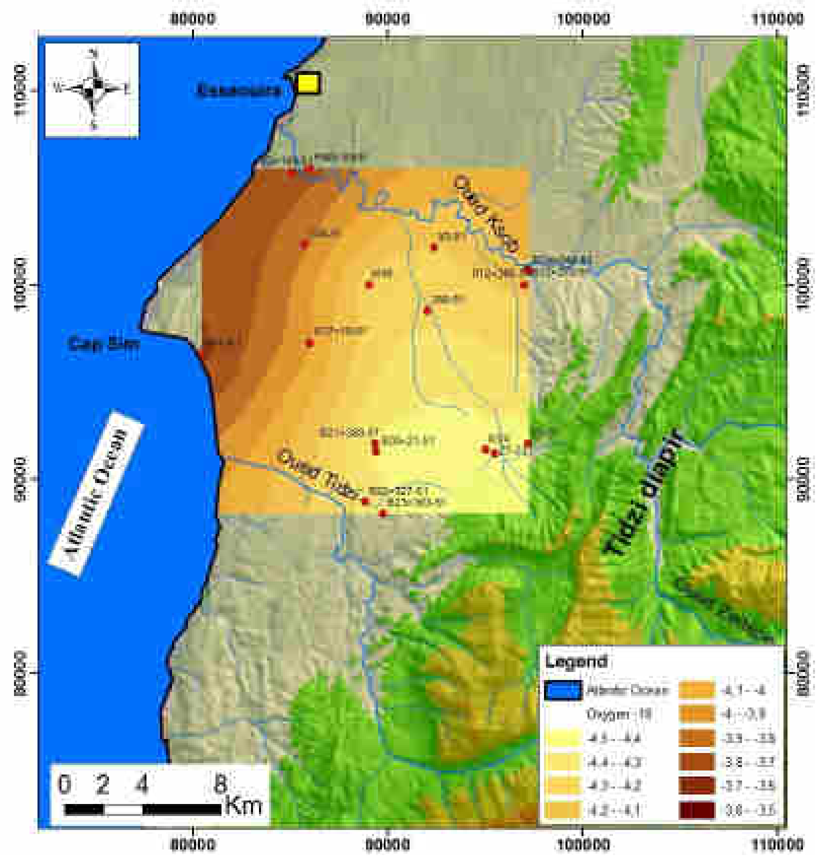


Fig. 18 Spatial distribution of oxygen 18 in the Essaouira Basin Syncline.

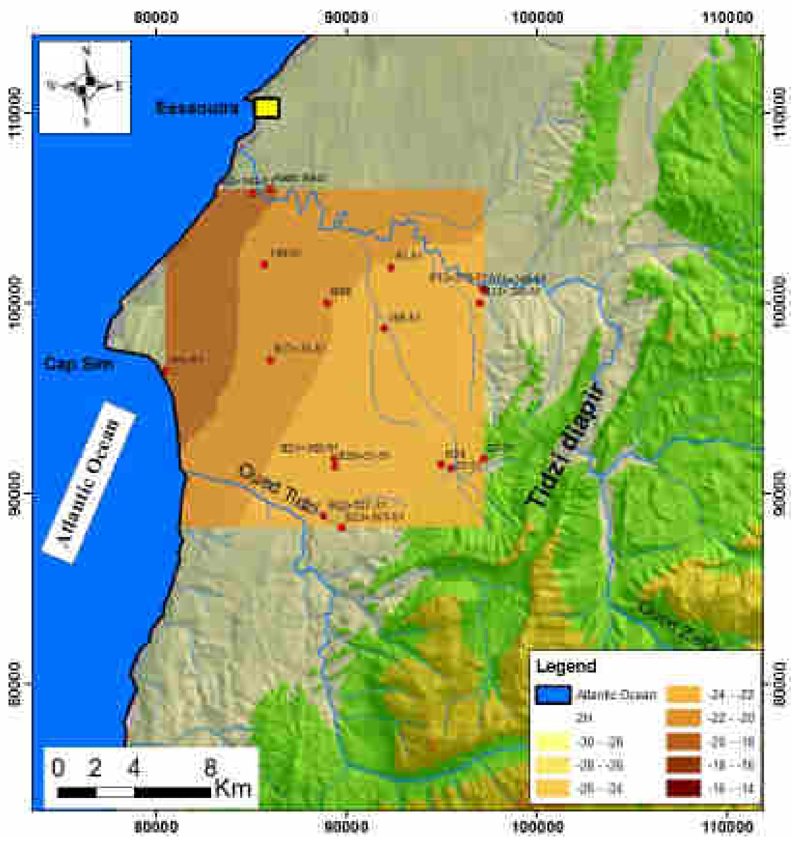


Fig. 19 Spatial distribution of Deuterium in the Essaouira Basin Syncline.

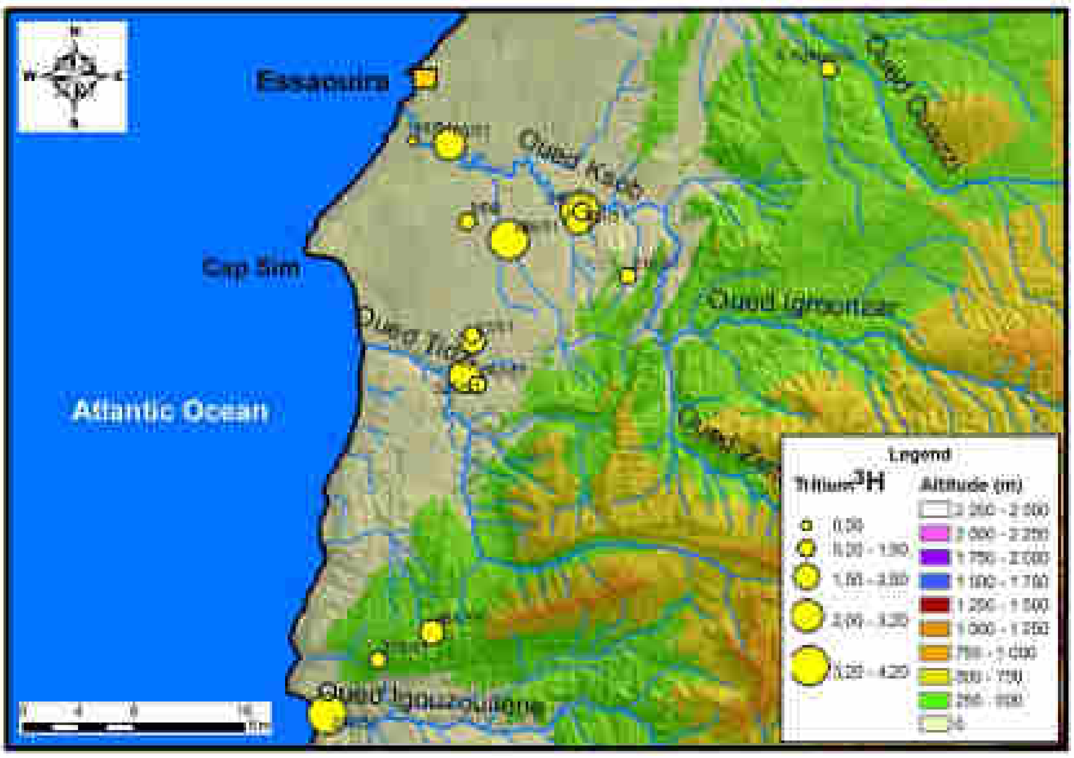


Fig. 20 Spatial distribution of tritium analysis.