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Contribution of GIS in the Mapping, Interpolation and Modeling of Isohypses of the Pliocene Aquifuge of the Free Water Table of the Fez-Meknes Basin

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ABSTRACT

In order to model the water flow of the free Quaternary aquifer of the Fez-Meknes basin, it is essential to determine the precise geometric limits of the aquifer. Indeed, the characterization and representation of the underground structure of the Miocene marl top which forms the aquiclude of the aquifer, constitutes the fundamental step to study and understand its influence on the groundwater flow. This study is facilitated by the available data, which allow to represent the underground formations on isohypses maps. The data base is formed by reconnaissance drillings, and the extraction of marl altitudes from previous geological works. During this work the generation of the marl top elevation map was based on the test of four interpolation methods, which correspond to : Kriging, IDW method, Natural Neighbors, and Topo to Raster, in order to choose the most reliable and best suited to the study area. On the one hand, the calculation of the conformity index between the values measured in the field and the estimated values for each method was successively (0.9796, 0.9848, 0.9814, 0.9842). On the other hand the values of the root mean square error (RMSE) were successively (13.59, 7.42, 21.27, 14.01). The comparison of these results allowed us to choose the IDW interpolation as the most reliable and suitable to interpolate the top of the aquiclude of the free water table of the Fez Meknes basin with a compliance index the highest and a RMSE the lowest compared to other methods.

Keywords: water table, substratum, interpolation, root mean square error.

INTRODUCTION

Worldwide, freshwater accounts for 2.8% of the global water volume, of which only 0.7% is reserved for groundwater (Cuenca et al., 2020). During the last 100 years, global water use has increased sixfold, and continues to increase rapidly at about 1% per year. The restriction of water resources and the pessimistic forecasts of their evolution are certainly the most important concern for a sustainable development of the countries located south of the Mediterranean. These are the countries most affected by this restriction, and by episodic droughts, given the seasonal nature of water resources, the natural interannual variability (Martinez et al., 2004), the high anthropic demand for ground and surface water (Anderson et al., 2012; Bolle et al., 2003). Morocco is among the countries that do not escape this observation. Consequently, groundwater is subject to overexploitation due to the continuous increase in needs following the extension of irrigated agriculture, the improvement of the standard of living, the demographic growth, the urban, industrial and tourist development.

The Sebou basin is one of the most important basins in the kingdom as it is one of the richest basins in groundwater in Morocco. The latter represent about 20% of the national potential. They are estimated at 800 Mm^3/year spread over several aquifers (Fez-Meknes, Maamora-Gharb, Middle Atlas Causses, Bou Agba, Fez-Taza corridor, Middle Atlas folded Taza) (ABHS, 2008). These aquifers are vulnerable to overexploitation and drought. The Fez-Meknes basin, which corresponds to the area of our study, is one of the basins constituting an important part of the hydraulic heritage of the Sebou basin. It ensures the supply of drinking and industrial water to urban and rural centers, and the satisfaction of the water needs of irrigated areas. The latter represent a total area of about 77.4% of the useful agricultural area (350,000 ha), of which 35,000 ha is irrigated from groundwater, and the rest in rainfed (ABHS, 2008). Groundwater in the Fez-Meknes basin has an undeniable contribution to the socio-economic development of the region. However, these water resources are subject to overexploitation due to the reduction of rainfall (El Ibrahimi et al., 2015; El Kamel et al., 2015), and to withdrawals for different uses (industrial, agricultural and domestic). This is the reason why we aim to model the underground flows of the free water table in the study area. However, it is essential to describe and determine precisely the geometric limits of the aquifer as its boundary and initial conditions, given their importance in the evaluation of the resource and the aquifer reserve on the one hand. On the other hand, the determination of its stratigraphic characteristics conditions the validity of the model. From a hydrogeological point of view, the Fez-Meknes basin is differentiated into two important aquifer reservoirs, of which the free surface water table circulates in the Plio-Villafranchian formations, while the deep water table is that of the dolomitic limestone of the Lias. These two nappes communicate with each other in places, either directly by flexures and faults or indirectly by upward drainage (Martinez et al., 2004; Belhassan et al., 2010). They are separated by the Miocene marls which constitute the impermeable substratum of the free water table. The latter has been the subject of work by several authors (Didi et al., 2017; Amraoui, 2005; Essahlaoui Ali, 2000; Harmouzi, 2010; Harmouzi et al., 2009). The characterization and representation of the subsurface structure of the marl roof, through the design of GIS (Mili et al., 2013; Mili et al., 2018) is the fundamental step to study its influence on the storage and circulation of groundwater. During this work, the generation of the isohypses map of the marl bedrock roof, is based on the test of four interpolation methods suggested by the ArcGIS software (Kriging, IDW, Natural Neighbors, and Topo to Raster), with the aim of having a map by the most representative and most suitable for the study area.

STUDY AREA

The Fez-Meknes basin is a vast syncline (total area 2100 km^2) asymmetric E-W. It occupies the median part of the south rift furrow, and extends from the threshold of El Kansera and the valley of Wadi Beht in the west to the Touahar pass to Taza in the east. The regional synthetic log of the basin (Figure 1) shows a marked vertical lithostratigraphic variability. Indeed, the Paleozoic is represented by shales and flysch, surmounted by formations called triassic trilogy (red clays with intercalation of basalts). These are followed by limestones and dolomites of the Lower Jurassic. Then the Neogene fill comes to settle on top of the primary and secondary deposits (Figure 2). During this study we will focus on the geological context of the Miocene substratum.

Miocene

The Miocene sequence unconformably overlies the Liassic terrains in the South Rifian trench. Its thickness varies gradually from a few meters in the south of the basin at the contact with the middle Atlasian causses, to several hundred meters at the contact with pre-Rifain rifts up to 1000 m. This sequence is subdivided into Lower, Middle and Upper Miocene:

a) Lower Miocene

Begins with a transgressive facies of molasse, sandstone, conglomerate, and sandy limestone of Aquitanian age, followed by detrital or biodetrital sandstone, sandstone, conglomerate and marl attributed to the Burdigalian.

b) Middle Miocene

Consists of a very thick layer of blue marl with intercalation of some sandstone levels.

c) Upper Miocene

- Tortonian begins with the deposition of a calcareous sandstone facies with marl pasts that can reach a dozen put, on which develops the deposition of an important sedimentary series of gray and blue marls interspersed with sandstone turbidities whose thickness can reach 1000 m;
- Messenian is directly discordant in places on the Triassic and sometimes on the Paleozoic. This stage is similar to the Tortonian. It is represented by a continuous and homogeneous sedimentation of grey marls. The latter locally present sandstone intercalations. It is not totally absent in the Meknes plateau, but we note

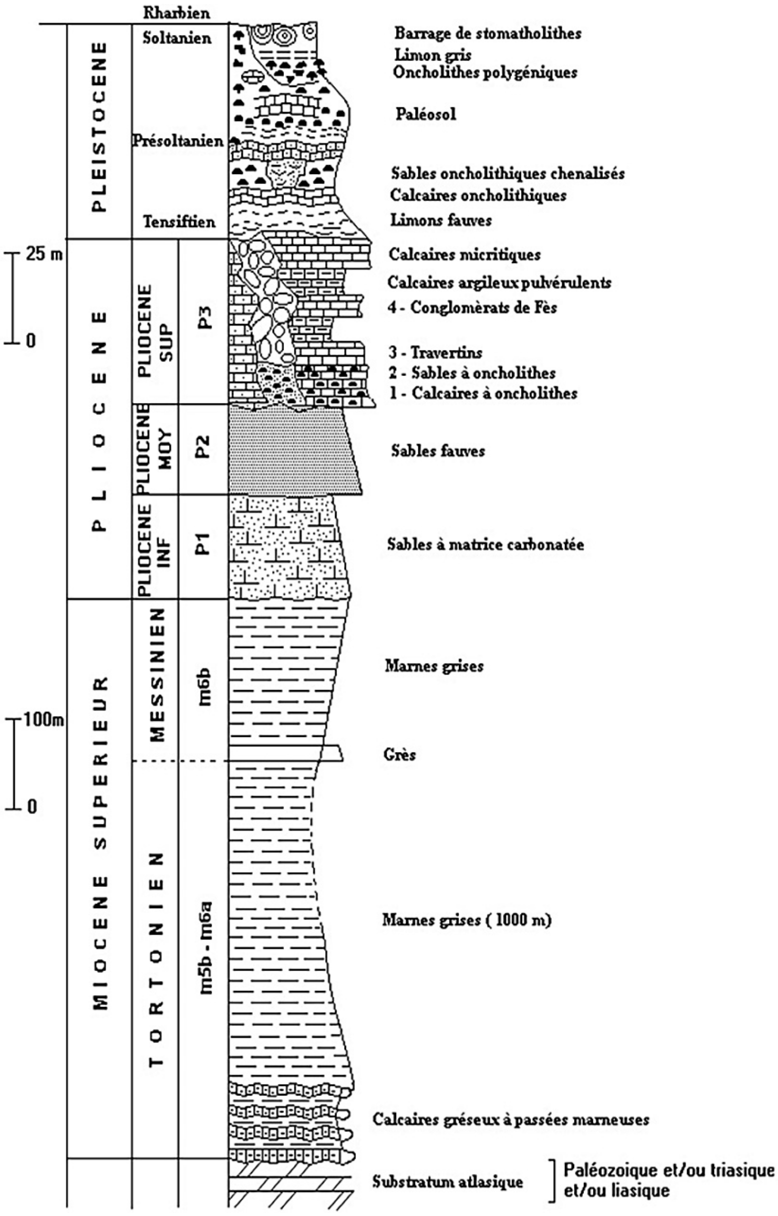

Figure 1. Synthetic lithostratigraphic log of the Fez-Meknes basin (in Chadli, 2005)

locally a sandstone level at the base, while at the top the facies changes to a marl and limestone sedimentation.

Pliocene

These formations surmount those of the Miocene. They are essentially represented by lacustrine limestones, sands and poudingues. On the Saïs plain the lacustrine deposits have a power of 40 to 100 m, and rest directly on the Tortonian.

1. Lower Pliocene is constituted by sands with a carbonate matrix, which overlie the grey marls of the Messinian and in the upper Pliocene change to sands which will constitute the future tawny sands.
2. Middle Pliocene is represented by sands formed by detrital material reworked from older sedimentary formations (Paleozoic, Jurassic and Miocene). Their colors are variable (red, brown, yellow, ochre and gray). This sandy series has an average thickness of about thirty meters. The outcrops are well visible in the plateau of Meknes.
3. Upper Pliocene corresponds to a lacustrine facies, materialized by an alternation of pulverulent clayey limestones and micritic limestones of 30 m thickness. In the plateau of Meknes, their average thickness is 20 m, they cover the sands, where they are interbedded in the latter and puddings (Chadli, 2005).

Quaternary

The top of the series is composed by deposits of known age by their heterogeneities (Amraoui, 2005), materialized by tawny silts, oncolithic limestones, and oncholitic sands.

STRUCTURAL SETTINGS

From a structural point of view, the Fez-Meknes basin is composed of two units corresponding to the Meknes plateau and the Saïs plain. They are specified by numerous families of faults and flexures, related to the structural evolution of the domains limiting the basin (Middle Atlas and the Rifan domain) (Charroud et al., 2006). These faults are of general direction NE-SW, E-W and NW-SE, which explains a tectonic-sedimentary and geodynamic evolution in several phases. The Fez-Meknes basin is characterized by two clearly individualized slopes in its topography that correspond to those of Tiniza-Ait Zaouit and Ain Taoujtat. This last flexure divides the study area to the Saïs plain and the Meknes plateau.

The plateau of Meknes

It occupies the western part of the basin with an altitude between 600 and 700 m and rises at the contact of Jbels Kafs and Zerhoun (Ahmed et al., 2016). It appears as a platform affected by 6 flexures of average direction NE-SW to NNE-SSW. These constitute the northern extension of the great Hercynian structural lineaments, which mark the central Paleozoic massif. These flexures are W to E (Figure 3):

- Aïn Lorma flexure;
- flexure of Toulal with a length of 12 km;
- flexure of Koudiat Zouar to the W of Boufekrane with a length of 23 km;
- Boufekrane-Haj Kaddour (or El Hajeb - Sebâa Aïoun), 25 km long;
- flexure of Souk Jemaa;
- flexure of Tiniza (ABHS, 2008).

Saïs plain

A number of flexures and topographic accidents of average NE-SW to ENE-WSW orientation appear on the plain. They are arranged in a kind of fan closing in W direction. The tectonic lineaments that specialize the plain correspond to

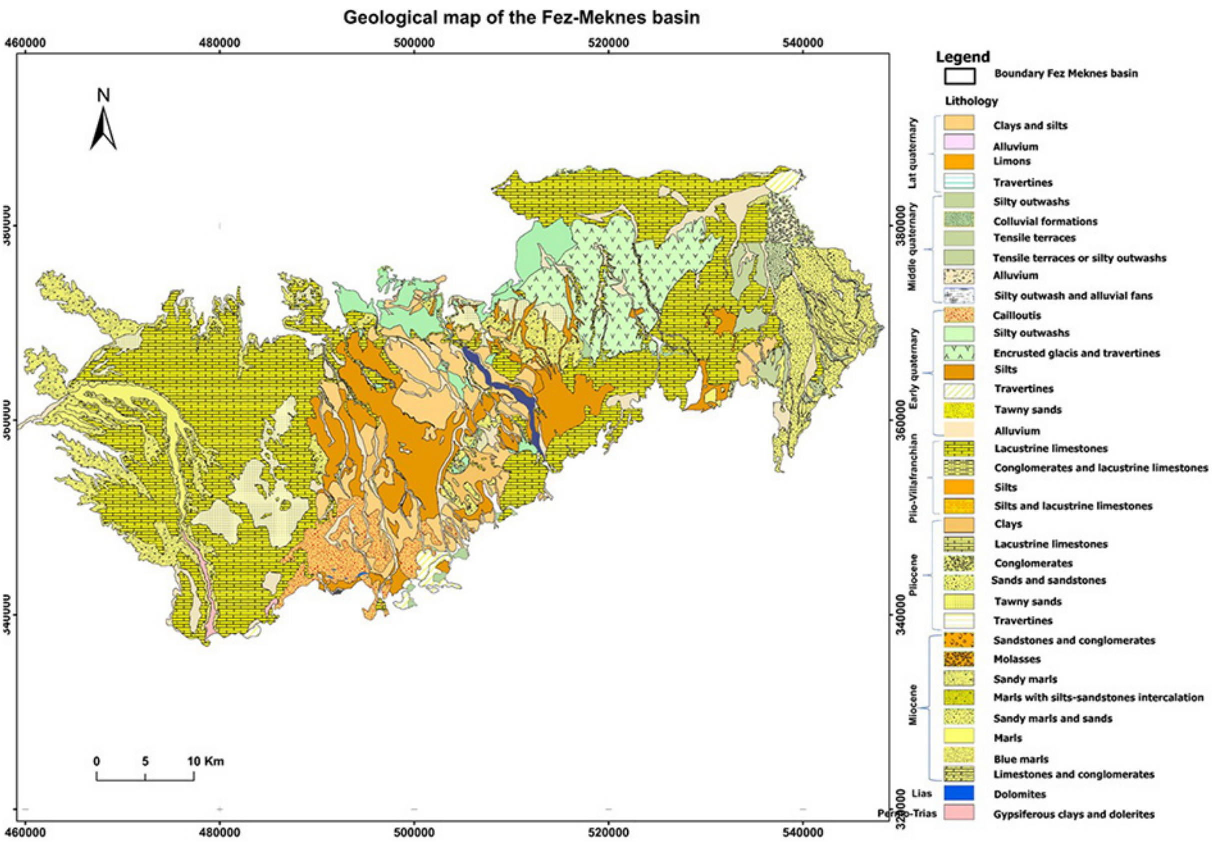

Figure 2. Geological map of the Fez-Meknes basin

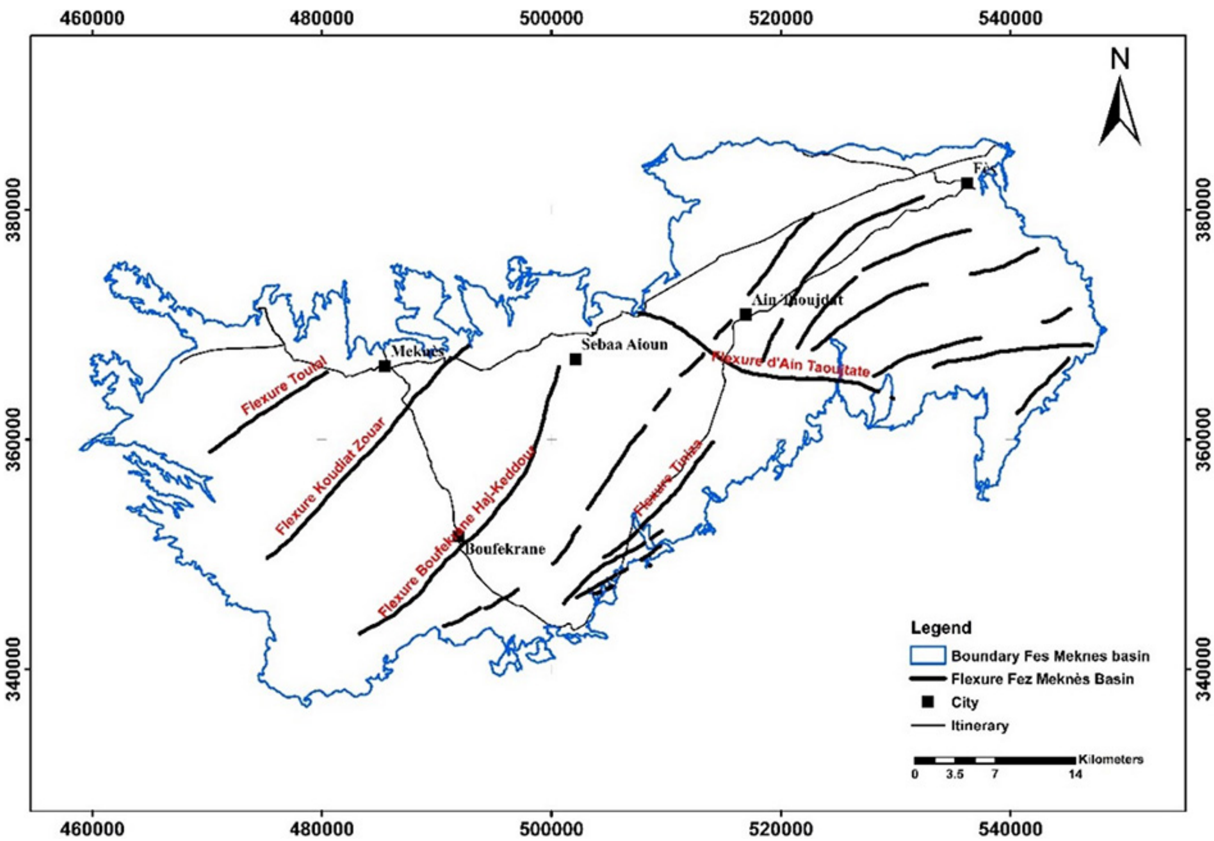

Figure 3. Flexures majeurs dans le bassin Fès-Meknès (in Amraoui, 2005)

those of Aïn Chegag, Ras El Ma and Bensouda (Benaabidate, 2010). The Rasel-Ma flexure subdivides the Saïs plain into two parts : the Fez flexure to the SE, and the Aïn-Taoujdate flexure to the NW. They are the result of the replay of Miocene faults into reverse faults allowing the creation of tectonic ramps at depth (Charroud et al., 2007). Between the Aïn-Taoujdate flexure and the city of Fez extends a low area with a relatively monotonous flat topography (varying between 250 m and 600 m), poorly drained and marshy (Douyet pond) (El Garouani and Aharik, 2021). This morphology is generated by watercourses not very deep and in some places stagnant, following their slope clearly low (Amraoui, 2005).

HYDROGEOLOGY

From a hydrogeological point of view (Figure 4), the Fez-Meknes basin is characterized by two important aquifer reservoirs. These are the free surface water table which circulates in the Plio-Villafranchian formations and the water table which circulates in the dolomitic limestone of the Lias. The aquifer system of the Fez-Meknes basin can be classified as a monolayer aquifer formed by several superimposed strata, with a vertical heterogeneity of facies. This induces a variation in permeability parameters (especially horizontal permeability) (Figure 4). It is fed mainly by direct inflow from the free part of the Liassic water table (Belkhirri, 2007; Bahaj et al., 2004), by the return of irrigation water, and by rainfall infiltration (Amraoui, 2005). Research in the region has identified rainfall infiltration and upward drainage as the main inputs to the unconfined water table, (Belhassan et al., 2010; El Ibrahimi et al., 2015). The Liassic water table is free at the level of the middle Atlasian causse, and then sinks under the thick series of impermeable Miocene marls (Belhassan et al., 2010), which put it in charge under the Fez-Meknes basin to constitute the captive water table. These two nappes intercommunicate in places either directly by flexures and faults, or indirectly by upward drainage.

METHODOLOGY

In order to map the top of the marl aquiclude, a database developed from the results of previous work was collected and structured. We distinguish

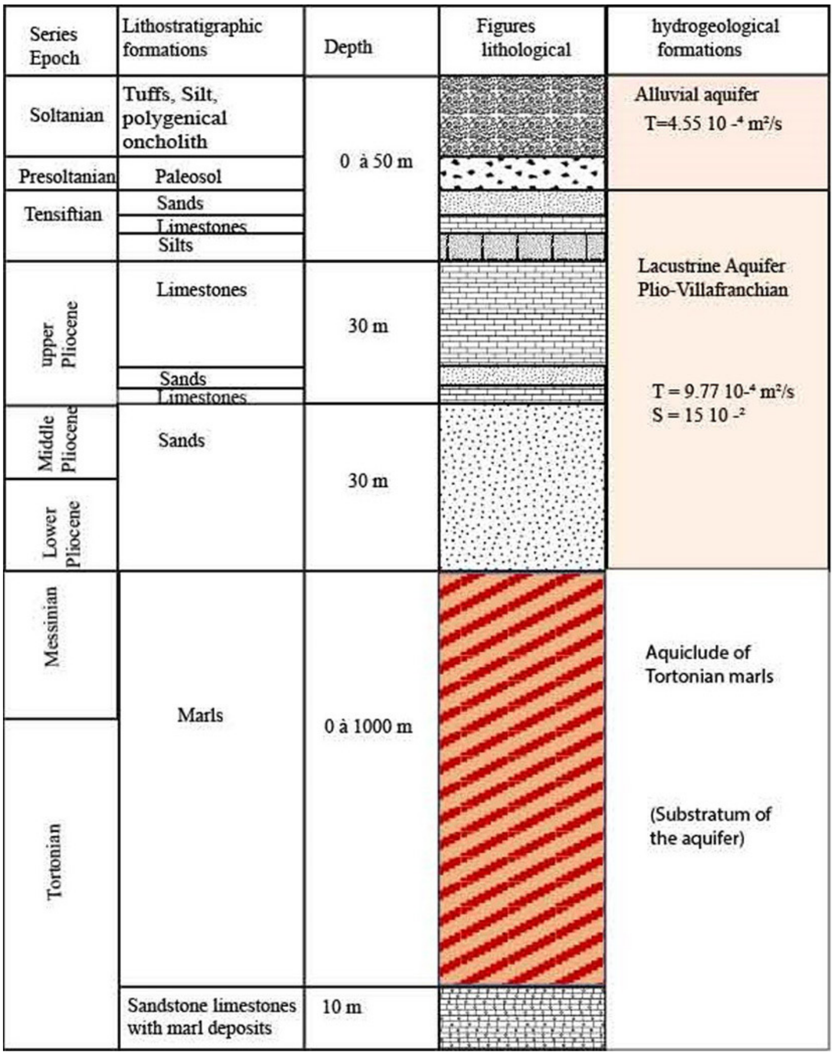

Figure 4. Hydrogeological column of the Plio-quaternary formations of the Fez-Meknes basin

a thematic database and a spatial database. The latter contains geological maps (El Hajeb 1/100000, Meknes North 1/100000, Sefrou 1/100000), geotechnical map of Fez 1/20000, hydrogeological map of Margat 1/100000, topographic maps 1/500000 of (Meknes, El Hajeb, Sefrou, Agouray, Taoujtat, Sebaa Ayoun, Fez East, Fez West), and structural maps. The delimitation of the study area was based on digitization following the boundary between the formations of the Fez-Meknes basin and the impermeable formations that belong to the domains that border it (Agouray causse, El Hajeb causse, Sefrou Causse, Immouzer causse, the pre-meridian wrinkles, El Gharb plain) using the geological maps cited above. As for the thematic data, they were collected on the basis of 365 reconnaissances drillings, (Agency of the Sebou Basin: ABHS), They aim to designate vertically the succession and the nature of the geological formations constituting the subsoil and the extraction of the altitudes of the top of substratum. In the same sense the altitude of marl was extracted from the digitization of the map of the top of Miocene of the hydrogeological map of Margat and that carried out by Amraoui 2005, as well as the extraction of the altitudes of the marly outcrops in the basin using geological maps (El Hajeb 1/100000, Meknes North 1/100000, Sefrou 1/100000), geotechnical map of Fez 1/20000) and the NTM of the area. All the information related to the altitude of the Miocene marls are recorded in a single attribute table containing columns that indicate the IRE number of each borehole, its geographical coordinates, the altitude of the marly substratum.

After the collection of data it appears essential to correct the altitude of the marl formations obtained by the DTM, and then proceeded to make a detailed exploratory analysis which is a necessary step allowing the detection of abnormal values, and the study of spatial correlations of data (Johnston, 2004). This will serve to obtain a more representative interpolation to our study (Thomas, 2003). Interpolation consists in translating information available for a limited number of locations into information available for the whole space. In fact it is a mathematical process that aims at estimating values for unknown points based on points with known values. The contribution of GIS software is very important in regional hydrogeological mapping (Boisvert et al., 2008). During this study we referred to the ArcGIS software that integrates the applications: ArcCatalog, Arctoolbox and ArcMap.

In order to model the water flow of the free Quaternary water table of the Fez-Meknes basin, it is necessary to interpolate the altitude of the top of marl obtained from different sources by four interpolation techniques: Kriging, IDW (inverse distance weighting) method, Natural Neighbors, and Topo to Raster. The interpolation must be limited beyond the contours of the marl outcrops in the study area. Finally, we will compare the values of the conformity index and the root mean square error (RMSE), for the four methods. This will be used to produce the closest and most representative map of reality.

RESULTS AND DISCUSSION

After the extraction of the heights of the Miocene marls that outcrop in the Fez-Meknes basin from the DTM requires a correction. Indeed, such a difference is noticed when comparing it with the heights presented by the topographic maps. This difference varies from one area to another over the entire study area. Indeed, the average error noted in the western part, is about -14.66 m, in the southwestern part is about -10.76 m. The southern end of the marly outcrops has a higher margin of error than the other areas. Indeed, it reaches an average of about -55.54 m. It has been corrected from the Agouray topographic map. As for the eastern part of the basin, the error reaches -5.25 m. Then we move on to the use of the tools offered by ArcGIS which are necessary for the exploratory study. Indeed, they allow to elaborate a semi-variogram model which releases the spatial auto correlation between the measured marl heights.

The observation of the variographic cloud (Figure 5) allows to define an isotropic distribution of the measurement points. The shape of the borehole cloud is adapted to a Gaussian model. The nugget effect is null, because the bedrock altitude varies regularly on a very short scale. That

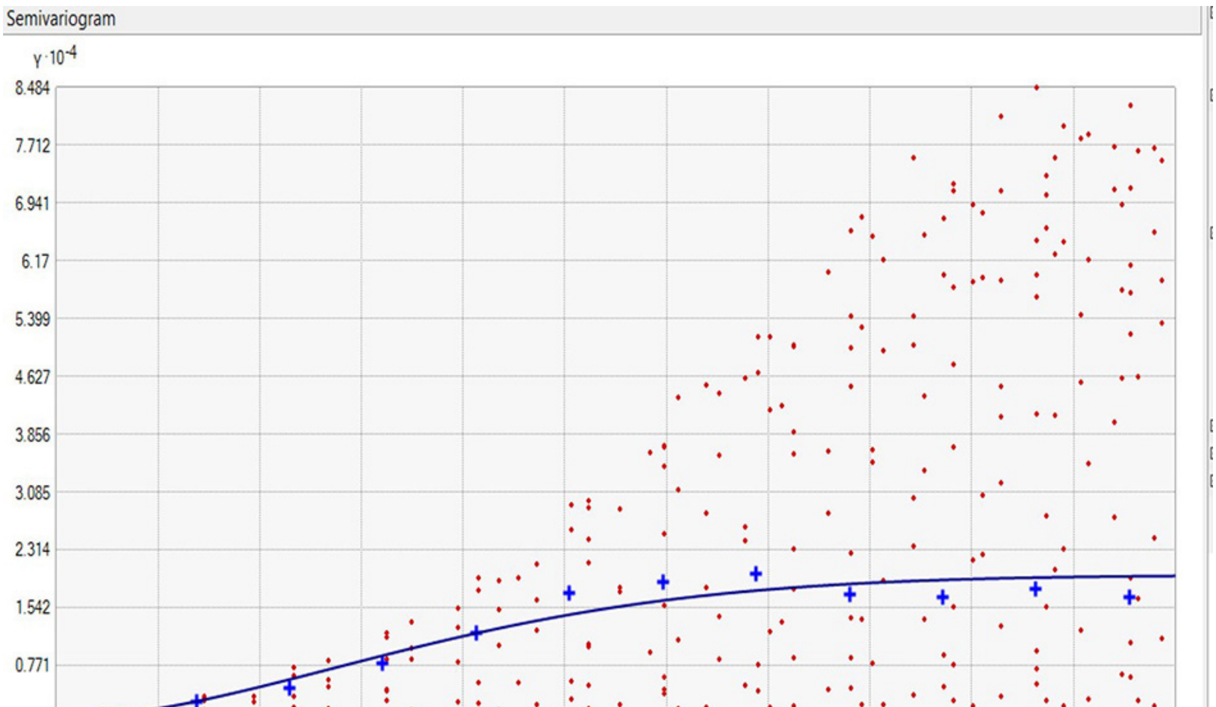

Figure 5. Semi-variogram model of the Miocene marl top elevation

is, there is a very small difference between the altitude measurements at the same location.

In ArcGIS the first step before interpolating the measurements is to make a histogram of the data (Figure 6) to represent the distribution of the marl elevation. The analysis of the figure reflects the distribution of the data as a unimodal symmetrical series with some values having a high

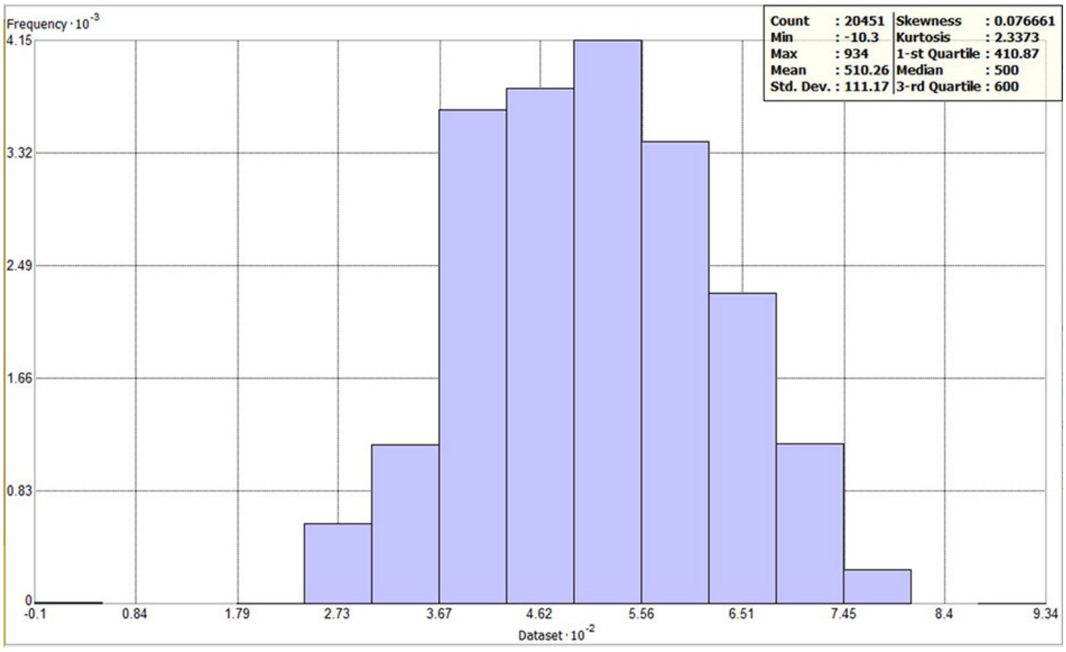

Figure 6. Frequency histogram of top elevation of the Miocene marl

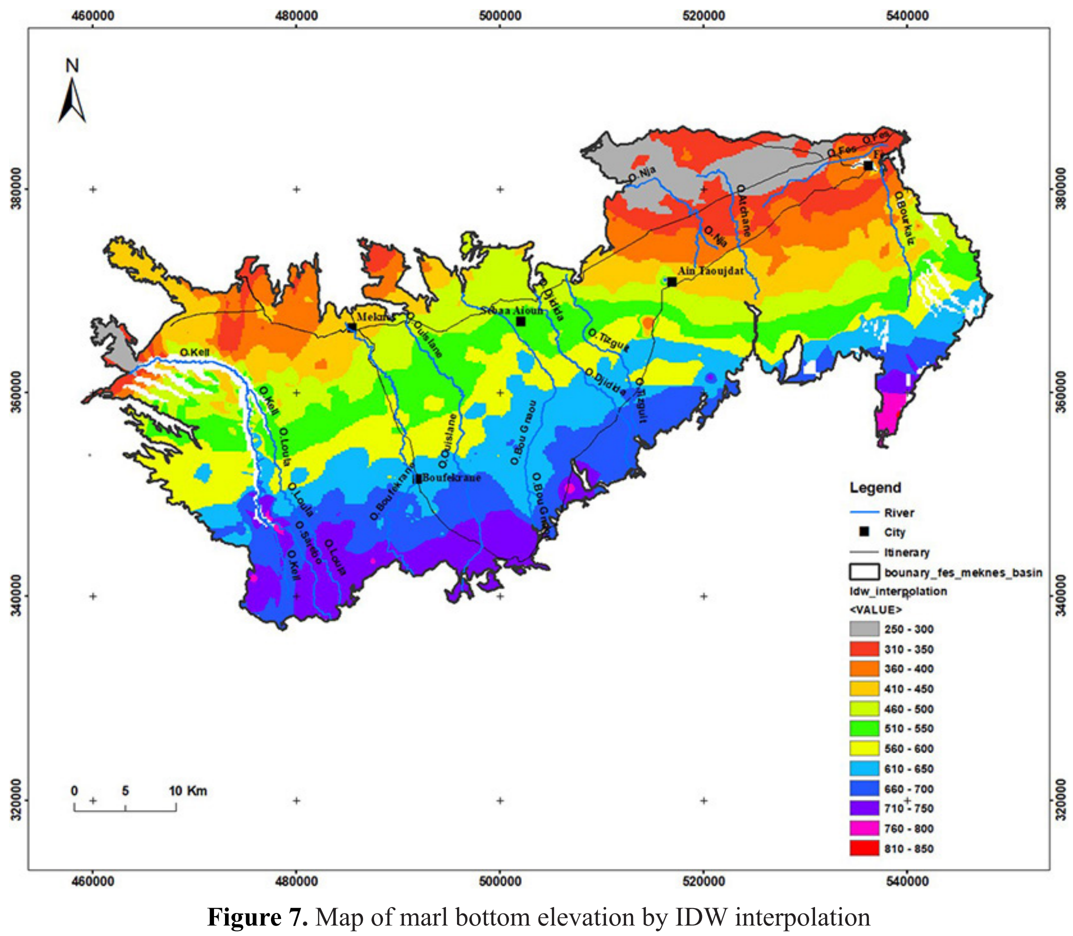

Figure 7. Map of marl bottom elevation by IDW interpolation

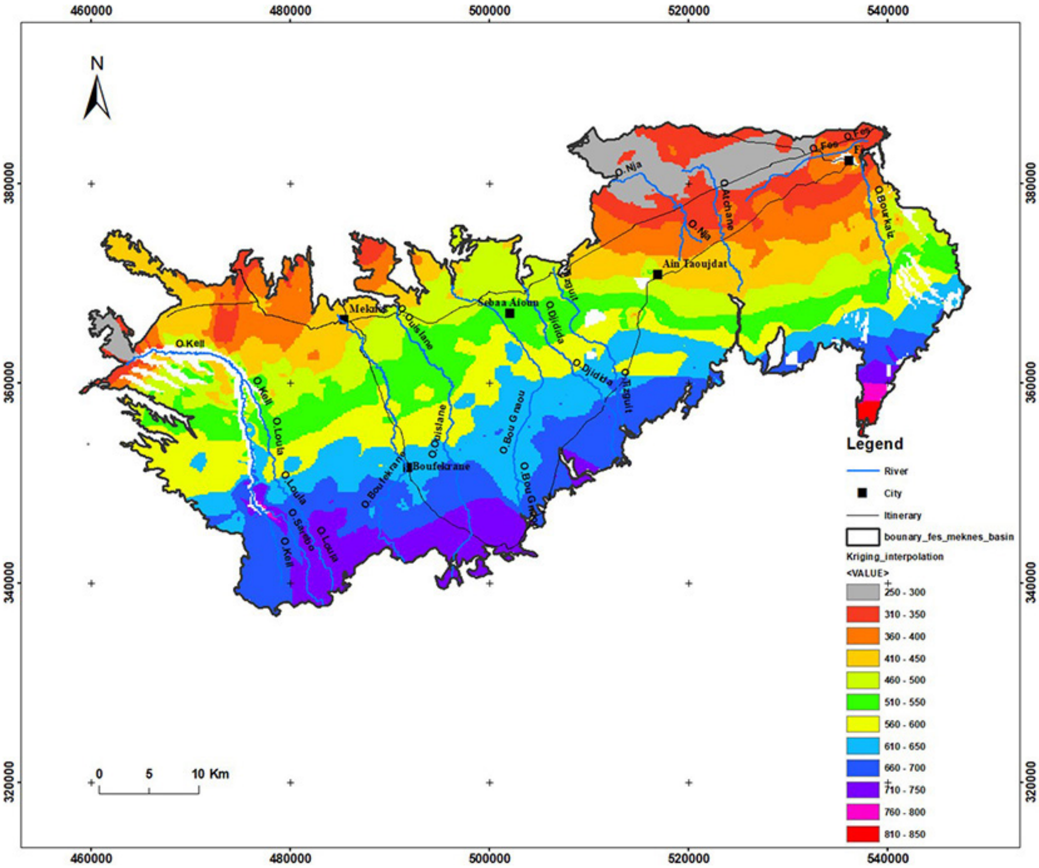

Figure 8. Map of marl bottom elevation by Kriging interpolation

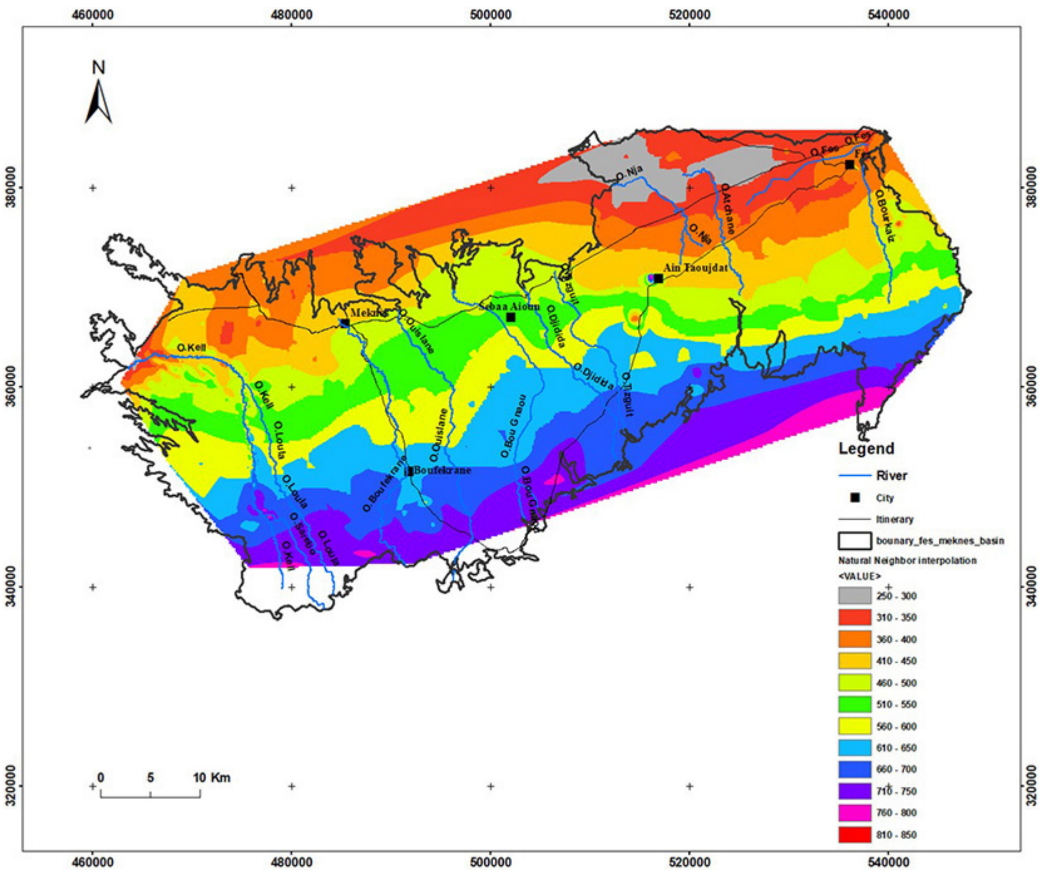

Figure 9. Map of marl bottom elevation by natural neighbor interpolation

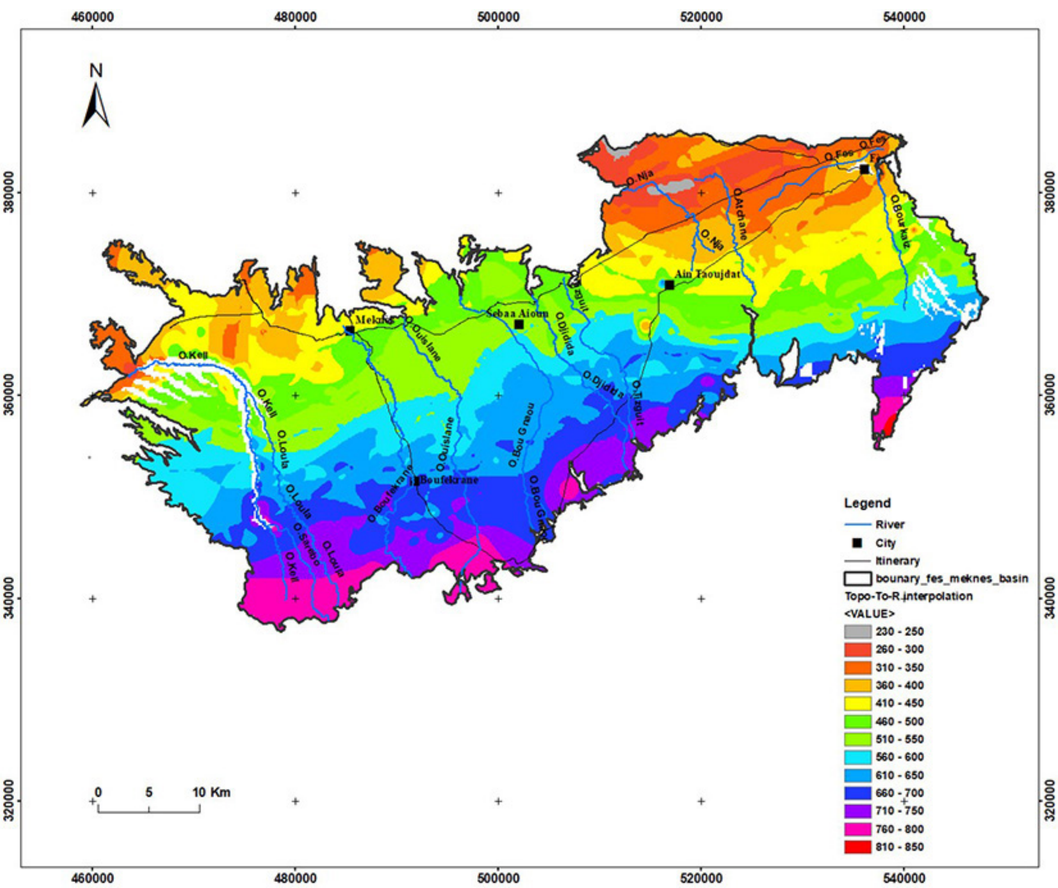

Figure 10. Map of marl bottom elevation by Topo to Raster interpolation

frequency, with a kurtosis value equal to 2.33. It qualifie to what extent the aqueous of the marl elevation distribution shows a difference from the aqueous of a normal distribution equal to 3.

After having an idea of how our data is distributed, we will proceed to the comparison of the four interpolation techniques in order to obtain the most suitable method for the study area as shown in the figures (Figure 7, Figure 8, Figure 9, Figure 10).

The comparative study of the results of these maps is based on the quantification of the strength of the linear relationships between the measured values and the values estimated by each method (Figure 11). This study is valid through the specific measurement of the correlation coefficients.

The figures below show the clouds of correlations that correspond to the confrontation of the measured heights in ordinates, and the estimated heights in abscissas. The results present a uniform point cloud and follow a straight line. This reflects a strong correlation between the real and estimated measurements. With a conformity index of about 0.9848 for IDW, 0.9796 for kriging. Concerning the two other methods Natural Neighbor and Topo to raster, the conformity coefficients give successively a close result (0.9814, and 0.9842).

On the other hand, the calculation of the mean square error for each method by the relation below is reported on the table:

$$RMSE = \sqrt{\frac{\sum(P_i - O_i)^2}{n}} \tag{1}$$

where: P_i – estimated value of the marl altitude;
O_i – measured value of the marl altitude;
n – is the number of measurements.

After the comparison of the RMSE results (Table 1), the method that brings an optimal and more representative result is the IDW. This choice can be justified by the higher value of the conformity index which reaches a value very close to 1, and a lower RMSE compared to the other methods. The results of the IDW method can be tested by three boreholes scattered in the basin carried out by ONEP (IRE : 2431/15, 3340/15 and 2487/15), and for which the marl altitudes are known. These boreholes were eliminated from the

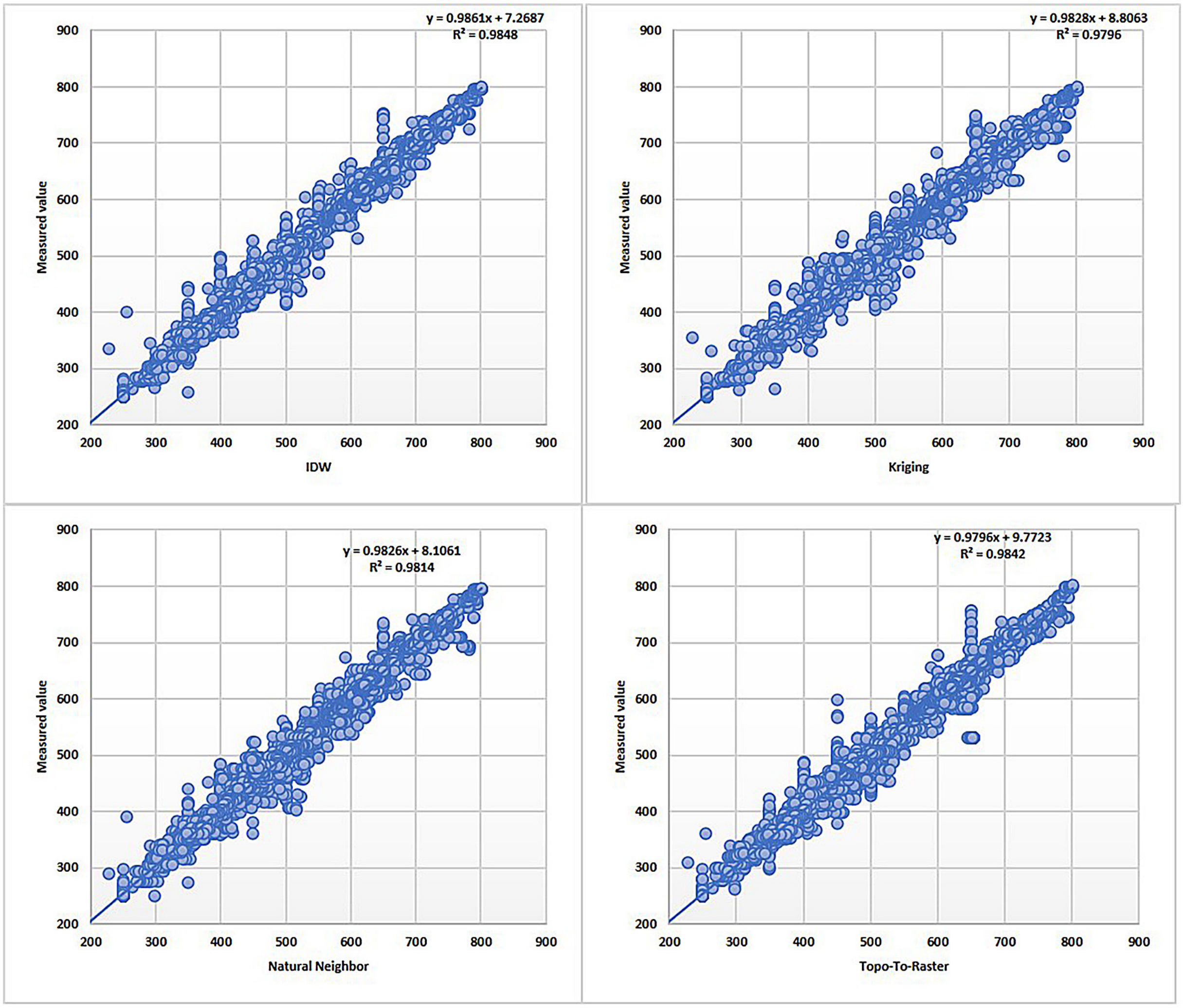

Figure 11. Linear correlation between measured and estimated marl elevations

Table 1. Comparison of the four des interpolation methods

Parameter	IDW	Kriging	Natural neighbors	Topo to raster
RMSE	7.42	13.59	21.27	14.01

Table 2. Comparison between measured and estimated marl elevations

IRE	X (m)	Y (m)	Altitudes of the marls measured in m	IDW	Topo to raster	Krigeage	Natural neighbors
2431/15	502500	363050	604	601.97	601.57	600.67	601.28
3340/15	501200	360952	618	614.37	611.52	614.77	611.86
2487/15	523450	371400	412	412.7	413.82	406.7	413.27

input data. Comparison of their elevations with the values estimated by the IDW method gives the following results (Table 2).

After the designation of the IDW method as the most reliable, we proceed to the interpretation of the altitude of the impermeable formations that separate the two aquifers of the Fez-Meknes basin. The map elaborated from the different data sources, show that the altitudes decrease from the southern part (710 to 850 m) to the northern part (250 to 300 m). However, if we superimpose the flexural map on the interpolated elevation map, we notice some exceptions. Indeed, west of the city of Meknes we observe the decrease of the top, and even their appearance in outcrop, this may be due to the effect of the Toulal flexure.

We also note a decrease in altitude that marks its irregularity at the flexure Ain Taoujtat. This can be explained by the effect of the latter which has influenced the topography of the marly roof by its rise. The latter can also be influenced by the effect of the Haj Keddour flexure. Indeed we can distinguish two zones at its place. Its southern half has an altitude that varies from 630 to 740 m while its northern part varies from 600 to 620 m.

CONCLUSION

The databases collected from the different sources, were used by the interpolation tools offered by ArcGIS, to develop a representative generative map of the surface of the Miocene marls. These constitute the top of substratum of the free water table. Based on the comparison of RMSEs and the study of correlations between the real and interpolated measurements of the four methods IDW, Kriging, Topo To Raster and Natural Neighbors, we note that the geostatistical interpolation by IDW is the most realistic compared to the other methods. The interpretation of this map allows us to point out a decrease in the altitudes of the marls from the South to the North with some exceptions around the flexure of Ain Taoujat and Toulal, which confirms the previous work done.

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