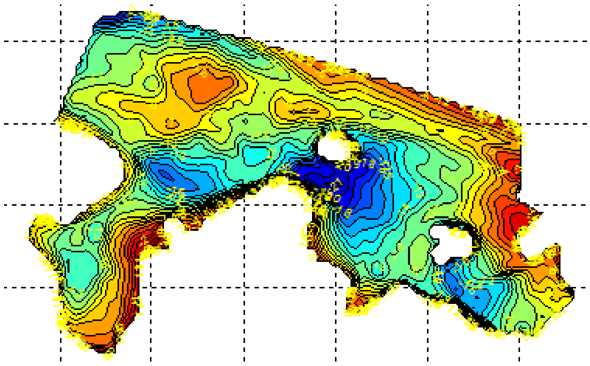
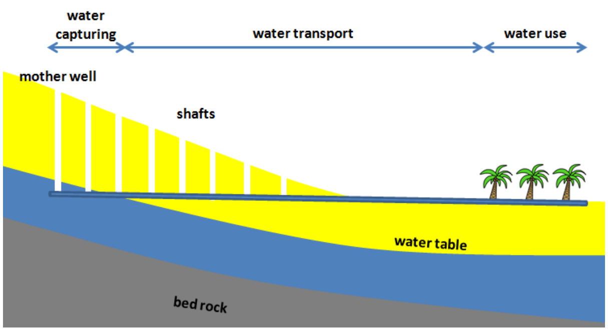
Groundwater modelling of the khettara area of Fezna-Jorf-Hannabou, Morocco





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Preface

With this report, I present my master thesis with the title "Groundwater modelling of the khettara area of Fezna-Jorf-Hannabou", which was developed in collaboration with ONEE-Branche Eau (Morocco) and Waternet (the Netherlands). This report marks the end of my study at the Faculty of Civil Engineering at the Delft University of Technology and serves as closure of the master Water-management.

This project would not have been possible without the help and support of so many people. First of all, I take this opportunity to express my appreciation to the persons who assisted me during my time in Morocco. I would like to sincerely thank Ir. Mokhtar Jaait who, as supervisor from ONEE-Branche Eau, put much effort in assisting me on the thesis topic and facilitated me during my fieldwork. Also, I wish to thank Ir. Hanane Benqlilou for sharing her knowledge on khettaras. Special acknowledgements go to Ir. A. Tabit, former director, and Ir. M. Kamal El Mokaddam, hydrologist, both from the l'Agence du Bassin Hydraulique du Guir-Ziz-Rheris, for their help and for giving me the opportunity to work at their office. My appreciation also goes to prof. Hilali and prof. M. Boujamaoui for sharing their hydrological and geological expertise. I would like to thank many others from the Université Moulay Ismail too, for lending me numerous measurement materials for my fieldwork. Finally, I want to gratefully thank Mister Lhassan Elmrani for his assistance in the field, our invaluable discussions and for bringing me in contact with key people in the area.

Furthermore, I would like to give special thanks to the members of my graduation committee in the Netherlands: prof. Theo Olsthoorn, prof. Giovanni Bertotti and Frank Smits, MSc. Apart from their great help on the contents, they also supported me during the setbacks I experienced during my graduation time. Finally, I would like to thank my mother, my father, the rest of my family and my closest friends for their admirable personal support during the many ups and downs I inevitably had while writing this thesis.

Coert Strikker
12/08/2014, Delft

Summary

The Tafilalet region in the east of Morocco is home to hundreds of khettaras, historical subsurface drainage tunnels, with a total length of 2900 km. Khettaras enable the extraction of groundwater and transportation under gravity, to the surface several kilometres away. For centuries, numerous communities rely on these systems as the water is used for irrigation, drinking, cleaning and cooking.

The khettaras, however, have become more and more threatened since the expansion of the number of motor pumped wells halfway the last century. In contrast to the khettaras, which rely on the sustainable mechanism of passive extraction of groundwater, pumping by means of tube wells potentially leads to the depletion of aquifers. As a consequence, a number of khettaras faced a significant reduction in discharge or even dried up completely.

This master thesis falls within the context of the collaboration between ONEE-Branche Eau (Morocco) and Waternet (Netherlands). The International Institute for Water and Sanitation (IEA) of ONEE Branche-Eau supports the preservation of khettaras, because they recognize the importance of the beneficial impact of khettaras on environment and communities in rural areas. This master study focuses on the sedimentary groundwater system of Fezna-Jorf-Hannabou, which is part of the larger Tafilalet aquifer and houses about 69 khettaras of which approximately only half of them are supplying water.

The first objective of this research is to get a better understanding of the behaviour of the groundwater system of Fezna-Jorf-Hannabou and the functioning of the khettaras in this region. In order to do this, a numerical groundwater model was set up based on the findings from own fieldwork and collected data and literature. The outcomes of the model are compared with the findings of Jean Margat, a famous French geohydrologist who carried out many surveys in the Tafilalet region, including the villages of Fezna, Jorf and Hannabou, during the 1950s and 1960s. The second objective is to use the model to evaluate the impact of several scenarios on the groundwater system. The scenarios address possible threats for the khettaras and potential measures to preserve the khettaras in the context of sustainable water resource management.

Information on the groundwater system of Fezna-Jorf-Hannabou was obtained during a two month period in Morocco. Geohydrological related literature, data and additional anecdotic information were gathered in Rabat and Errachidia from various governmental institutions (ONEE-Branche Eau, Agence Hydraulique du Bassin Guir-Ziz-Rheris and CEDTOD) and universities (Université Moulay Ismail). Furthermore, fieldwork was carried out in the area of Fezna, Jorf and Hannabou, which included the carrying out of observational visits, interviewing local people and performing measurements. Most of the measurements were done on the khettaras, including the measurements of discharges and elevations.

A numerical groundwater model was set up after processing and analyzing the collected information. The modelling was done through *mflab,* which is an open interface for groundwater modelling using the modular finite-difference flow model computer code MODFLOW. Google Earth was used as a Geographic Information System (GIS) to store, manage and visualize geographical data. With these programmes, the geological structure of the model was built, consisting of the most dominant sedimentary layers of the groundwater system: silt, gravel, limestone and conglomerate. Hydraulic conductivity values, based on the estimations of Margat, were attributed to each formation. The most relevant hydrological flows were computed to complete the model, such as: pumping, khettara

extraction, recharge from floods, irrigation return flow and incoming and outgoing groundwater flow. Drains were used in the model to simulate the khettaras. Subsequently, the model was calibrated by comparing the generated model outcomes with available observed groundwater level data and incoming and outgoing groundwater flows as well as khettara discharges estimated by Margat. The calibration focused on the periods 1959-1969 and 2000-2010, for which data was available.

When using Margat's upper limit of 43 m/d for the conglomerate, applied to the simulation period 1959-1969 when Margat did most of his surveys, the model calculated groundwater levels upstream Fezna that are above ground surface, incoming groundwater flow along the outcrop of Gara Gfifate 45 % lower than estimated by Margat, and a groundwater flow across the line between the Anti-Atlas and the village of Krayr that is only 15 % of Margat's value. Four hypotheses were investigated to solve these discrepancies:

1. The first hypothesis comprises the idea that the hydraulic conductivity of the conglomerate might be beyond the maximum value of 43 m/d given by Margat. The hydraulic conductivity of these conglomerates depends mainly on the degree of cementation, which varies significantly in the area as often pebbles without any cementation are observed in the study area. Given the sizes of the pebbles, which reach up to 10 cm, the conductivity of conglomerate may easily reach hundreds of m/d. The calibration of the model suggests an average conglomerate conductivity in the study area of 86 up to 192 m/d, respectively two to four times the maximum value given by Margat.
2. The river infiltration amount in the bed of the oued Rheris of 5 Mm^3/y estimated by Margat may well be too high, which could be one reason for the groundwater levels above groundwater surface upstream of the outcrop Gara Gfifate calculated by the model. A lower river recharge of 2 Mm^3/y, equal to 133 m^3/m/y, was suggested by both river infiltration simulation with MODFLOW (River package) as well as by analytical calculation. The model gives reasonable results with 133 m^3/m/y infiltration for the entire length of the Rheris.
3. Wadi structures indicates that substantial amounts of flood water go through this passage overland as surface water, instead of underground, and infiltrate in the plain between the Anti-Atlas and the villages of Fezna and Jorf to feed the khettaras. The model verifies that the infiltration in this plain might be more than estimated by Margat (3 Mm^3/y instead of 2 Mm^3/y).
4. It is suggested that the irrigation return flow in the agricultural areas may be larger than Margat's estimate of 5 Mm^3/y, because Margat did not include irrigation infiltration from khettaras and pumps. An irrigation infiltration of 6 Mm^3/y was proposed, which was computed with the model and led to reasonable khettara discharges matching their measured values.

Subsequently, the calibrated model, including all its uncertainties, was used to evaluate various past and future scenarios. The historical scenario showed that the groundwater levels before human intervention, i.e. before the 14^{th} century when the first khettaras were constructed, might have been shallow in an extended part of the study area. The model indicates that water tables declined significantly, firstly after khettaras were constructed, later by the introduction of groundwater pumps. The increasing use of solar energy driven groundwater pumps may deplete groundwater resources even more in the future. Furthermore, the combination of sustainable use of groundwater and modern technologies was investigated, because sustaining khettaras may become more difficult due to emigration of young people. Therefore, the possibilities of modern khettaras are explored. The model showed that a modern khettara would be able to extract significant amounts of groundwater, equal to multiple traditional khettaras. Next, the impact of drip irrigation instead of surface irrigation was evaluated. The model showed that water tables will decline due to the reduction of irrigation return flow, resulting in a decrease of the khettara discharges. Nevertheless, crop production may rise in the agricultural areas of Fezna and Jorf by a factor 2.6 compared to the current situation. Lastly, the model shows that the total khettara discharge increases when the combination of drip irrigation and khettaras is used, while groundwater pumping is abandoned. This combination would lead to a crop production rise by a factor 2.3 with respect to the current situation, as is suggested by the model.

Finally, various recommendations are given both in relation to further improvement of the concept of the groundwater system of Fezna-Jorf-Hannabou as well as future sustainable water resource management in the area. It is recommended to collect and copy all of Margat's original reports, including all Margat's original data from measurements, because they are expected to give more information on the groundwater system. Also, it is recommended to extendedly map the elevation of the bedrock, depth of the conglomerate and gravel layer as wells as the depth of the water table by means of geophysical measurements. Lastly, it is recommended to investigate the degree of cementation of the conglomerate and to record the fluctuation of the water table, especially in flood areas.

Résumé

La région du Tafilalet, à l'est du Maroc, est historiquement connue pour être le bercail de centaines de khettaras: des tunnels de drainage souterrains d'une longueur totale de 2900 km. Des Khettaras permettent l'extraction de l'eau souterraine et le transport par gravité à la surface, sur une distance de plusieurs kilomètres. Pendant des siècles, des nombreuses communautés dépendent de ces systèmes pour avoir accès à l'eau pour l'irrigation, la consommation, le nettoyage et la cuisine.

Les khettaras, cependant, sont devenue de plus en plus menacées depuis l'expansion du nombre des puits à moto dès le milieu de siècle dernier. Contrairement aux khettaras, qui reposent sur un mécanisme durable d'extraction passive des eaux souterraines, le pompage au moyen de puits tubulaires conduit potentiellement à l'épuisement des nappes. En conséquence, un nombre des khettaras ont subi une réduction significative de leur débit ou même un assèchement total.

Cette présente thèse de Master s'inscrit dans le cadre de la collaboration entre l'Office National d'Eau et d'Electricité du Maroc (Branche Eau (Maroc)) et Waternet (Pays-Bas). L'Institut International de l'Eau et de l'Assainissement (IEA) de l'ONEE-Branche Eau soutient la préservation des khettaras, parce qu'il reconnait l'importance de leur impact bénéfique sur l'environnement et sur les communautés dans les zones rurales. Cette étude se concentre sur le système des eaux souterraines sédimentaires de Fezna-Jorf-Hannabou, qui fait partie des plus grandes nappes du grand Tafilalet, et abrite environ 69 khettaras dont environ la moitié fournissent encore un approvisionnement en eau.

Le premier objectif de cette recherche est d'obtenir une meilleure compréhension du comportement du système des eaux souterraines de Fezna-Jorf-Hannabou et du fonctionnement des khettaras dans cette région. Pour ce faire, un modèle numérique a été mis en place sur la base des conclusions recueillies sur le terrain, des données collectées et des recherches. Les résultats du modèle sont comparés avec les résultats de Jean Margat, un célèbre hydrogéologue français qui a effectué de nombreuses études dans la région des villages de Fezna, Jorf et Hannabou durant les années 1950 et 1960. Le deuxième objectif est d'utiliser le modèle pour évaluer l'impact de plusieurs scénarios sur le système des eaux souterraines. Les scénarios se penchent sur les menaces possibles sur les khettaras et les mesures possibles pour les préserver dans le contexte de la gestion durable des ressources en eau.

Des informations sur le système des eaux souterraines de Fezna-Jorf-Hannabou ont été collectées au cours d'une période de deux mois au Maroc. Les travaux de recherche hydrogéologiques et les données et les informations anecdotiques supplémentaires ont été recueillies à Rabat et à Errachidia, auprès de diverses institutions gouvernementales (ONEE-Branche Eau, l'Agence du Bassin Hydraulique Guir-Ziz-Rheris et CEDTOD) et d'universités (Université Moulay Ismail). En outre, le travail de terrain a été réalisé dans la région de Fezna, Jorf et Hannabou. Ce travail comprenait des visites d'observation, des entretiens avec la population locale et des prises de mesures. La plupart des mesures ont été effectuées sur les khettaras, y compris celles sur les débits et les élévations.

Un modèle numérique de la nappe phréatique a été mis en place après le traitement et l'analyse des informations recueillies. La modélisation a été réalisée à travers *mflab*, une interface ouverte pour la modélisation des eaux souterraines à l'aide du programme informatique de flux modulaires aux différences finies MODFLOW. Le système d'information géographique (SIG) Google Earth a été utilisé pour le stockage, la gestion, et la visualisation des données géographiques. Ces programmes ont permis de construire la structure géologique du modèle, constituée des couches sédimentaires les

plus dominantes du système des eaux souterraines: limons, graviers, calcaires et conglomérats. Des valeurs de conductivité hydraulique, sur la base des estimations de Margat, ont été attribuées à chaque formation. Les flux hydrauliques les plus pertinents ont été calculés pour compléter le modèle, tels que: le pompage, l'extraction des khettaras, l'infiltration des eaux des crues, les flux de retour de l'irrigation et les flux entrant et sortant des eaux souterraine. Des drains ont été utilisés dans le modèle pour simuler les khettaras. Par la suite, le modèle a été calibré en comparant les résultats du modèle généré avec les données disponibles observées au niveau des eaux souterraines et des écoulements souterrains entrants et sortants estimés, et les débits de khettara par Margat. Le calibrage a porté sur les périodes 1959-1969 et 2000-2010, pour lesquelles des données étaient disponibles.

En utilisant la limite supérieure de Margat de 43 m/j pour le conglomérat, appliquée à la période de simulation 1959-1969 durant laquelle Margat réalisa la plupart de ses études, le modèle a calculé des niveaux d'eaux souterraines en amont de Fezna qui sont au-dessus de la surface du sol, le flux des eaux souterraines entrant le long de l'affleurement de Gara Gfifate et calculés comme étant de 45% inférieur à celui estimé par Margat, et un flux d'eaux souterraines sur la ligne de démarcation entre l'Anti-Atlas et le village de Krayr équivalent à seulement 15% de la valeur de Margat. Quatre possibilités ont été étudiées pour résoudre ces divergences:

1. La première hypothèse met en avant l'idée que la conductivité hydraulique du conglomérat pourrait être supérieure à la valeur maximale de 43 m/j avancée par Margat. La conductivité hydraulique de ces conglomérats dépend principalement du degré de cimentation, qui varie considérablement dans la zone au vu des galets sans la moindre cimentation qui sont observés dans la zone d'étude. Compte tenu de la taille des galets, qui atteignent jusqu' à 10 cm, la conductivité du conglomérat peut facilement atteindre des centaines de m/j. Le calibrage du modèle suggère une conductivité moyenne du conglomérat dans la zone d'étude allant de 86 à 192 m/j, respectivement de deux à quatre fois la valeur maximale donnée par Margat.
2. L'infiltration d'eau de crue dans le lit de l'oued Rheris, estimée par Margat à 5 Mm^3/an pourrait bien être trop élevée, ce qui pourrait constituer une raison expliquant les niveaux phréatiques au-dessus de la surface de l'eau souterraine en amont de l'affleurement de Gara Gfifate calculée par le modèle. Une infiltration d'eau des crues de 2 Mm^3/an, égale à 133 m^3/m/an, a été proposée à la fois par une simulation d'infiltration de la rivière avec MODFLOW (River package) ainsi que par calcul analytique. Le modèle donne des résultats raisonnables de 133 m^3/m/an d'infiltration sur toute la longueur du Rheris.
3. Les structures des oueds indique, cependant, que des quantités importantes d'eau de crue passent par ce passage terrestre comme eau de surface, et non pas de manière souterraine, et s'infiltrent dans la plaine entre l'Anti-Atlas et les villages de Fezna et Jorf afin d'alimenter les khettaras. Le modèle apporte la preuve que l'infiltration dans cette plaine pourrait être plus élevée que l'estimation donnée par Margat (3 Mm^3/an au lieu de 2 Mm^3/an).
4. Il est suggéré que le flux de retour d'irrigation dans les zones agricoles pourrait être supérieur à l'estimation de Margat de 5 Mm^3/an et ce car Margat n'a pas pris en compte le flux de retour d'irrigation des khettaras et des pompes. Un flux de retour d'irrigation de 6 Mm^3/an a été proposé, qui a été calculé avec le modèle et a conduit à des débits de khettara correspondant à leurs valeurs mesurées.

Ensuite, le modèle calibré, avec toutes ses incertitudes, a été utilisé afin de donner une autre dimension à différents scénarios passés et futurs. Le scénario historique laisse apparaître que les niveaux d'eaux souterraines avant l'intervention humaine, c'est à dire avant les khettaras datent du

14eme siècle, pourraient avoir été superficiels dans une partie étendue de la zone d'étude. Le modèle indique que le niveau des eaux souterraines a diminué de manière significative, dans un premier temps après la construction des khettaras, par la suite par l'introduction de pompes à eaux souterraines. L'utilisation croissante des panneaux solaires pour produire l'énergie pour les pompes des puits risque d'encore plus épuiser les ressources en eaux souterraines. En outre, la combinaison de l'utilisation durable des eaux souterraines et de technologies modernes a été étudiée, au vu du fait que l'entretien des khettaras pourrait devenir plus difficile par l'émigration des jeunes gens. Par conséquent, les possibilités de khettaras modernes sont explorées. Le modèle a montré qu'une khettara moderne serait capable d'extraire d'importantes quantités d'eaux souterraines, égale à plusieurs khettaras traditionnelles. Ensuite, l'impact de l'irrigation goutte à goutte à la place de l'irrigation de surface a été évalué. Le modèle laisse apparaître que le niveau des eaux souterraines diminuera du fait de la réduction du flux de retour d'irrigation, entraînant une diminution des débits de khettara. Néanmoins, la production agricole pourrait augmenter dans les zones agricoles de Fezna et Jorf par un facteur de 2,6 en comparaison à la situation actuelle. Enfin, le modèle montre que le débit total de la khettara augmente lorsque la combinaison de l'irrigation goutte à goutte et des khettaras est utilisée, tout en abandonnant l'utilisation de pompage des eaux souterraines. Cette combinaison conduirait à une augmentation de la production agricole par un facteur de 2,3 en comparaison à la situation actuelle, comme il suggère le modèle.

Enfin, diverses recommandations sont données à la fois par rapport à une nouvelle amélioration du concept du système des eaux souterraines de Fezna-Jorf-Hannabou, ainsi qu'en lien avec une future gestion durable des ressources en eau dans la région. Il est recommandé de recueillir et de copier l'ensemble des rapports originaux de Margat, en compris les données d'origine de prise de mesures, parce qu'ils sont sensés fournir plus d'informations relatives au système d'eaux souterraines. En outre, il est recommandé de cartographier de manière étendue l'élévation du substratum, la profondeur du conglomérat et de la couche de gravier, ainsi que la profondeur du niveau phréatique au moyen de mesures géophysiques. Enfin, il est recommandé d'examiner le degré de cimentation du conglomérat et d'enregistrer les fluctuations du niveau des eaux souterraines, en particulier dans les zones inondables.

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1 Introduction

The Tafilalet region (Morocco) is home to hundreds of subsurface drainage tunnels with a total length of about 2900 km. *Khettaras*, as they are called in Morocco (mostly known as *qanats* in other regions in the world), were introduced in the Tafilalet in the fourteenth century most probably by the Arabs who spread the technique following the Islamic revolution (Lightfoot, 1996). Khettaras enable the extraction of groundwater and transportation under gravity to the surface, several kilometres downstream. Here the water is used for irrigation, sanitation and drinking, both for men and cattle.

The Moroccan villages of Fezna, Jorf and Hannabou are located in the Tafilalet region, 350 km southwest of the capital Rabat. The agricultural fields around these villages depend in large part on the groundwater supplied by khettaras. Of the about 69 khettaras present in this area, currently approximately only half is functioning. The others fell dry mainly due to rapidly increased use of private motor-driven pumps in the area since the 1950s (Ruhard, 1977). Where khettara practices are a relative sustainable way to use groundwater resources, it relies entirely on passive tapping of groundwater, withdrawal by wells on the other hand can lead to aquifer depletion and salinization. The fall of the groundwater table in the Tafilalet region, caused by pumping, resulted in a significant decline of the discharges of the khettaras.

This master thesis is done in the context of the partnership between ONEE-Branche Eau, the public organisation responsible for the production and distribution of drinking water in Morocco, and Waternet, the public company responsible for both drinking water, urban drainage, wastewater transport and treatment as well as water management in and near the city of Amsterdam, and ABH Guir-Ziz-Rheris, which is responsible for the resource water management in the area of the basins of the oueds Guir, Ziz and Rheris. The International Institute for Water and Sanitation (IEA) of ONEE Branche-Eau supports the preservation of khettaras as it recognizes the importance of the sustainable impact of khettaras on the environment and the communities in rural areas.

As most studies on khettaras are related to social and economical aspects, this research focuses on the physical part. A conceptual model of the groundwater system of Fezna-Jorf-Hannabou, including all khettaras, was based on the findings from own fieldwork and information collected from literature. Much of the information from the literature originates from the extensive surveys undertaken in the area by Jean Margat, a French expert on geohydrology and winner of the 2008 International Hydrology Price, in the 1950s and 1960s. The conceptual model is translated into a numerical groundwater model, which can be seen as a consistent framework that enables the integration of all available physical and hydrological information about the groundwater system. Many simulation results are analyzed in the view of Margat's findings.

The first objective of this research is to gain a better insight in the behaviour of the groundwater system of the basin of Fezna-Jorf-Hannabou by setting up a numerical groundwater model, considering which geological and/or hydrological aspects are most crucial for the functioning of the khettaras. The setup and the calibration of the model should be such that a comparison can be made with Margat's geohydrological research results.

The second objective is to use the model to evaluate the effects of several scenarios on the groundwater system. These scenarios are primarily related to urgent issues such as an increased use of pumps, climate change and the reduction in labour capacity available for maintenance of khettaras. In addition, potential measures to preserve the khettaras should be considered, modelled and evaluated, all in the context of sustainable water resource management.

The report continues with a description of the topography, geology, climate and hydrology of the study area in chapter 2, followed by the applied methods in chapter 3. Chapter 4 presents the set up of the model and chapter 5 describes the calibration process. Subsequently, the scenarios and the related model outcomes are presented in chapter 6. The report ends with conclusions and recommendations in respectively chapter 7 and chapter 8.

2 Description of the study area

2.1 Geography

The area of study is situated in the Tafilalet region, more or less corresponding with the Province of Errachidia, in the East of Morocco near the border of Algeria (see figure 1). The region has a surface of around 60.000 km^2 (SEEE, 2007) and is physically bounded by the mountains of the High-Atlas in the north, the Anti-Atlas in the west and the Sahara desert in the south and east.

The Tafilalet region is a rural area, only 35% of the population lives in an urban environment (La Direction Régionale de Meknès-Tafilalet, 2006). The two most important cities are Errachidia and Erfoud, having a population of 75.000 and 20.000 respectively (Moroccan Ministry of Health, 2004). Due to the arid conditions, vegetation is rare and mainly concentrated in the oases near the oued Rheris and oued Ziz (oued is the Moroccan word for wadi). The Tafilalet is known for these oases, mainly consisting of palm groves, where, inter alia, large amounts of dates are produced.

The Tafilalet region should not be confused with the Tafilalet plain. The latter is only the low alluvial plain around Erfoud (see figure 1).

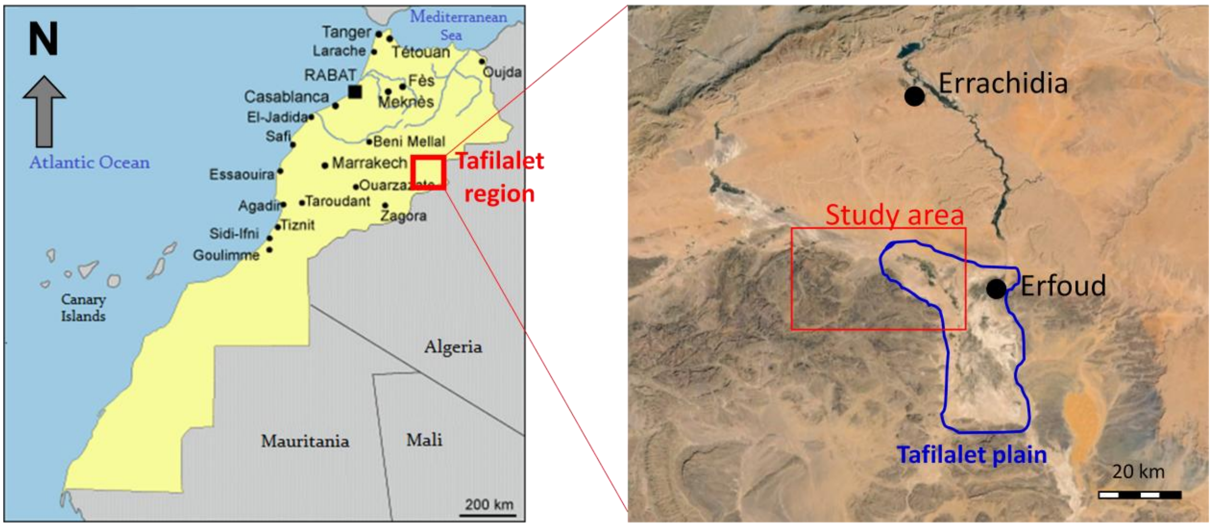


Figure 1: Left: map of Morocco. Right: map of the Tafilalet region.

The study area, with roughly a surface of 50 by 30 km^2, is situated in the Northwest of the Tafilalet plain around the urban areas of Fezna, Jorf and Hannabou (see figure 2). They have a population of around 4000, 12000 and 5000 respectively (ORMVA, 2006). The area is marked by the numerous khettaras, which are, just like the villages, located in the sedimentary plain. They can be recognized by numerous hills widespread throughout the area, consisting of soil excavated from the gallery and shafts. Together with many wells and the oued Rheris they provide water for the agricultural areas, i.e. the palm groves, around the villages.

In the Northwest, the plain side of the study area has an elevation ranging from highest 860 m AMSL (above mean sea level) down to around 790 m near the village of Hannabou. The mountains of the Anti-Atlas reach up to approximately 1200 m AMSL.

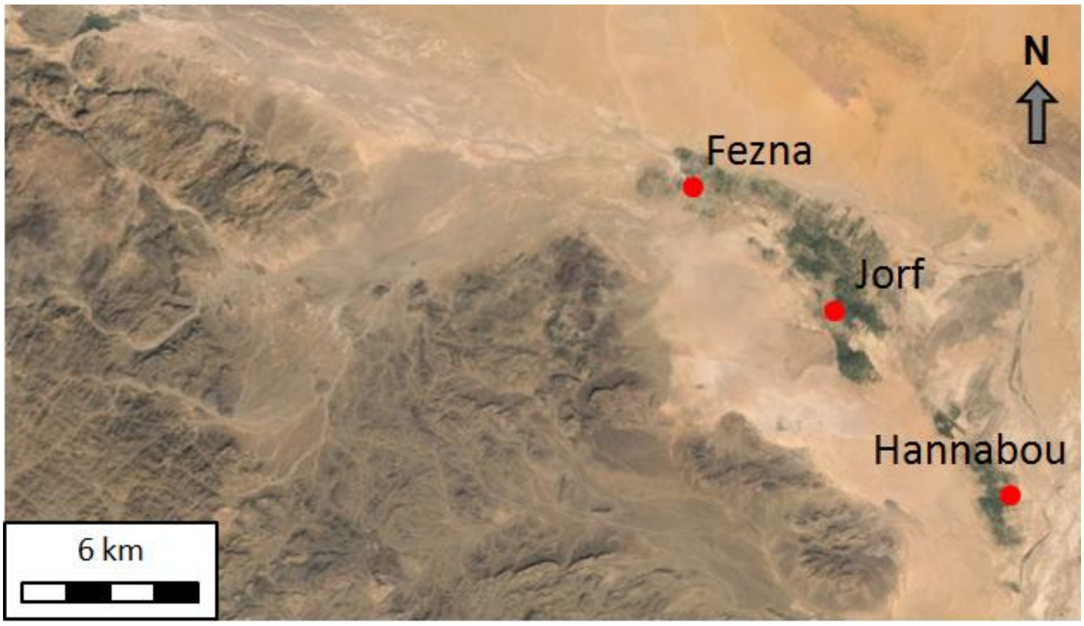


Figure 2: Map of the study area.

2.2 Geology

2.2.1 Morocco

The geological structures of Morocco are part of larger ranges that extend from the Atlantic Ocean in the west to the Algeria and Tunisia in the east (see figure 3). The Rif and Tell Atlas mountains near the Mediterranean Sea form the northern range. South of these are the High Plateaus and the Atlas systems which can be classified in two groups; the Middle and High Atlas in the north and the Anti-Atlas in the south. They form the northern boundary of dominantly low-elevation Saharan domain. The study area is located at the junction of the High Atlas, the Anti-Atlas and the Saharan platform. Figure 4 shows the geological outline of Morocco.

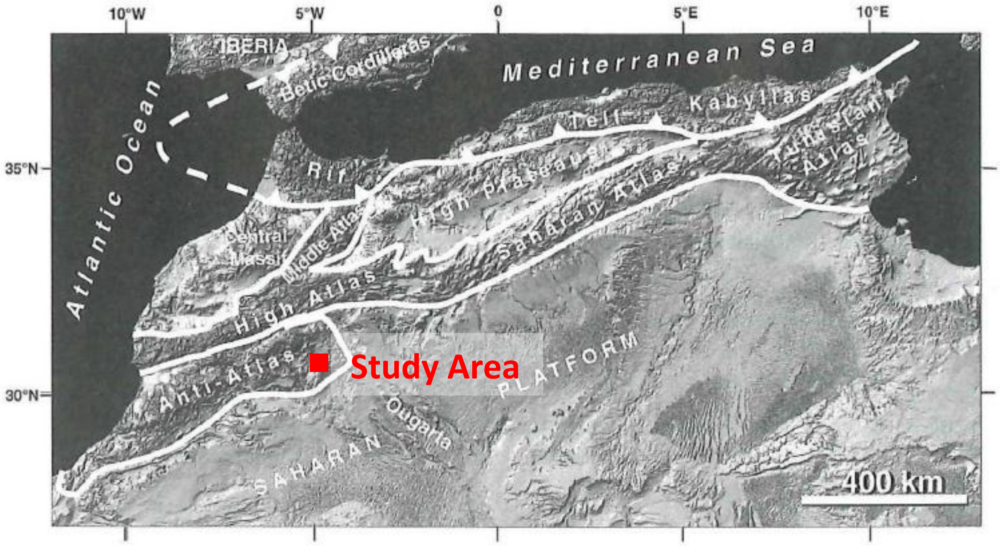


Figure 3: Physiography of northwestern Africa. Morocco extends approximately west of the meridian 2°W, and further south of the lower border of the picture (Michard et al., 2008).

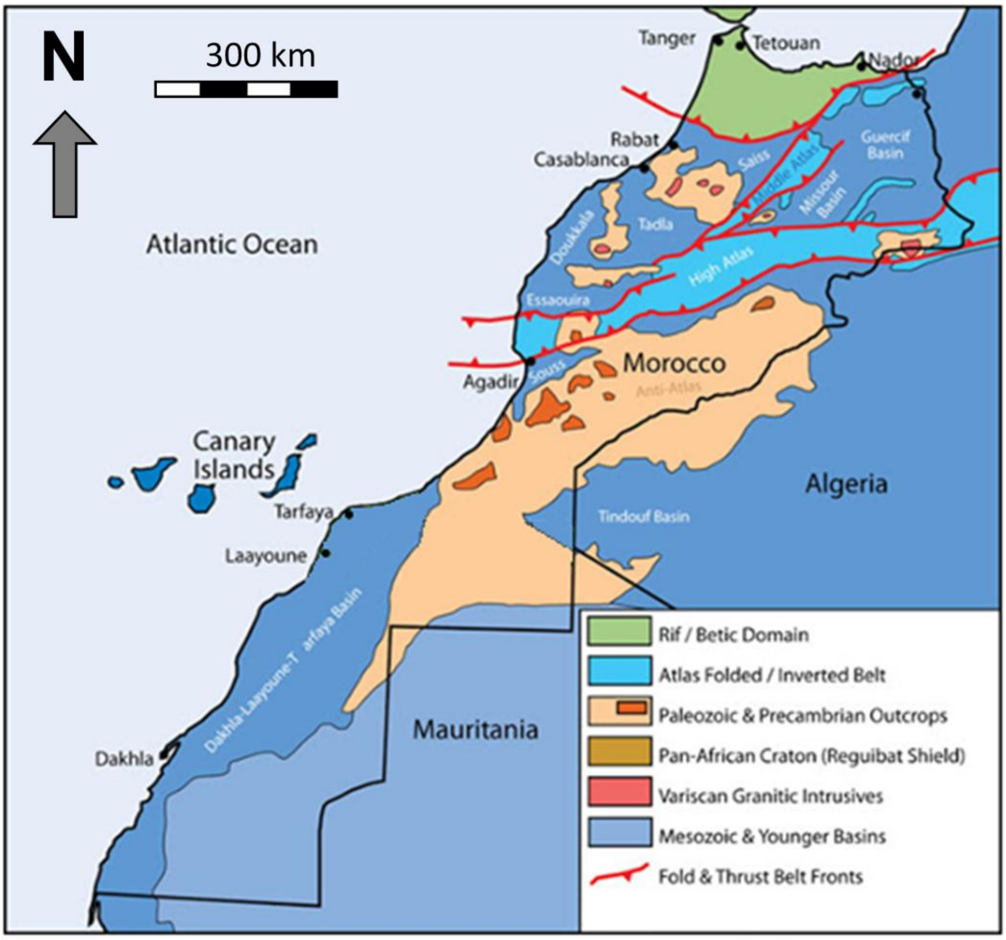


Figure 4: Geological map of Morocco including the Atlas Mountains.

2.2.2 Formation of the Anti-Atlas

During the Late Precambrian, series of terranes were formed in Africa, part of the supercontinent Grondwana (Burkhard et al., 2006). This was followed by a heavy subsidence during a large part of the Paleozoic era 500-330 million years ago (see geological time scale in appendix A). The created inland sea was subsequently filled with fine-grained clastic material. In the Late Carboniferous, 300 million years BC, a collision took place between the two supercontinents Gondwana and Euramerica. This led to compression and inversion, lifting up the sedimentary basins. During this process the Anti-Atlas fold has formed. Simultaneously, the Appalachian chain arose on the American side (Euramerica continent), see also appendix A. Following the orogenesis, the Anti-Atlas was flattened by erosion. The current topography also includes Quaternary formations. Today, its highest point is Jbel Siroua with an elevation of 3.300 m.

2.2.3 Formation of the Middle and High Atlas

The Middle and High Atlas have formed as a response to two major geological events (A. Teixell et al., 2003; see also a conceptual evolution model in appendix A) The first phase was the rifting and extension of the Central Atlantic/Rif-Tell and the African plate during the Triassic and the Jurassic periods (250-160 million years ago). The basin between these plates subsided and consequently sediments accumulated on top of pre-rift Paleozoic formations, the same formations as the Anti-Atlas (Michard et al., 2008). Due to the extension, two elements of the sedimentary formations rifted; the Middle Atlas and High Atlas. By erosion and sedimentation new flat horizontal formations have formed during the Cretaceous and early Tertiary. This relatively calm period then was followed by the Africa-Europe continental collision in the middle Cenozoic, around 30 million years BC, resulting in compressional forces. The rift systems were lifted up forming the Middle and High Atlas Mountains (Beauchamp et al., 1996). In between and on the edges of both mountain ranges plateaus formed. The plateau structures consist of the same type of sedimentary formations as the Middle and High Atlas. One example is the Hamada System located south of the High Atlas and north of the Tafilalet plain.

2.2.4 Tafilalet region and study area

The geological variation in the Tafilalet region is extensive. The mountainous areas are the High Atlas in the north, of which the sediments are formed in the Triassic-Jurassic period, and the Anti-Atlas in the southwest, constituted during the Palaeozoic (see figure 5). Immediately south of the High Atlas fault, Lower Cretaceous to the Miocene and Pliocene sedimentary formations form an extended plateau structure, containing multiple superimposed plateaus, also called the Hamada System. A hamada is a desert type landscape consisting of high, hard, rocky plateaus, of which the sand has been almost removed by deflation. The structure of the Hamada System is highly asymmetric, tabular and slightly wavy, which can reach a total thickness of several kilometres, and rests on the Paleozoic basement (Margat, 2012; see also the geological cross section in figure 104 in appendix A). The formation adjacent to the Tafilalet plain, of which the study area is part of, exists of Lower Cretaceous red beds.

More south, the Tafilalet region comprises the lower elevated Tafilalet plain. Essentially, the plain exists of Quaternary sediments, which rest on an enormous erosive depression resulting from removal of the secondary and tertiary coverage and the deepening in the Paleozoic substratum

(Ruhard, 1977). The erosion was mainly driven by hydrological processes that started in the Pliocene at the end of Neogene. The Paleozoic Formation becomes visible through the large numerous outcrops, mainly near the Anti-Atlas, but also in the Quaternary plain itself (see figure 6). The substratum exists predominantly of limestone, schist and sandstones.

The present alluvial sediments in the Tafilalet plain are deposited from the Lower Quaternary until today. This sedimentation was from time to time alternated by periods of erosion, caused by climatic variations over time (pluvial and interpluvial periods) and resulting in today's sedimentary layering. The thickness of the Quaternary Formation reaches up to 30 m.

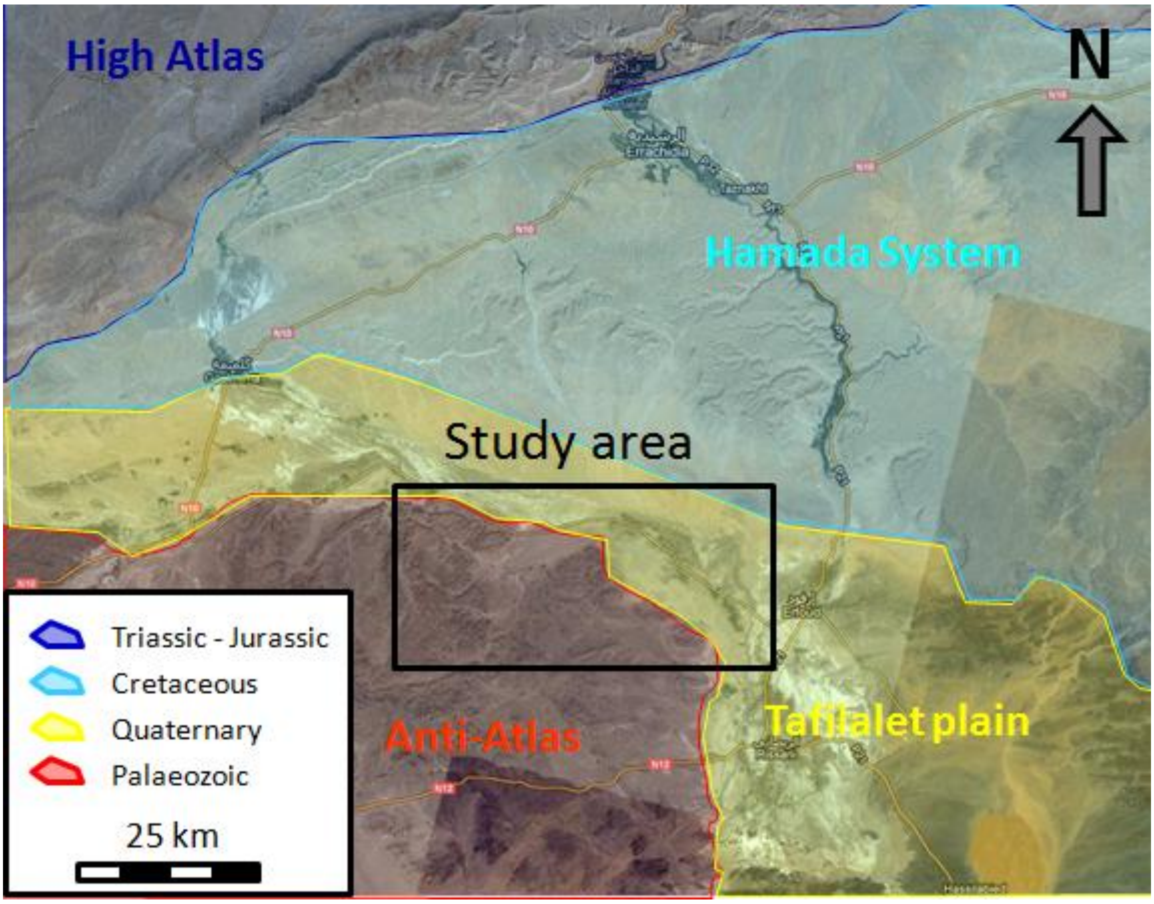


Figure 5: Geological map of the Tafilalet region.

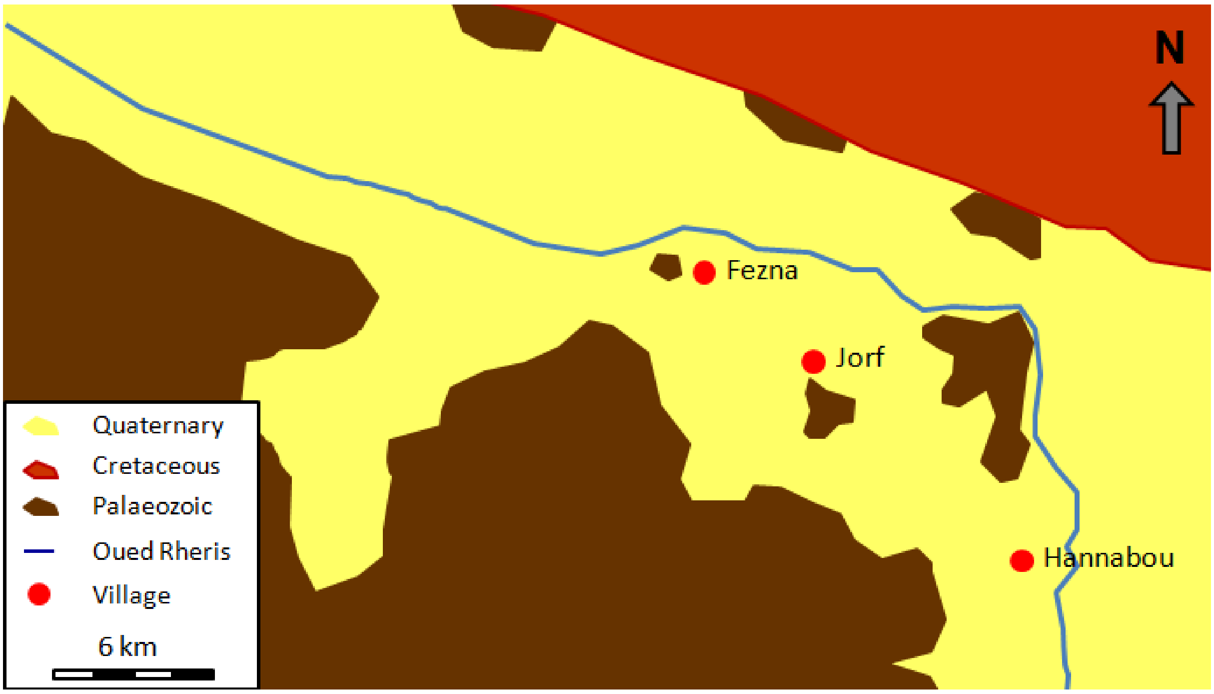


Figure 6: Geological map of the study area.

2.2.5 Sediments in study area

The Quaternary sediments of the Tafilalet originate from the High Atlas, Anti-Atlas and Hamada System. The different sedimentary layers are generally found as tabular strata with a small slope of about 0.0025 equal to that of the surface. The most important Quaternary sediments in the study area are:

- Conglomerates, sedimentary rock consisting of rounded gravel stones within a finer-grained matrix that have become cemented together, generally form the bottom alluvial layer. One can observe various degrees of cementation and it is commonly incomplete, leaving a network of interstices available for water flow. The cement exists of calcareous sediments (Ruhard, 1977). The first conglomerates were formed during the Lower Pleistocene (around 1 million years BP, see the geological time scales in appendix A). The majority of today's conglomerates was deposited during the Middle Pleistocene and the early Late Pleistocene (Amirien and Tensiftien period) under strong pluvial conditions. Conglomerate outcrops can regularly be seen near and in the bed of the river Rheris, which carved its way through the finer overlying sediments. The conglomerate layer is considered to be most contributable to the Tafilalet plain aquifer. This is because of its widespread presence in the plain and contributing most to the transport network. However, the permeability is believed to be highly heterogeneous as a result of the variation in cementation (Ruhard, 1977). Within the study area, drillings show that the thickness of the conglomerate layer varies between 5-15 m (see figure 7).

- Lacustrine limestone deposits formed predominantly in the Middle Pleistocene (Amirien period) and, to a smaller degree, during the Late Pleistocene (Tensiftien period) (Ruhard, 1977). Therefore this formation is mostly present next to or on top of the conglomerates. The word 'lacustrine' already explains that the limestone formation was mainly formed under lake conditions. It less widespread than the conglomerate, but its permeability is comparable due to the occurrence of fissures (Ruhard, 1977). The thickness of the limestone formation generally varies between 5 – 10 m.

- Gravelly alluvium contains sediments with sizes varying from fine sands to coarse gravels with clasts of several centimetres in diameter. One can distinguish recent and fossil gravel formations. The ancient gravels were mainly deposited by the end of the Late Pleistocene (Soltanien period; 100 to 10 thousand years ago) and are covered by silt. Recent gravel beds are found in the bed of the oued Rheris. The permeability of the gravelly sediments is high. However, the thickness of the gravel formations is generally small, only a few meters. They sometimes form lens-shaped beds and, therefore, give rise to preferential flow paths for the groundwater.

- Silt deposits are widespread in the Tafilalet plain. Generally, the silt sediments form the upper layer and are sporadically covered by dune sands. The silt formation was deposited at the end of the Pleistocene (Soltanien period), but even today silt deposition continues through floods in the plain and the supply of flood water in the irrigation areas. Hydrologically, the silt is important: it is used for agricultural activities and facilitates the recharge of the aquifer by irrigation infiltration. Its permeability is low, but its storage capacity is high. The thickness of the silt layer is on average 10 m throughout the entire Tafilalet area, but may reach up to 20 m, and it is largely homogeneous.

The Quaternary sediments rest on a Paleozoic substratum, of which the permeability is considered to be very poor, even negligible in comparison to the alluvial deposits (Ruhard, 1977).

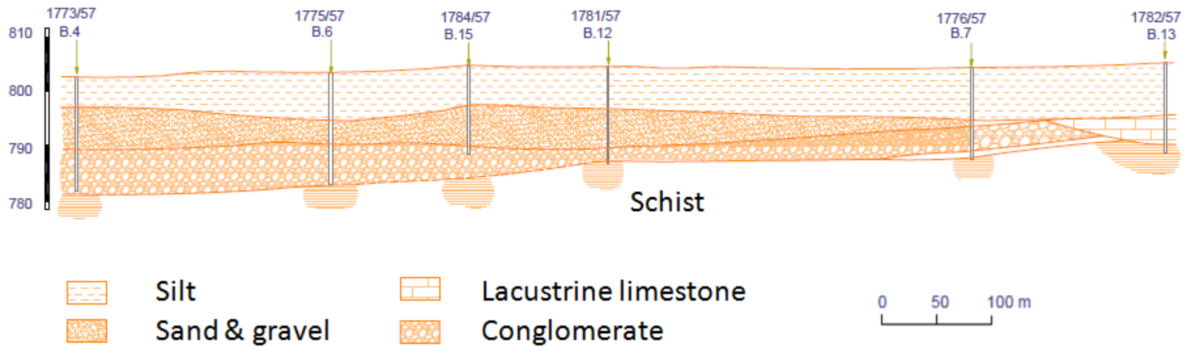


Figure 7: Typical stratigraphy of the Tafilalet plain (Ruhard, 1977).

2.3 Climatology

2.3.1 Temperature

Average daily temperature in the study area varies between 10 °C in winter to 30 °C in summer (see figure 8). The amplitude of the minimum and maximum temperatures is significant; the average of the minimum temperatures in the coldest month January is -3 °C, and the average of the maximum temperatures of the warmest month July is 43 °C (Samuel, 2006).

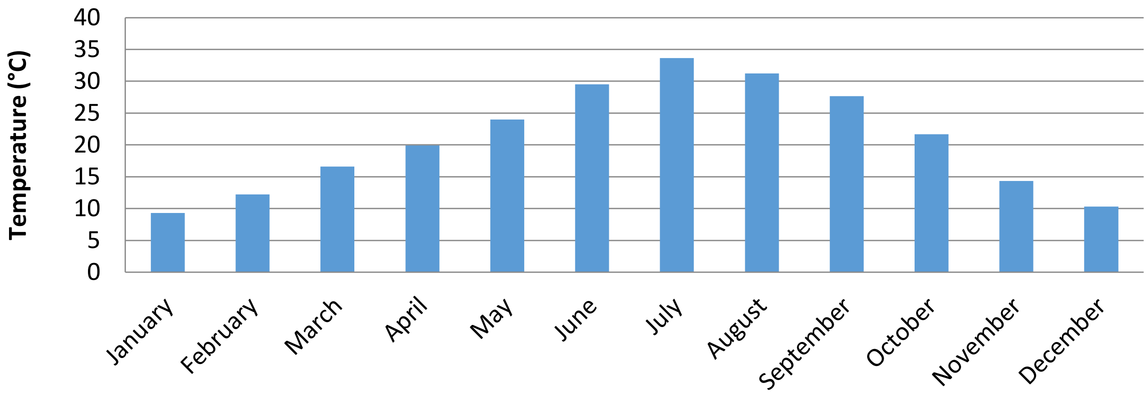


Figure 8: **Average temperatures in Erfoud for the period 1982/1983-1999/2000 (Samuel, 2006). The meteorological years in Morocco start in September.**

2.3.2 Precipitation

The average yearly precipitation in the study area in the period 1977/1978 - 2009/2010 is 87.5 mm, which is relatively low. The rainfall is lowest between June and August with a minimum in July of 1 mm (see figure 9). During the rest of the year the precipitation varies between 5 and 16 mm per month. Large amounts of the yearly precipitation fall in a small number of days. For the period 1977/1978 - 2009/2010, on average, 75 % of the total monthly rainfall amounts is generated by only one single rain event. Figure 10 shows the yearly precipitation during the period 1989-2009 including some very dry years, especially 2000/2001 and 2002/2003.

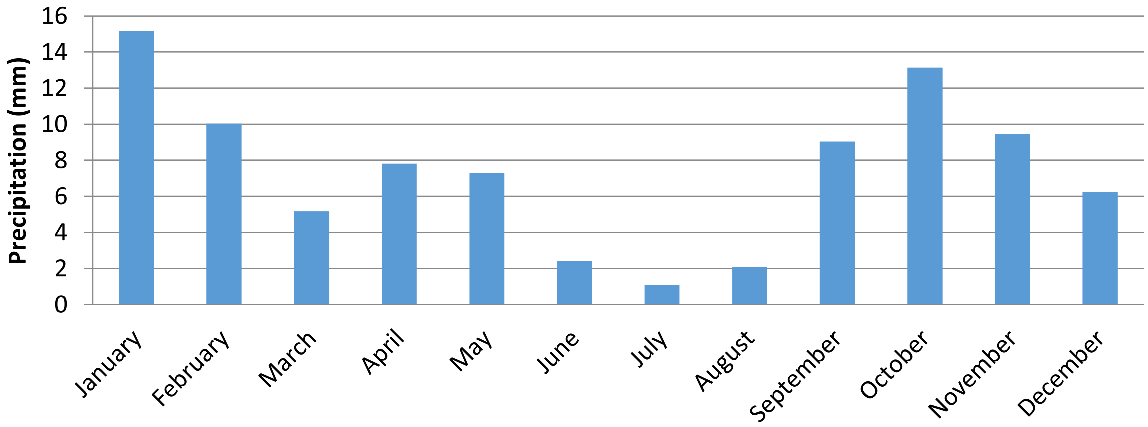


Figure 9: **Average monthly rainfall in H'mida-Jorf for the period 1977/1978 - 2009/2010. No data is available for the period 1996/1997 – 2002/2003.**

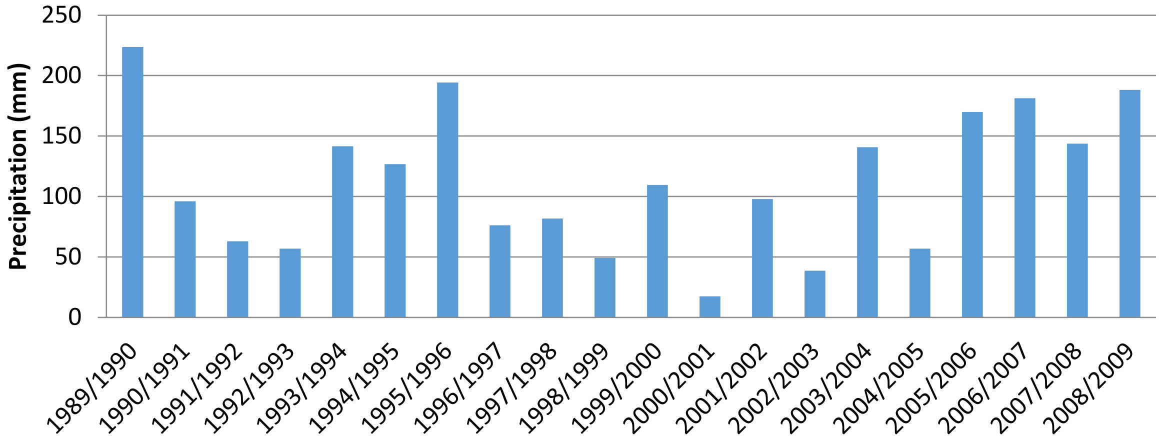


Figure 10: Precipitation at the station of Merroutcha during the period 1989-2009. The metrological season runs from September until August. The entire data set can be found in appendix B.

2.3.3 Evaporation

The potential evaporation in the Tafilalet region is very high, which is characteristic for the arid and Saharan climate. It is largely influenced by the intensity of insolation, the strength of the wind and the low air humidity. Figure 11 shows the periodic monthly variation with high values in summer and low values in winter. Such values are obtained with the pan evaporation method with continues availability of water. The actual evaporation is much lower due to the scarcity of surface water and the inaccessibility of deeper groundwater for evaporation. Furthermore, inside the palm groves the evaporation is lower than in the open plain. This is due to the minimization effect of the micro climate created by the covering of palm and olive trees.

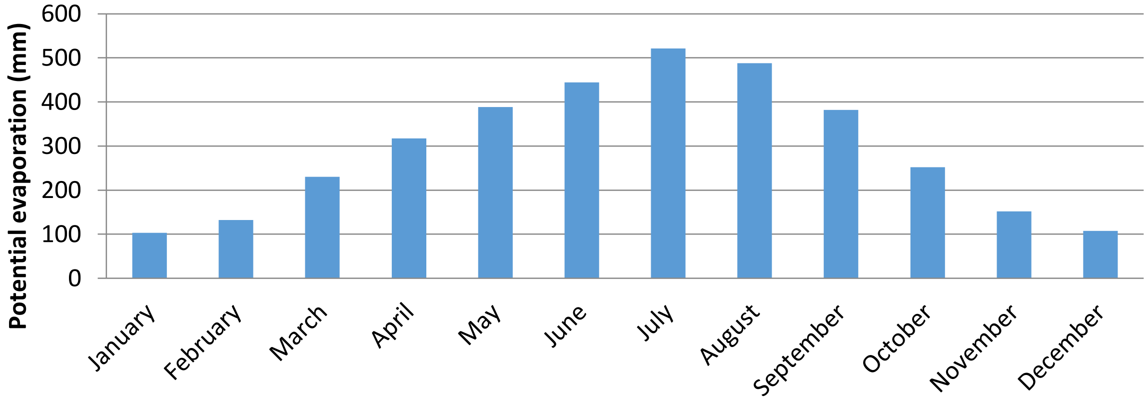


Figure 11: Potential evaporation measured with the class "A" pan method in Erfoud during the period 1982/1983 - 2007/2008 (source : L'Agence du bassin Hydraulique du Guir-Ziz-Rheris).

2.4 Hydrology

2.4.1 Surface water

The main source of surface water in the study area is the oued Rheris during floods (see figure 12 and figure 13). The water originates from the Anti-Atlas and the High Atlas with an estimated average total volume of 28 Mm^3 per year (ORMVA JICA, 2005) and 33 Mm^3 (ABHGZR, 1997). The presence of water in the oued Rheris is rare, only during floods which occur 4-5 times a year (Bouhamid Alaoui, 2011). During extreme events large parts of the plain are flooded as well.

During floods water is partly being directed to the irrigation fields by four dams and associated irrigation canals. However, the capacity of the canals is heavily reduced due to sedimentation and a lack of maintenance. The water volume extracted from the oued Rheris for irrigation purposes is estimated at 25% of the incoming surface water (ORMVA JICA, 2005).

The remaining surface water either evaporates (which is assumed to be the largest part), infiltrates in the sedimentary layers (recharging the groundwater reservoir) or flows downstream, southward, as surface water into the lower parts of the Tafilalet plain to eventually disappear in the Sahara.

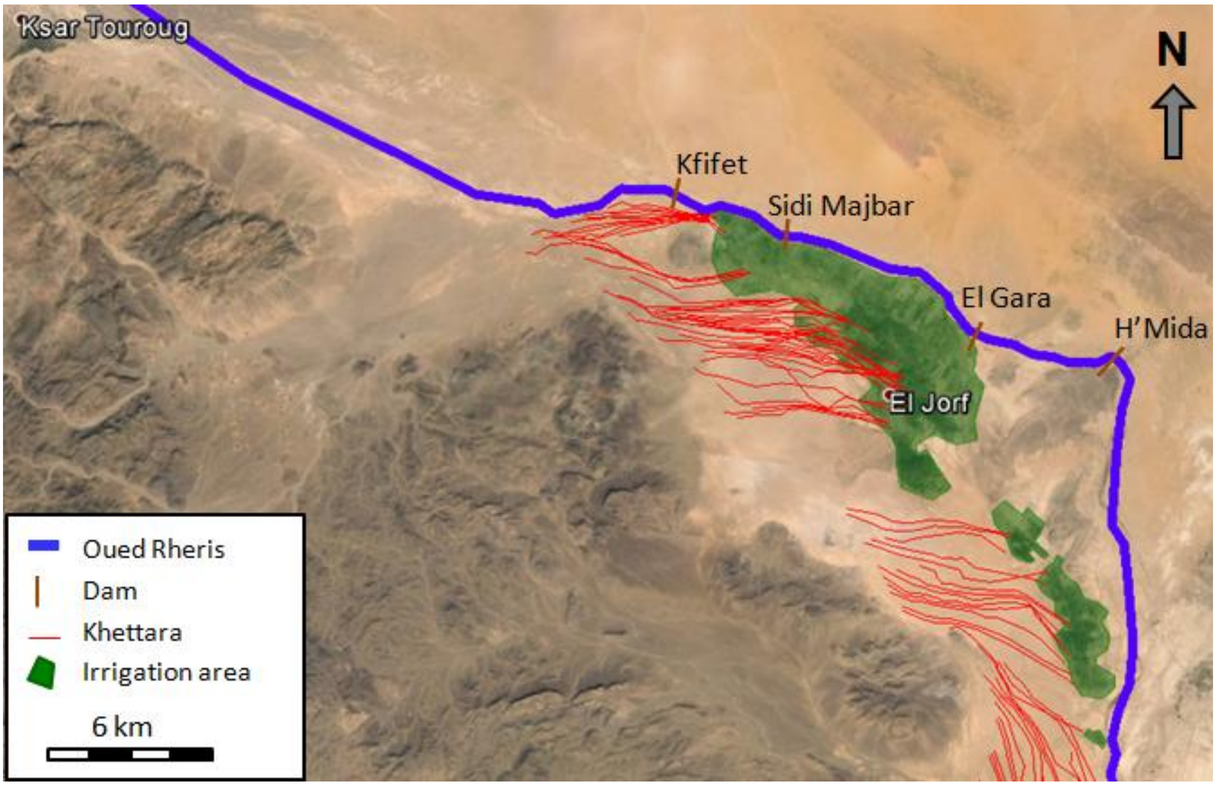


Figure 12: Hydrological map of the study area including water structures. A majority of the presented khettaras have fallen dry.

Figure 13: Left: surface water in the oued Rheris. Right: surface water in an irrigation canal.

2.4.2 Groundwater

Groundwater flow in the study area is essentially limited to the sedimentary layers that jointly form an extensive phreatic aquifer. Especially the conglomerate and the gravel layers contribute most to the transport capacity of the aquifer due to their favourable permeability, while the silt formation contributes most to the groundwater storage. The bedrock below the conglomerate is assumed to be largely impermeable and consequently is not part of the aquifer (Ruhard, 1977). It however determines the direction of the groundwater flow by its shape and elevation.

The groundwater system of Fezna, Jorf and Hannabou is part of the larger aquifer of the Quaternary Tafilalet plain. Similar to the surface water, the main groundwater inflow originates from the High Atlas (see figure 14). In fact, the groundwater flow direction generally follows the route of the oued Rheris in south-east direction dictated by the bedrock inclination. There is also a lateral groundwater inflow that originates from precipitation in the catchments of the Anti-Atlas south to the study area. The groundwater influx from the Cretaceous Formation (Hamada System) is insignificant and is negligible compared to the longitudinal flow (Ruhard, 1977)

Other sources for groundwater relate to the infiltration of surface water in the study area itself. The first flux is by floods, occurring a few times a year. This infiltration takes mainly place in the oued Rheris, but also in the part of the plain where the khettaras are located. Secondly, there is infiltration and recharge in the agricultural areas as a result of field irrigation.

The largest groundwater outflows from the aquifer are generated by khettaras and motor driven pumps in the agricultural areas (for location see figure 12). Both fluxes are of the same order of magnitude and together their extraction is significant. Especially pumping has a severe impact on the groundwater reservoir. The introduction of an extensive number of wells in the area in the nineteen fifties led to substantial groundwater lowering (see figure 15). Another groundwater outflow is the river drainage through the oued Rheris. This only regularly occurs at some locations near Hannabou where the groundwater table is close to ground surface. Quantitatively, this outflow is negligible compared to the other flows, because the Rheris mainly recharges to the aquifer. South of Hannabou, the “remaining groundwater” flows into the Tafilalet plain in southern direction.

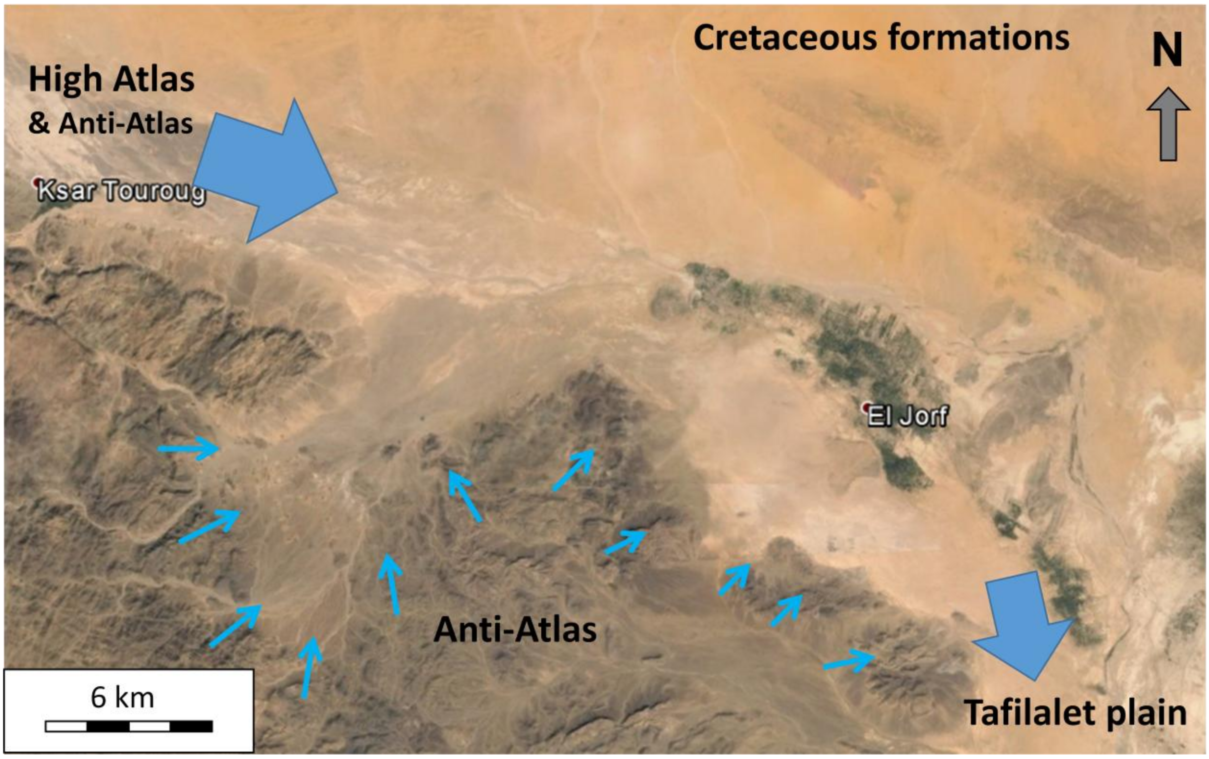


Figure 14: Groundwater in- and outflows and their origins/destinations.

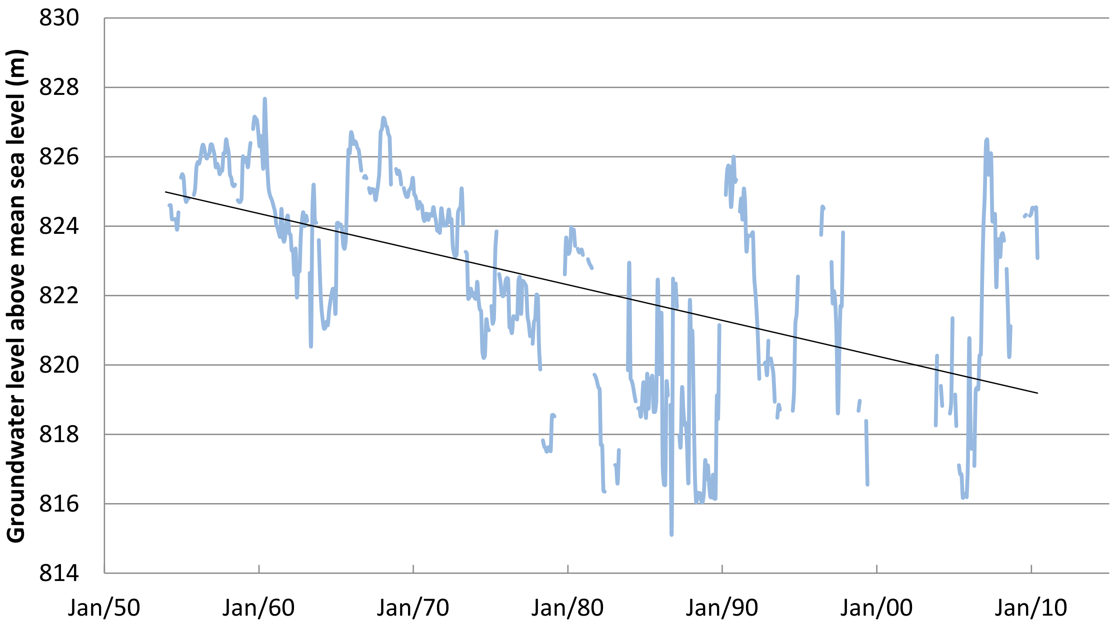


Figure 15: Groundwater table (blue) measured in the study area in monitoring well 1028/57 (for location, see appendix C). The black line represents the water level trend, which is determined by linear regression.

2.4.3 Khettaras

Khetteras (known as qanats, foggara, karez or galerias in other countries) are subsurface drainage tunnels to collect groundwater. The first khettaras in Morocco were introduced in the twelfth century, probably following the Islamic revolution through Northern Africa, and later in the Tafilalet region in the fourteenth century (Lightfoot, 1996; El Faïz, 2005).

Khettara were usually dug into alluvial soils of foothills wherein groundwater tables gradually follow elevation (see figure 16 and figure 17). Extraction occurs where the khettara gallery intersects with the groundwater table, this forces groundwater to seep into the khettaras through its walls. Subsequently, the water is channelled under gravity to the surface level several kilometres away. The canal bed is covered with fine sediments to prevent infiltration in the part of khettara where the groundwater is below the tunnel. The water is mainly used for irrigation, but also for other purposes like drinking, cleaning and cooking. Because khettara discharge entirely relies on passive extraction of groundwater, khettaras cannot overexploitate the groundwater reservoir (Lightfoot, 1996), which is in sharp contrast to pumping wells which presence potentially leads to aquifer depletion.

The area of Fezna, Jorf and Hannabou houses approximately 60 khetteras (see figure 12). Just half of them are currently functioning. The other half has fallen dry due to excessive pumping, including all khettaras of Fezna (Ruhard, 1977). At the moment all khettaras of Hannabou and some of Jorf are supplying water. All these khetteras extract water from the aquifer near the foot of the Anti-Atlas and transport the water in eastern direction to surface at the irrigation fields. A rehabilitation project performed in the previous decade by a Japanese cooperation agency (JICA) and the local agricultural office (ORMA/TF) resulted in the revival of multiple khettaras of Jorf.

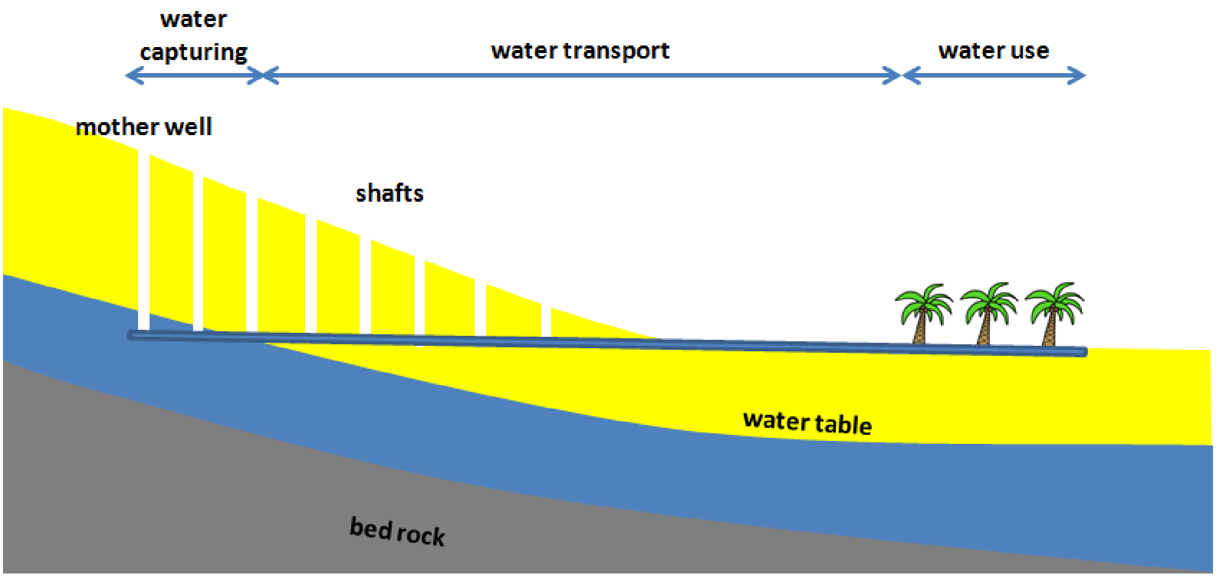


Figure 16: Schematic cross-section of a khettara.

Figure 17: Satellite top view of several khettaras in the study area existing of hills which are made of excavation material from the shafts and the tunnel.

2.4.4 Pumping

The first (public) pumps in the Tafilalet region date back to the 1930's, when they were installed by the French. Later, in the nineteen fifties and sixties, private motor pumps were introduced when they became more affordable for individual farmers (Lightfoot, 1996) (see figure 18). With private wells, farmers are more independent compared to shared water systems like khettaras or canal irrigation systems. Also, the money transfer from emigrated family members, working in the more urban areas of Morocco or in Europe, stimulated the growth of pumps (De Haas, 2006).

Concerning the groundwater system of Feza-Jorf-Hannabou, most pumps are located in the agricultural areas (see figure 12). Official figures show that in 2006 there were a little over two hundred pumps, both collective and private (ORMVA, 2006). The regulation of diesel pumped wells by the authorities was inadequate for a long time (Lightfoot, 1996). Most wells extract water from the conglomerate formation (see figure 18), because of the favourable permeability and depth.

The introduction of wells had and has a severe impact on the groundwater system. Groundwater tables dropped significantly, sometimes almost 10 meters (see figure 15), and resulted subsequently in many khettaras falling dry with severe consequences for the social cohesion of the communities (Dvoran, 2012).

Figure 18: A typical diesel pump next to an open well. The hill behind exists of excavated material and indicates that the well reaches down to the conglomerate layer.

3 Methods

3.1 General approach

To explain the followed approach, the generalized groundwater resource plan of Lerner (1990) is used. The procedure follows the steps below, including a short explanation on how it was done.

1. Determine study goals
   Study objectives are founded on the desires of the main actors in his research – ONEE Branch Eau, Waternet and TU Delft (more information on the actors can be found in section 3.4) - through discussions with the supervisors. The study objectives were refined during the research period, but were sometimes refined as a consequence of limitations and collected information. It can be seen as an iterative process.

2. Collect preliminary available information
   First-hand literature was consulted in the Netherlands in order to get a first insight in the topic of the research. Both specific information on the study area and more general information were studied.

3. Define a conceptual hydrological model
   The information gained in the previous step was processed in order to set up a first concept of the groundwater system of the basin of Fezna-Jorf-Hannabou. Hydrological processes and the geological components were defined as well as a first estimation of the boundaries of the groundwater system. This could be seen as the first step for defining the structure of the numerical groundwater model.

4. Identify key feature and data shortages
   An inventory on the required information was done. Key elements of the geohydrological system in the study area were determined to improve the conceptualisation, together with information and data shortages.

5. Preparations for fieldwork
   From the identification of the key features and the data shortage, it was deduced which actions had to be taken. A fieldwork was planned. Contacts were made with organisations which were or could be relevant for the fieldwork. A working plan was set up, usable for in the field.

6. Carrying out fieldwork
   A fieldwork was performed in the study area in the Tafilalet region, Morocco. This included observations, measurements and interviews. In addition, more data and information was gathered from governmental organisations. More detailed information about the fieldwork is given in section 3.2.

7. Processing and analyzing data and finalise conceptual model
   After the fieldwork the data and information is processed and analysed in Delft, the Netherlands. With this information the conceptual model was refined and data was prepared in order to set up the numerical groundwater model.

8. Setting up a numerical model
   A numerical groundwater model was created based on the conceptual model. The first step was to set up the geological structure and implement the relevant hydrological processes including 'filling' the model with the data. More information on the composition of the model can be found in chapter 4.

9. Calibration of the model
   The model was calibrated to the situation of the groundwater system in the period 1959-1970 and the period 2000-2011. During this process more insight into the behaviour of the groundwater system of Fezna-Jorf-Hannabou was gained, achieving the first research objective. Consequently, recommendations could be distilled for further investigation. More information on the calibration of the model can be found in chapter 5.

10. Water resource development plan: scenarios
    As a last step scenarios were determined and implemented in the model. By running and studying the outcomes of these scenarios, the second research objective was achieved: Examination of the possible effect of likely future changes on the groundwater system of the basin of Fezna-Jorf-Hannabou (see chapter 6).

11. Presentation
    Finally, the research is presented and defended at the TU Delft. In addition, presentations are held for the different parties involved.

3.2 Fieldwork

3.2.1 Chronological summary

The first two weeks in Morocco, starting at the 5th of February 2013, were spent in Rabat where preparations for the fieldwork were done at the office of ONEE – Branche Eau (for more information on the actors see section 3.4). Under supervision of Ir. Mokhtar Jaait, head of the R&D department, and Ir. Hanane Benqlilou, researcher at the R&D department, the research and the planned fieldwork was discussed. Also, meetings took place with Prof. Hilali and Ir. K. Nadifi to discuss the research and to gather of information and data. At the 18th of February the journey to Errachidia in the Tafilalet region was made. This was the base location during the fieldwork. Contacts were made with the Université Moulay Ismail (UMI), which provided several measurement equipment (see section 3.2.3), and the L'Agence du Bassin Hydraulique du Guir-Ziz-Rheris, which facilitated office accommodation in Errachidia. At the latter, mister A.Tabit, former director, and M. Kamal El Mokaddam, hydrologist, provided assistance on the research and the preparations of the fieldwork. The actual fieldwork was done by a total of ten trips to the study area (including the villages of Fezna, Jorf and Hannabou), of which the travel was facilitated by ONEE – Branche with a car including a driver. Here most of the fieldwork was guided and assisted by Mister Lhassan Elmrani, head of the Centre d'étude et de développement des territoires oasiens et désertiques Jorf Errachidia MAROC (CEDTOD). In the field many observations, measurements and interviews were performed (for more information see the sections 3.2.2, 3.2.3 and 3.2.4). Also a geological tour was given by prof. M. Boujamaoui, of the Geological department of UMI. Prof. T.N. Olsthoorn, supervisor from the TU Delft and Waternet, joined during the last week of the fieldwork. The period in the Tafilalet ended at the 17th of March 2013 and lasted in total five weeks. More information on the collected information and data is given in section 3.3.

3.2.2 Observations

Observations were intended to gain more information about the geological and hydrological structure of the groundwater system of Fezna-Jorf-Hannabou. The following sites have been visited:

- oued Rheris
- small dams used for irrigation purposes
- agricultural fields
- Anti-Atlas foothills
- plain
- khettara mother wells
- khettara outlets

The locations of the above mentioned sites and related photographs can be seen in appendix D.

3.2.3 Measurements & instruments

Various measurements have been performed in the study area. They are intended to gain data, which are directly usable as input for the model or to improve the geohydrological concept of the area. Table 1 shows these measurements and the corresponding instruments. The measurement locations were determined with GPS. The locations of the measurements and corresponding pictures can be seen in appendix E. Furthermore, the results can be found in appendix F.

Table 1: Scheme of the measurements performed during the fieldwork together with the related instruments.

Measurement	Description	Instruments	Number of measurements
Infiltration capacity	Measuring the decline rate of the water level in a drilled hole in the topsoil.	Edelman auger, stopwatch, tapeline	7
Khettara mother well depth	Measuring the depth of mother wells by lowering a cord with an attached weight.	Cord, weight, tapeline	15
Khettara discharge at outlet	Measuring the velocity and the wet surface of the water in a khettara canal.	Floating device (orange), stopwatch, tapeline	22
Water content	Measuring the water content profile over depth from ground surface.	Edelman auger, TDR-probe, tapeline	1
Groundwater table	Measuring the groundwater table in an open well with respect to the surface level.	Water level meter	4

3.2.4 Interviews

In total, seventeen interviews were taken, fifteen of which specifically directed to gathering information on khettaras and two on motorized pumping (see questionnaire in appendix G). The objective of the interviews was to gain more information on the quantity of the extractions.

Khettaras

The interviews were taken to get an idea on the variability of the khettara flows at different time scales of a month, season, year and a decade. More general questions were asked about the purposes of the water and the number of people depending on each khettara.

Pumping

Farmers owning an open well, including a pump, were also interviewed. They were mostly asked about their pumping regimes and capacities.

3.3 Collected data

The following data was collected:

- bore logs from drillings (see appendix H)
- precipitation (see appendix B)
- groundwater levels (see appendix C)
- khettara discharges (see appendix F)
- geological maps (see appendix I)

3.4 Actors

3.4.1 Morocco

L'Office National de l'Electricité et de l'Eau potable (ONEE) - Branche Eau

ONEE – Branche Eau is the national public drinking water supply company of Morocco and is the leading organisation on drinking water and sanitation in Morocco. ONEE – Branche Eau is responsible for the country wide planning and production of fresh water resources. It has the task to distribute drinking water in most parts of the country, except in a number of major cities.

International Institute for water and Sanitation of ONEE (ONEE-IEA) is a department within ONEE, founded in 2008, wich has the objective to create human resources capacity and develope knowledge and expertise in the fields of water and environment, based on a holistic and sustainable approach, and in the context of a public non-profit partnership.

ONEE – Branche Eau and ONEE-IEA have much interest in the conservation of khettaras, as they are a sustainable way to extract groundwater, in contrary to individual pumping, which potentially leads to groundwater depletion. Evidently, the issue of groundwater depletion is of high concern to ONEE – Branche Eau as it affects the groundwater resources in Morocco.

ONEE – Branche Eau has been, in collaboration with World Waternet and TU Delft, the key organisation in the formulation of the topic and objectives of this Master thesis. Also, they facilitated supervision (Ir. M. Jaait, also member of the graduation committee) and additional expertise (Ir. H. Benqlilou), the travel to and from Morocco, most of the travel within Morocco, office accommodation in Rabat, preparations for the fieldwork and the residency during the fieldwork period in the Tafilalet region.

L'Agence du Bassin Hydraulique du Guir-Ziz-Rheris (ABH Guir-Ziz-Rheris)

ABH Guir-Ziz-Rheris is responsible for the resource water management in the area of the basins of the oueds Guir, Ziz and Rheris. Its principal objective is to manage the utilisation of public water and as a result to stimulate the socio-economical development in the region. The agency has its main office in Errachidia.

The ABH Guir-Ziz-Rheris provided office accommodation in Errachidia and facilitated connections with other institutions (UMI and CEDTOD). Besides it also provided valuable data, like bore logs, precipitation data, anecdotal information and background information during the many useful discussions with Ir. A. Tabit, the then current director, and Ir. M. Kamal El Mokaddam, hydrologist.

Université Moulay Ismail (UMI)

The UMI is a multi-disciplinary university of which the Faculty of Science and Technology is situated in Errachidia.

The Université Moulay Ismail was able to provide important measurement instruments. In addition, helpful hydrological and geological information was supplied by respectively prof. Hilali and prof. M. Boujamaoui.

Centre d'étude et de développement des territoires oasiens et désertiques Jorf Errachidia MAROC (CEDTOD)

The CEDTOD is founded with the intention to create public awareness and initiatives concerning desertification. The department in Jorf is led by Mister Lhassan Elmrani.

Mister Lhassan Elmrani provided many tours and useful information about the study area (geology, hydrology, agriculture and more). He also made connections with important local people.

3.4.2 Netherlands

Waternet

Waternet is a public organisation responsible for the drinking water supply and urban drainage in the city of Amsterdam as well as the water management in Amsterdam and its surroundings (the area of Amstel Gooi and Vecht). World Waternet is the international unit of Waternet; it works together with local governments and public water companies all over the world. The aim of World Waternet is the exchange of expertise in order to enhance water management performances.

The research was made possible by Waternet through its collaboration with ONEE – Branche Eau in Morocco. Waternet facilitated the supervision and expertise by its hydrologists prof.dr.ir. T.N.

Olsthoorn and PhD candidate F.J.C. Smits, MSc. (both also working for the TU Delft), financial compensation and office accommodation.

Delft University of Technology (TU Delft)

The Delft University of Technology is the largest and oldest public technical university in the Netherlands located in the city of Delft.

The research is performed in the context of the Master thesis of C.J. Strikker BSc. The Master thesis is part of the curriculum of the Master Water Management of the Civil Engineering and Geosciences Faculty. TU Delft facilitates three members of graduation committee: prof.dr.ir. T.N. Olsthoorn, PhD candidate F.J.C. Smits, MSc (Department Watermanagement) and prof.dr.ir. G. Bertotti (Department Applied Geology).

3.5 Software programmes

3.5.1 *mfLab*

The modelling was done through *mfLab,* which stands for MODFLOW-laboratory, an open source interface designed for groundwater modelling using the well-known modular finite-difference flow-model computer code, MODFLOW, and also other related computer programs as MT3DMS and SEAWAT.

In *mfLab*, the modelling workflow is scripted and, therefore, it is reproducible. Furthermore, *mfLab* exploits the numerical computing environment of Matlab. Matlab is used to create models, to write their input files and to process and visualize their output. An Excel file is used for the input of simulation parameters and partly as a manual. Matlab allows line-by-line interactive script development, visualization, testing and debugging. This also allows access to external databases, geographic information systems (GIS) and facilitates, integration and combination with other models, output processing and visualization.

For more information on *mflab* see https://code.google.com/p/mflab/.

For more information on Matlab see http://www.mathworks.nl/products/matlab/.

3.5.2 MODFLOW

mfLab makes use of MODFLOW which is a computer code that solves the groundwater flow equation. MODFLOW is a modular finite-difference flow model computer code and is considered as the standard code for groundwater simulation.

The main partial differential equation solved by MODFLOW is:

$$\frac{\partial}{\partial x}\left[K_{xx}\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_{yy}\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[K_{zz}\frac{\partial h}{\partial z}\right]+W=S_s\frac{\partial h}{\partial t} \quad (1)$$

Where:

K_{xx}, K_{yy}, K_{zz} = hydraulic conductivities in x, y and z-direction (L/T)

h = potentiometric head (L)

W = volumetric flux per unit volume representing sources and/or sinks of water (1/T)

S_s = specific storage (1/L)

t = time (T)

The Newton-Raphson version, MODFLOW-NWT, was used. This was necessary to achieve convergence, which was not possible with the standard version due to the very few fixed-head locations, inherent to deserts. In such a system, stability is difficult or impossible to achieve and many of its computation cells regularly fall dry, causing the model to be strongly non-linear. The more sophisticated Newton-Raphson version can properly handle such situations.

Furthermore, the following parts within MODFLOW were used:

- Output list
- Basic Package
- Discretization Package
- Upstream weighting
- Recharge Package
- Well Package
- River Package
- Drain Package
- Time variant constant head Package
- Output control Package

For more information on MODFLOW see http://water.usgs.gov/ogw/modflow/.

3.5.3 Google Earth

Google Earth is a virtual globe, map and geographical information program. It maps the Earth by the superimposition of images obtained from satellite imagery, aerial photography and a three-dimensional geographic information system (GIS) globe. It is often not accessible in Morocco due to banning.

Google Earth was used as a geographic information system to draw the different geological and hydrological objects. By saving the objects as kml-files, *mfLab* was able to read all geographical information: X, Y coordinates and elevation.

4 Model setup

4.1 Model structure

4.1.1 Spatial boundaries

One of the main objectives of this study is to compare the hydrological information from Ruhard (1977), which is mainly based on the research of Margat, with the model outcomes. To ensure that, the model area should at least include the basin of Fezna-Jorf investigated by Margat. This area stretches in longitudinal direction from the outcrop near Fezna, also named Gara Gfifate, down to the village of Krayr (see figure 19). This study region is part of the larger sedimentary Tafilalet basin (see the geological maps in appendix I) and, consequently, groundwater enters in the northwest and leaves in the southeast (see figure 14).

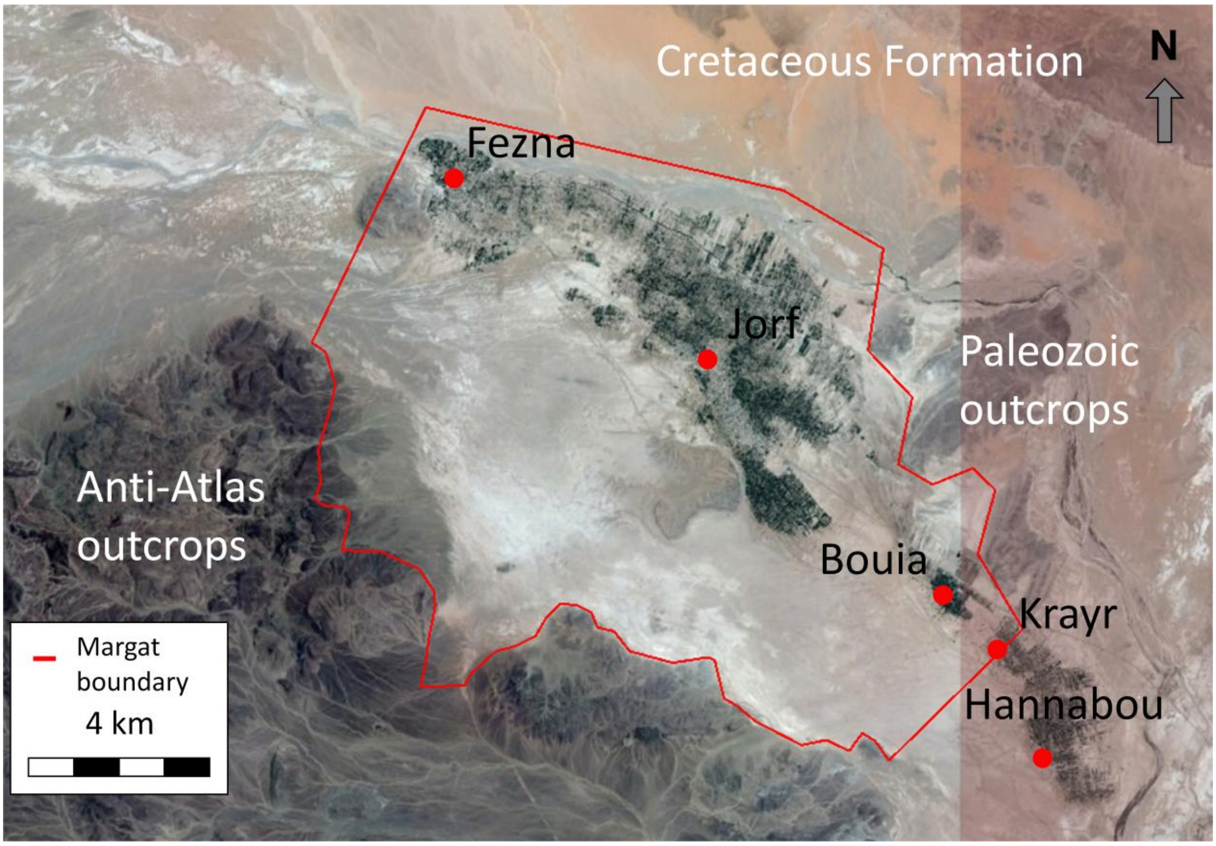


Figure 19: The area researched by Margat.

In the southwest direction, the Anti-Atlas outcrops form a closed geological boundary. Here predominantly surface water crosses the boundary originating from precipitation in the mountains. However, the associated amounts are small compared to the longitudinal flows because the sizes of the adjacent catchments are marginal. In the north, several km's north of the oued Rheris, the Paleozoic bedrock is shallow and outcrops at some locations (see geological map in figure 6 and more detailed in appendix I). Just north of the palezoic outcrops, coarse sandstone outcrops of the southern boundary of the Cretaceous formation are present, part of the larger Hamada system. Groundwater from the north exists through a thin layer of Quaternary on top of both the Paleozoic and Cretaceous formations, from which it essentially evaporates before reaching the Rheris and locally leaving salt crusts (Ruhard, 1977; Google Earth, 2014). The ABH Guir-Ziz-Rheris (see section 3.4.1) commissioned the modelling of the Cretaceous system. This regional model also has its southern boundary at the Rheris. It shows shallow southward groundwater flow ending just north of the Rheris (see groundwater isohypse map in appendix N). This flow is now interpreted as being evaporated, in accordance with Ruhard, before it reaches the Rheris. At least the inflow of groundwater from the north is considered negligible as Ruhard (1977, p375) did. In the northeast Paleozoic hard rock outcrops are of the same formation as the Anti-Atlas and hence also form a closed boundary.

The area researched by Margat contains the following geohydrological processes:

- Extraction of khettaras of Jorf and Hannabou.
- Extraction by pumping in the irrigation areas around Fezna and Jorf .
- Infiltration in the oued Rheris caused by floods.
- Infiltration of irrigation water in the irrigation areas around Fezna and Jorf.

The upstream boundary of the area presented by Margat (Ruhard, 1977) is close to the khettaras of Jorf. Using a head boundary in the model at this location could have significant impact on the model outcomes. Therefore, it has been chosen to extend the model about 10 km in upstream direction. In this way, also the lateral flows from the direction of Oukhit, where several adjacent Anti-Atlas catchments are located discharging into the plain, are included (see figure 20).

Downstream, the agricultural area of Hannabou is assumed to be important for the groundwater system through its infiltration of irrigation water (Ruhard, 1977). Also here the downstream boundary of the area presented by Margat is too close to various khettaras, especially to those of Hannabou. Therefore, the model was also extended to the southwest, to the oued Rheris in the east and to about 5 km south of Hannabou. The riverbed of the oued Rheris in this region consists of limestone hardrock (see geological cross section in figure 142 in appendix H), hence, it forms a closed boundary. In the south, the model is in contact with the Tafilalet aquifer and a fixed head boundary or a flux was, therefore, imposed (for more information on this choice see section 4.3.1).

Concerning the lateral boundaries, the borders presented by Margat (Ruhard, 1977) are reasonable due to their relative impermeability. Consequently, the model is bounded by the Anti-Atlas in the south and the Cretaceous Formation in the north.

The outcrops of Gara Gfifate, near Fezna, and Monkara near Jorf are considered impermeable. Therefore, they are not included in the model.

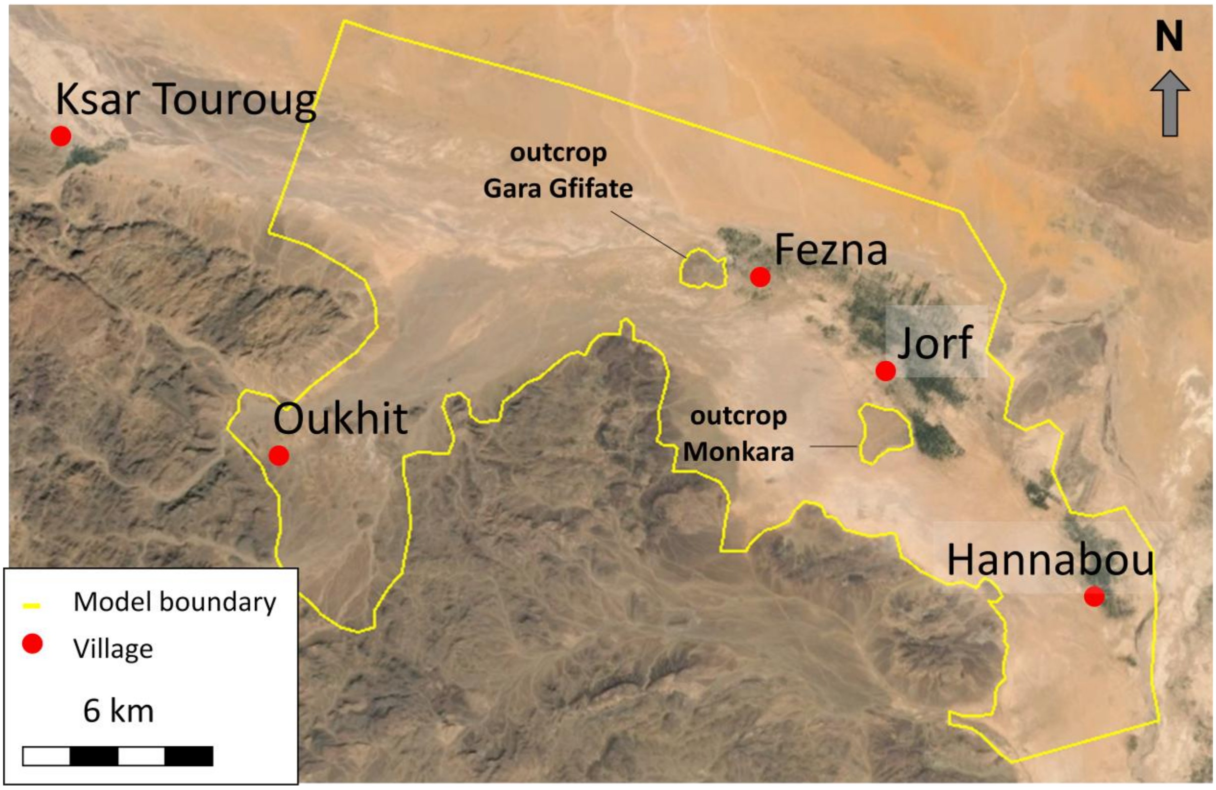


Figure 20: The model area.

4.1.2 Spatial discretisation

The surface level of the model was obtained from the Digital Elevation Model (DEM; see section 4.1.3) and has a cell resolution of 90 by 90 meter. The grid cells size used in the model is 270 by 270 meter, which is a multiple of the original DEM resolution. With the use of 180 by 180 m more accuracy in outcomes was expected, but comparison with simulation results with cell size 270 by 270 m showed that the differences were not worth the higher computation time (see appendix M). Moreover, the reason of the differences being so small is that the essential model features are of a much larger scale. For example, the khettara length exceeds 2000 m and the pumping area has a size of 800 by 9,000 m. Moreover, the computational time with cell sizes 270 by 270 m was substantially lower and hence more acceptable for the calibration process, in which many adjustment steps were expected have to be taken. A visualisation of the model grid on top of a satellite image can be seen in figure 169 in appendix M.

4.1.3 Geological layering

The build-up of the vertical structure of the model starts with the implementation of the surface level. It forms the upper physical boundary of the model.

The elevation information of the surface level is supplied by the DEM and is based on data from the Space Radar Topography Mission (SRTM), an international research effort that obtained digital elevation models on near global scale by the use of modified radar system that flew on board of NASA space shuttles. The original DEM was smoothened with the use of Matlab in order to filter the noise from the higher resolution network. For each model cell, with size 270 by 270 meter, an elevation value is assigned by projection of the elevation information from the DEM. Figure 21 shows the contour map of the elevation of the surface level of the model.

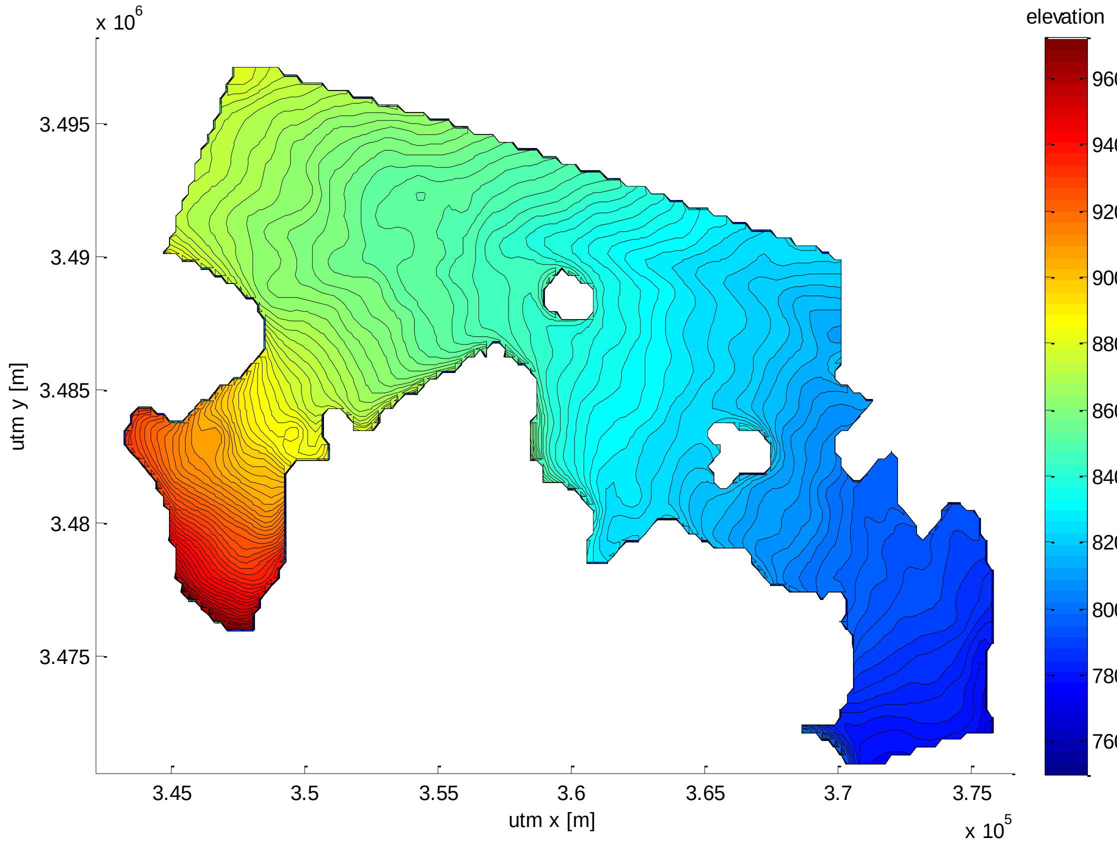


Figure 21: Contour lines of the elevation of the study area with grid cells of size 270 by 270 m. The elevation is expressed in meters above mean sea level.

To continue the model structure set-up, geological layers were made based on information from bore logs and geological cross sections from literature (Ruhard, 1977; see appendix H). Descriptive information from the literature, explaining remarkable geological elements in the study area, was also used. First, there is the channel of gravel located in longitudinal direction of the basin, following more or less the axe Fezna-Jorf-Hannabou (Ruhard, 1977) (for location see figure 22). This gravel has been deposited by the oued Rheris in ancient times and is therefore also called the fossil river bed. Generally, the channel has a thickness of several meters and is located underneath the silt deposits. It is considered to be the main preferential groundwater flow route due to its great permeability. Secondly, there is a rise of the bedrock, not visible from the surface, near the area of Bouia (see figure 19). The thickness of the sedimentary formation at this location is small (Ruhard, 1977). As a result, the groundwater level upstream comes close to the surface, generating a substantial evaporation flux, and resulting in the formation of salt crusts on the ground surface (Ruhard, 1977).

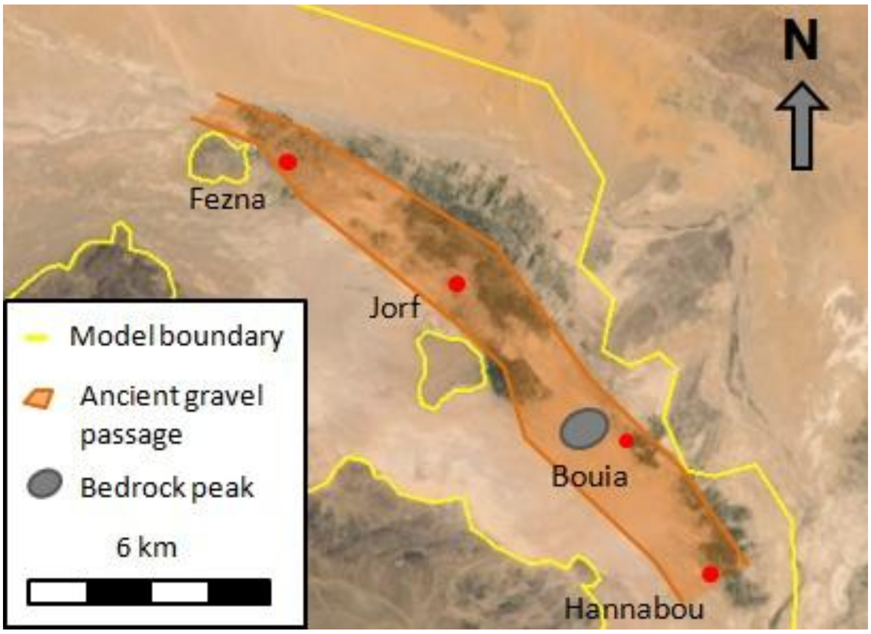


Figure 22: Locations of remarkable geological elements in the study area. The bedrock peak near Bouia is covered with sediments and, hence, it is not an outcrop.

The next step is the generation of the model layers. The geological information shows that the most dominant sedimentary layers are, in sequence from top to bottom:

Silt: This formation constitutes the bulk of the soil of the plain. It is spatially almost omnipresent in the study area, except at Paleozoic outcrops and in the bed of the Rheris. The silt layer has on average a thickness of 10 m.

Gravel: One can distinguish two types of gravel formations: recent and fossil deposits. The first were deposited by recent floods and consequently these gravel sediments are present in the current bed of the oued Rheris. The more ancient gravel deposits are located at previous flow paths of the Rheris, roughly at the line of Fezna, Jorf and Krayr, covered by the silt formation. Both gravel formations have a thickness of several meters and are usually connected. Furthermore, they are generally situated on top of the limestone and conglomerate formations. As a result they are modelled combined as one layer.

Limestone: The limestone formation in this area was deposited under lacustrine circumstances. It is mainly present in the centre of the study area between the outcrops of Gara Gfifate and Monkara more towards the Anti-Atlas in downstream direction. Its thickness generally varies between 5 and 10 m.

Conglomerate: The gravel and pebbles of the conglomerate formation were deposited under fluvial conditions and this formation is widely spread throughout the study area. Its thickness varies between 7 and 10 m.

The other lithologies (mainly marl and pebbles with silt) are basically mixtures of the above mentioned formations. Assigning model layers to all formations would make the modelling process complicated. Therefore, only the most dominant formations (silt, gravel, limestone and conglomerate) were chosen to become individual layers for the model. The other lithologies are allocated to one of these categories based on their similarity in permeability.

Subsequently, the geological data were digitized to Google Earth. For each layer, point information was created where each point represents the thickness of the corresponding layer (see results in appendix J). Then, geological contour lines were drawn in Google Earth based on the geological points, each contour line representing a specific thickness. A thickness of zero is allocated to the boundaries between the outcrops and the sedimentary formation. Finally, the layers were generated in *mfLab* by interpolating the contour lines (see appendix J).

To obtain the entire model structure, the thicknesses of the layers are subtracted from the surface level one by one. This is done in sequence from top to bottom (silt, gravel, limestone, and conglomerate). The resulting bottom of the structure forms automatically the elevation of the bedrock.

Finally, there are still regions in the study area of which no bore logs are available. This is mainly the case for the area upstream of the outcrop of Gara Gfifate (see figure 20, and figure 138 in appendix H). As was discussed above, the silt and conglomerate formations are almost omnipresent in the sedimentary basin of which the geology is known. Therefore, it is assumed that these formations are also present in the above mentioned unknown area, with a similar thickness of 5-10 m for each formation. Moreover, during fieldwork, silt has been observed to be the top layer in most of that area. The gravel channel is assumed to be present near the oued Rheris, just as in the downstream part. Another part of the model area where the geology is unknown is the area near Oukhit. Satellite images show that sediments are present here; they are assumed to be deposited by the surface water flows coming from the Anti-Atlas.

Figure 23 shows the final result of a translation of the geological information to the model for a specific cross-section in the study area.

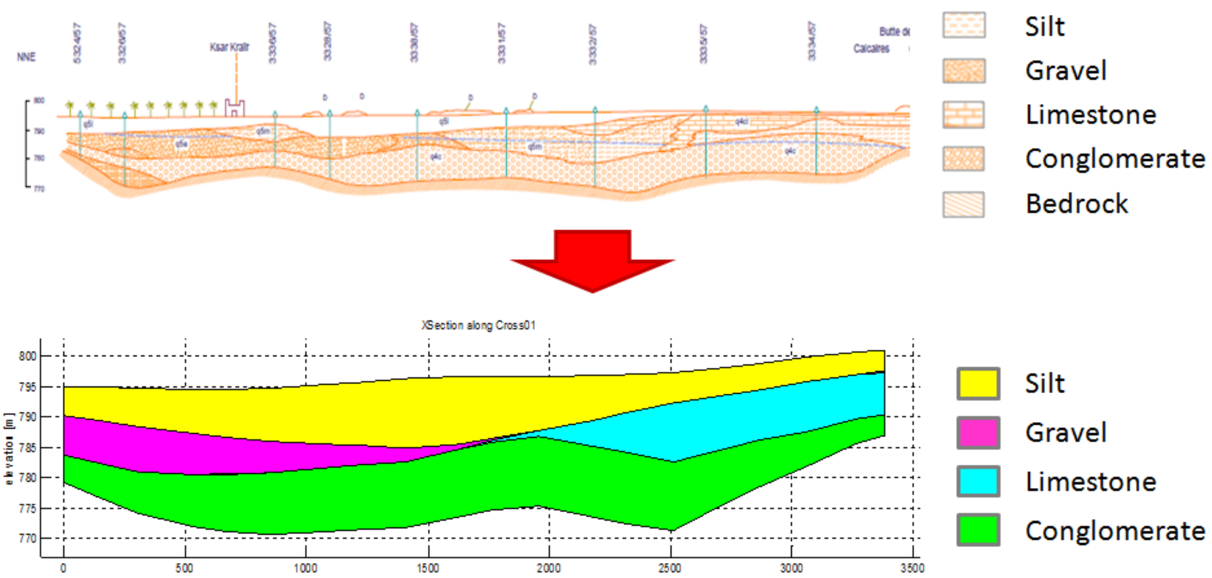


Figure 23: Translation of a geological cross-section from literature (above) to the model (below).

4.1.4 Hydraulic conductivities

Of the sedimentary formations, the silt formation has the lowest hydraulic conductivity and thus contributes least to the groundwater flow in the study area. The sand and gravel formations have the highest hydraulic conductivity; they form preferential flow paths, especially the deeper alluvium because it is generally fully saturated. Less, but still significant permeable formations are conglomerate and limestone. In the conglomerate, water can flow through the extended network of mazes due to poor cementation, while the permeability of the limestone is mainly driven by the presence of fissures (Ruhard, 1997). The bedrock below the sedimentary formations mainly exists of schist, compact limestone and sandstone. The hydraulic conductivity of the bedrock formation is significantly less than that of the sedimentary formations. Therefore, the flows in the substratum were considered to be negligible compared to that in the Quaternary formations (Ruhard, 1977).

Table 2 shows the hydraulic conductivities ranges presented by Margat, which are mainly based on pumping test results.

During the calibration of the model, it was tried to stay as much as possible within these ranges and to seek for optimal values (see chapter 5).

Table 2: The hydraulic conductivities of the dominant formations in the study area presented by Margat (Ruhard, 1977).

Soil type	Hydraulic conductivity		Initial model
	m/s	m/d	m/d
Silt	10^{-6} - $5{\cdot}10^{-5}$	0.1 - 1	0.5
Sand & gravel	1 - $3{\cdot}10^{-3}$	90 - 260	175
Limestone	10^{-5} - $5{\cdot}10^{-4}$	1 - 43	21
Conglomerate	10^{-5} - $5{\cdot}10^{-4}$	1 - 43	21
Bedrock (schist & sandstone)	Impermeable		

4.2 Time

4.2.1 Time steps

The simulated time is divided in stress periods, which are computational time intervals in which transient stresses, like pumping, fluxes and fixed head boundaries, stay constant within the model. the stresses can only change at the beginning of each stress period. For this model, it was chosen to use monthly stress periods, because much used hydrological information, like precipitation and groundwater levels, are only available in months. The period length is equal to 365/12 ≈ 30.5 days. Each stress period can be subdivided into one or multiple time steps. In this model the stress periods exists of a single time step as this is assumed to be sufficiently accurate. However, more time steps were used when convergence conditions were not met. In that case it was chosen to temporarily use two to five time steps.

4.2.2 Modelling period

The model periods were adapted to the available information; two modelling periods are used: 1959-1969 and 2000-2010.

The first period corresponds with the time when Margat did his investigations in the study area, approximately in the period 1953-1969. However, the precipitation data set, crucial as input for the model, starts from 1959. Therefore, the period 1959-1969 was chosen as the first modelling period, a period of eleven years.

The model was improved by performing a calibration for an additional period, 2000-2010, because relatively much (geo)hydrological information was available that is useful for the calibration.

4.3 Hydraulic boundary conditions

This section describes the hydraulic boundaries used in the model in space and time. This information applies only to the initial model, which was used for the calibration (see chapter 5).

4.3.1 Fixed head boundaries

Upstream boundary

There is an incoming groundwater flux at the northwest side of the study area, from the direction of Ksar Touroug (see figure 14). It generally follows the course of the oued Rheris. Together with the flux coming from the southwest region of Oukhit (see figure 20), these are considered to be the main groundwater inflows.

Concerning the magnitude of the flow, literature only gives information of the incoming groundwater flow along the outcrop of Gara Gfifate near Fezna (see the area of Margat in figure 19 and figure 20). The incoming flux at this location was estimated to be 16 Mm^3/y in the nineteen sixties (Ruhard, 1977; see table 3) and 12.2 Mm^3/y in the nineteen nineties (Ourahou, 1998; see table 4). However, no information could be obtained on the ratio of the groundwater coming from the direction of Ksar Touroug with respect to the flux coming from the direction of Oukhit (see figure 20). The only information specifically related to the inflow from Ksar Touroug is groundwater table data (see figure 24).

Table 3: Groundwater balance of the aquifer of Fezna-Jorf-Hannabou (Ruhard, 1977). Groundwater emergence is where groundwater comes visible as the surface is locally lower than the surrounding terrain.

IN (Mm^3/y)		**OUT (Mm^3/y)**	
Groundwater inflow from upstream	16	Groundwater outflow downstream	11
Infiltration by floods in oued Rheris	5	Extraction by pumping	2
Infiltration through irrigation	5	Extraction by khettaras	12
Lateral inflow (from the Anti-Atlas) and infiltration by precipitation	2	Emergences	0.5
		Evapotranspiration	2.5
Total	**28**	**Total**	**28**

Table 4: Groundwater balance of the aquifer of Fezna-Jorf-Hannabou (Ourahou, 1998).

IN (Mm^3/y)		OUT (Mm^3/y)	
Groundwater inflow from upstream	12.2	Groundwater outflow downstream	11
Infiltration by floods in oued Rheris	2.2	Extraction by pumping	8.0
Infiltration through irrigation	11.0	Extraction by khettaras	3.7
Infiltration by precipitation	-	Emergences	0.5
		Evapotranspiration	2.2
Total	**25.4**	**Total**	**25.4**

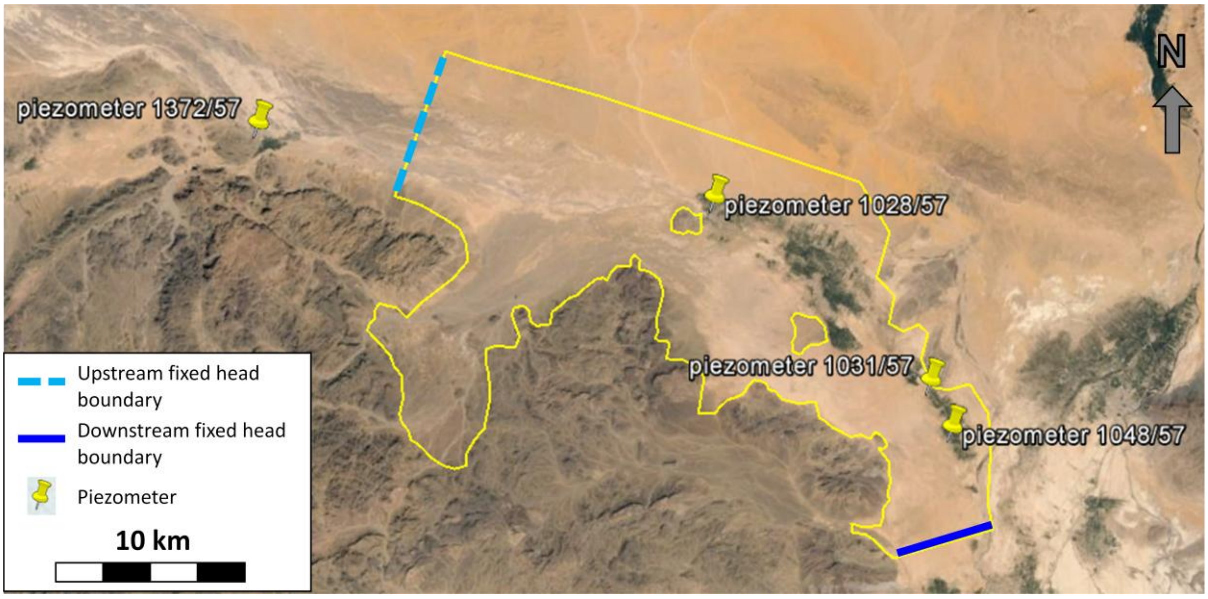


Figure 24: Location of the fixed head boundaries and relevant piezometers.

For the northwest boundary (see figure 24), a fixed-head boundary or a fixed flux boundary can be applied. However, accurate groundwater levels and groundwater flow quantities are not available. A fixed-head boundary stabilizes the model and guarantees that the groundwater table near the boundary will not assume extremes (e.g. far above surface level). Therefore, it was decided to impose a fixed-head boundary at the northwest boundary.

Due to the absence of prolonged groundwater data series, the value for the fixed-head boundary is constant in time. For both model periods (1959-1969 and 2000-2010) the same head was applied because the average yearly precipitation for both periods is about equal, respectively 101 and 111 mm.

The groundwater level in the entire study area is generally lower than 2 m below ground surface. Surface water in the oued Rheris is only present during floods (Ruhard, 1977). Floods in the Rheris occur on average four or five times per year (Spoerry, 2007). The elevation of the surface level is on average 875 m above mean sea level (AMSL) and the topography is almost flat along the northwest boundary. On the other hand, the groundwater table must above the bedrock. The elevation of the bedrock near the boundary is 20 m below ground surface. Consequently, the value of the fixed-head of the boundary should be between 855 and 875 m AMSL.

More groundwater table information is given by piezometers data. The average groundwater level at the piezometer 1372/57, for the period 2011-2012, is 898 m AMSL (see figure 24 and figure 25). The groundwater table at piezometer 1028/57 was in the period 1954-2012 on average 823 m AMSL (see figure 15). By linear interpolation, the groundwater level at the fixed-head boundary was set to 872 m AMSL. This value is used for the initial model.

During the calibration process it appeared necessary to adjust the value for the upstream fixed-head boundary (see chapter 5).

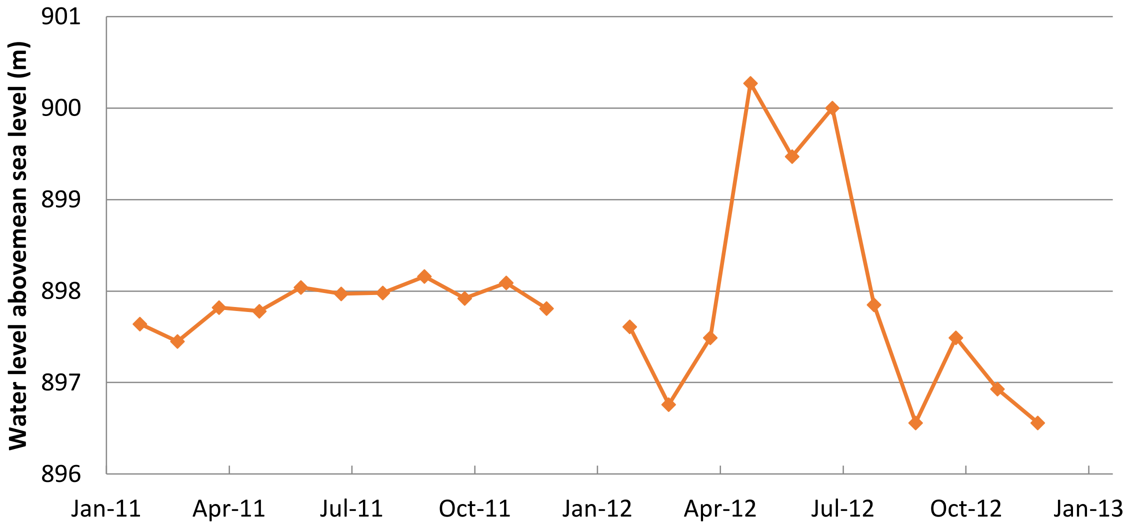


Figure 25: Water levels at piezometer 1372/57. The location of the piezometer can be observed in figure 24.

Downstream boundary

The downstream boundary is located 5 km south of Hannabou. This is the only location of the study area where groundwater outflow occurs. No information is available on the flow at this boundary. However, Margat estimated the discharge at the downstream boundary of his study area near the village of Krayr in the nineteen sixties to be 11 Mm^3/y (Ruhard, 1977; see table 3). Ourahou (1998) estimated the same flow (see table 4).

A fixed-head boundary is applied to the downstream boundary, because this stabilizes the model. The groundwater levels at piezometers 1031/57 and 1048/57 (see figure 26 and figure 27) are extrapolated to obtain the height of the groundwater at the downstream boundary. This was feasible because the piezometers are at the same flow path. A value of 770 m AMSL is determined for the initial model of period 1959-1969. As the precipitation is about the same in both model periods, the same fixed-head value was used for the model period 2000-2010.

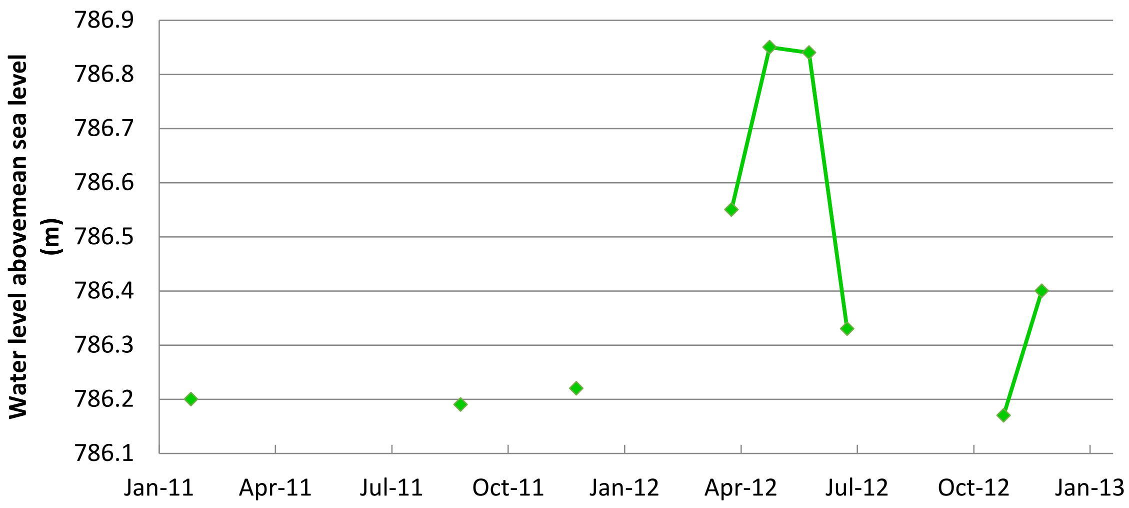


Figure 26: Water levels measured at piezometer 1031/57. The location of the piezometer can be seen in figure 24.

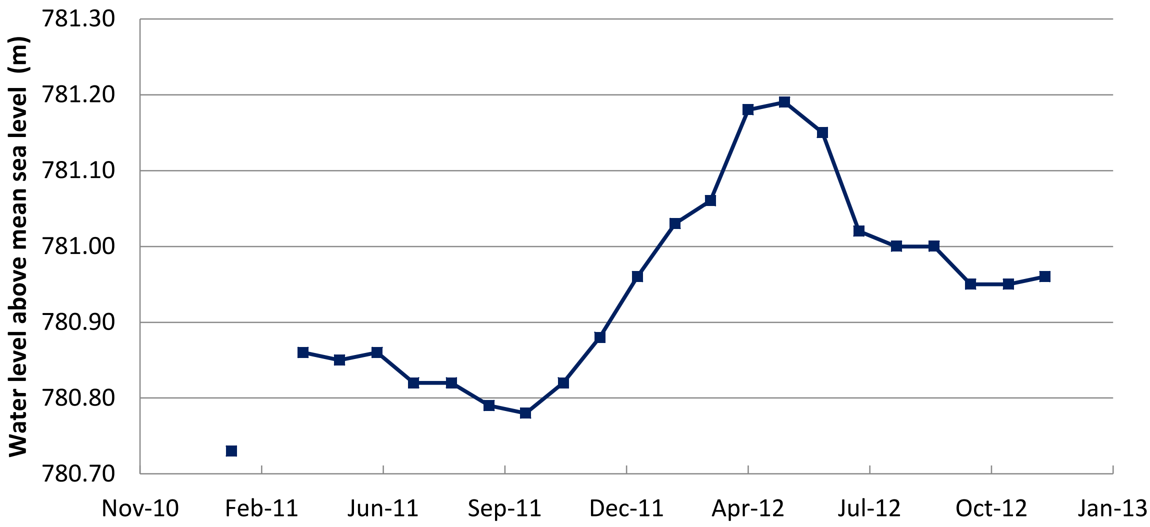


Figure 27: Water levels measured at piezometer 1048/57. The location of the piezometer can be seen in figure 24.

4.3.2 Fluxes from the Anti-Atlas

In the southwest, the model borders the Anti-Atlas from which it receives surface water and groundwater (see figure 14). From satellite images contours of minor wadis are clearly visible, suggesting that substantial periodic surface flows occur.

Margat estimated the groundwater flow from the Anti-Atlas to be 2 Mm^3/y (Ruhard, 1977; see table 3). However, the flows coming from the direction from Oukhit are not included in his estimation, which are assumed to be significant.

Literature does not provide direct information on the total discharge from the Anti-Atlas. Consequently, an algorithm was setup to deal with flows from the upstream catchments. This algorithm is based on the general process of rainfall-runoff in arid areas. Gheith (2002) describes that precipitation falling in a catchment turns into initial loss, infiltrates into the alluvium or becomes runoff. The initial loss describes the part of the precipitation which is lost by evaporation. It contains a threshold, which means that the entire precipitation is lost until the prescribed initial loss is satisfied. Sherif et al. (2010) estimated the threshold to be 20 mm under equal arid circumstances as in the Tafilalet. Geith (2002) describes that when the threshold is overcome by the precipitation, the exceeding rainfall proportionally contributes to both infiltration and runoff. He found that in similar catchments in Egypt approximately 85 % of the exceeding rainfall turned into runoff (runoff factor = 0.80) and around 20 % infiltrates into the groundwater system. A schematization of the process can be seen in figure 28.

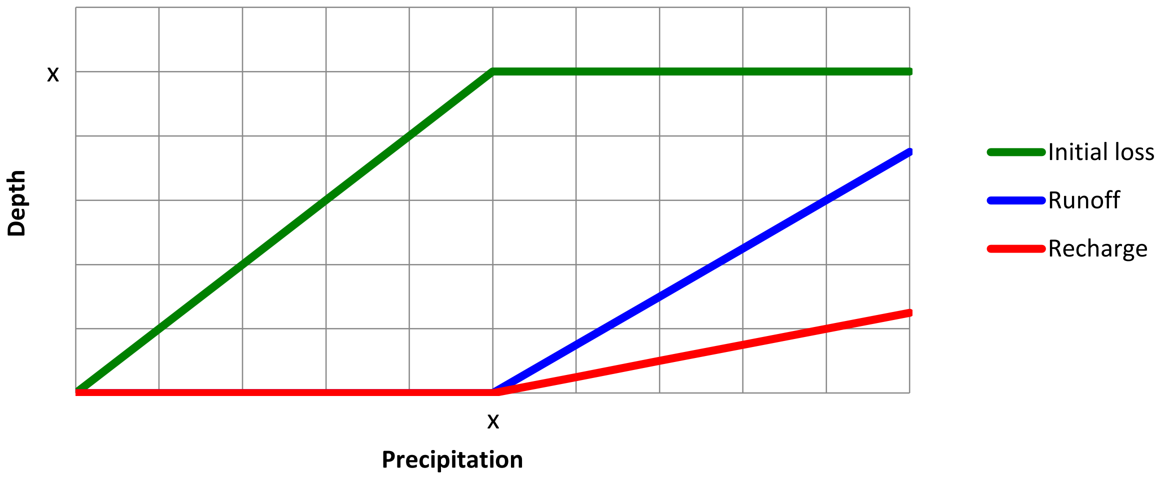
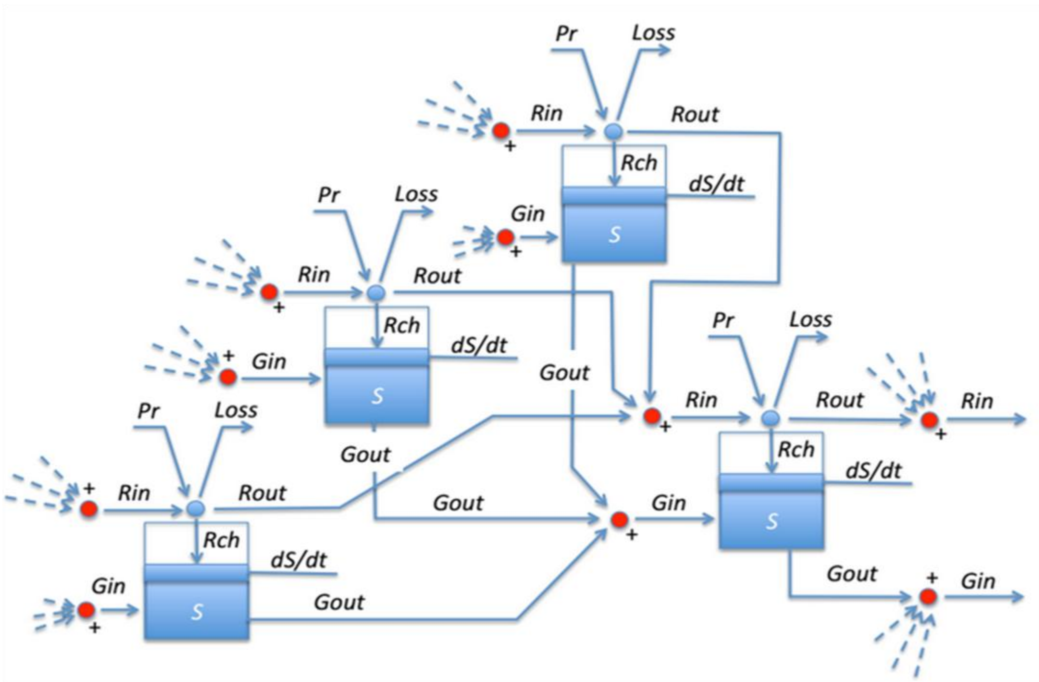


Figure 28: The evolution of initial loss (evaporation), runoff and infiltration in relation to precipitation of a single rain event.

The catchment algorithm is developed in such a way that the above described process can be applied to a hierarchy of connected catchments (see figure 29). For an individual random catchment the procedure then becomes:

1. Direct inflow:
    a. The surface of the catchment receives water from precipitation and runoff from higher catchments.
    b. The groundwater reservoir of the catchment receives and stores groundwater from higher catchments.
2. A part of the surface water becomes initial loss and evaporates.
3. The remaining surface water partly:
    a. infiltrates to recharge and is stored by the groundwater reservoir.
    b. continues as runoff to a downstream catchment.
4. The groundwater system of the catchment discharges water to the groundwater system of a downstream catchment.
5. The downstream catchment is subject to the same procedure (steps 1-4).

For the model, the algorithm was applied to a system of three-catchment levels, called: primary, secondary and tertiary catchments (see figure 30). The boundaries of these catchments equal the water divide.The primary catchments are those adjacent to the study area and drain into the secondary catchments that are located in the model area. There is only one tertiary catchment, which is located in the plain and downstream of all primary and secondary catchments in the algorithm. The input for the algorithm is the monthly aggregated precipitation data (see appendix B). These precipitation values mainly represent single rain events (see the monthly cumulated precipitation and monthly maximum precipitation data sets in figure 53 and figure 55 respectively in appendix B), and are also applied as such in the algorithm. Figure 31 shows a section of the used data set, in which can be seen how much of the monthly rainfall becomes initial loss, run off or infiltrates.



Pr =	*precipitation*	*Gout =*	*outgoing runoff*
Loss =	*initial loss*	*S =*	*storage*
Rin =	*incoming runoff*	*dS/dt =*	*change in storage in time*
Gin =	*incoming groundwater*	*Rch =*	*recharge*
Rout =	*outgoing runoff*		

Figure 29: Scheme describing the algorithm, including multiple catchment levels.

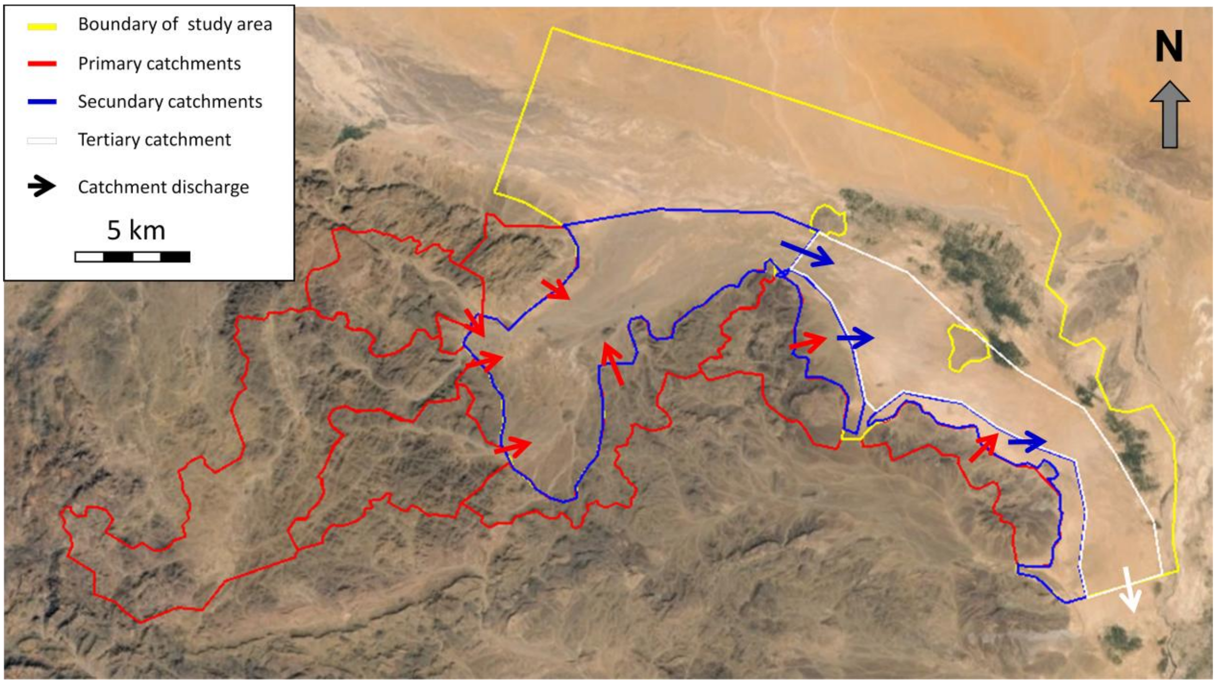


Figure 30: Primary, secondary and tertiary catchments.

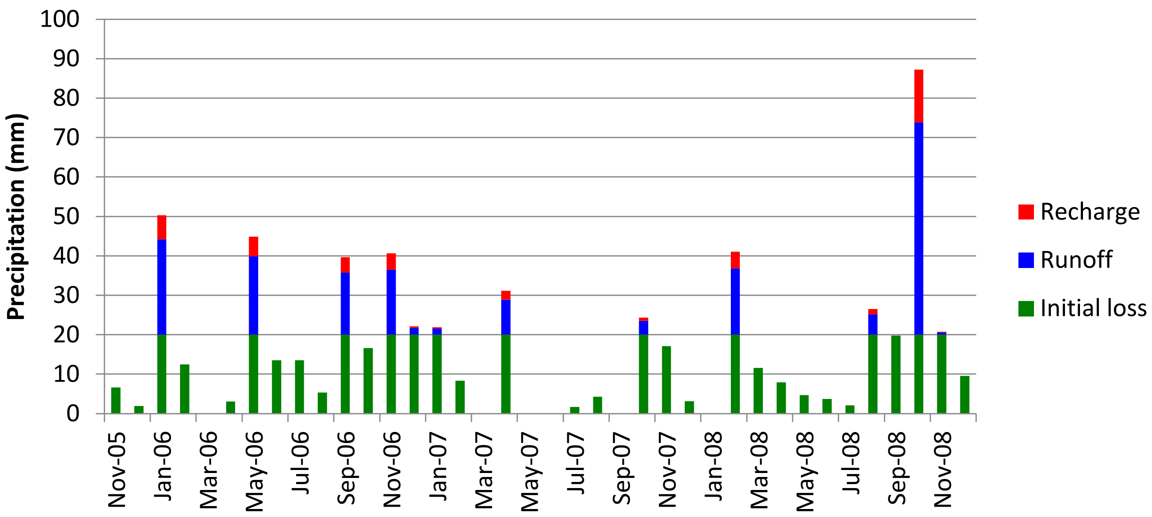


Figure 31: The modelled distribution of the precipitation for the period 11-2005 until 12-2008. The initial loss threshold is equal to 20 mm. Of the exceeding precipitation 80 % becomes runoff and 20 % infiltration.

The resulting recharge amounts per catchment level are shown in table 5. The recharges in the period 2000-2010 are slightly larger than in the period 1959-1969. This is because the rainfall in the latter period is a bit less: 100 mm against 110 mm. During the calibration, the recharge values have been adjusted to optimize the model (see chapter 5).

Table 5: Recharge for each catchment level estimated by the algorithm. These values are used in the initial model.

Catchment level	Recharge (Mm^3/y)			
	1959 - 1969		2000 - 2010	
	Entire model area	Margat Area	Entire model area	Margat Area
Primary	1.5	0.2	1.7	0.2
Secondary	1.2	0.2	1.3	0.3
Tertiary	1.2	0.9	1.4	1.1

4.3.3 Khettaras

The khettaras are modelled as "drains" in the groundwater model, which means that they only extract water when the given elevation of the drain is below the calculated groundwater table in that grid cell. So drains form head-dependent boundary conditions. In order to model the khettaras, the following information is required: the three-dimensional (x,y,z) location and their entry resistance. The modelled total khettara discharge will be compared with discharge information from literature and measurements.

The X and Y coordinates of the khettaras were determined from satellite images (Google Earth). The khettaras can be recognised by the line of hills made of excavation material of the tunnel and the shafts. In total 39 khettaras are modelled (see figure 32). The downstream parts of various khettaras of Hannabou were not included in the model because they lie outside the model area. The khettaras of Fezna were left out, because they already fell dry in the early nineteen fifties (Ruhard, 1977). Furthermore, the khettaras of Essifa were excluded because no information is available on their functionality and discharges.

The Z-locations of the khettaras were determined by linear interpolation between the elevation of the bottom of the khettara tunnel at the downstream outlet on the one side, and that of the mother well at the upstream end of the tunnel. It was observed during fieldwork that the elevation of the tunnel at the outlet is generally 0.5 m below surface level. The mother well depths of the khettaras of Hannabou were measured (see appendix F). These depths have been assigned to the khettaras that were already distilled from Google Earth with the use of global positioning information (GPS).

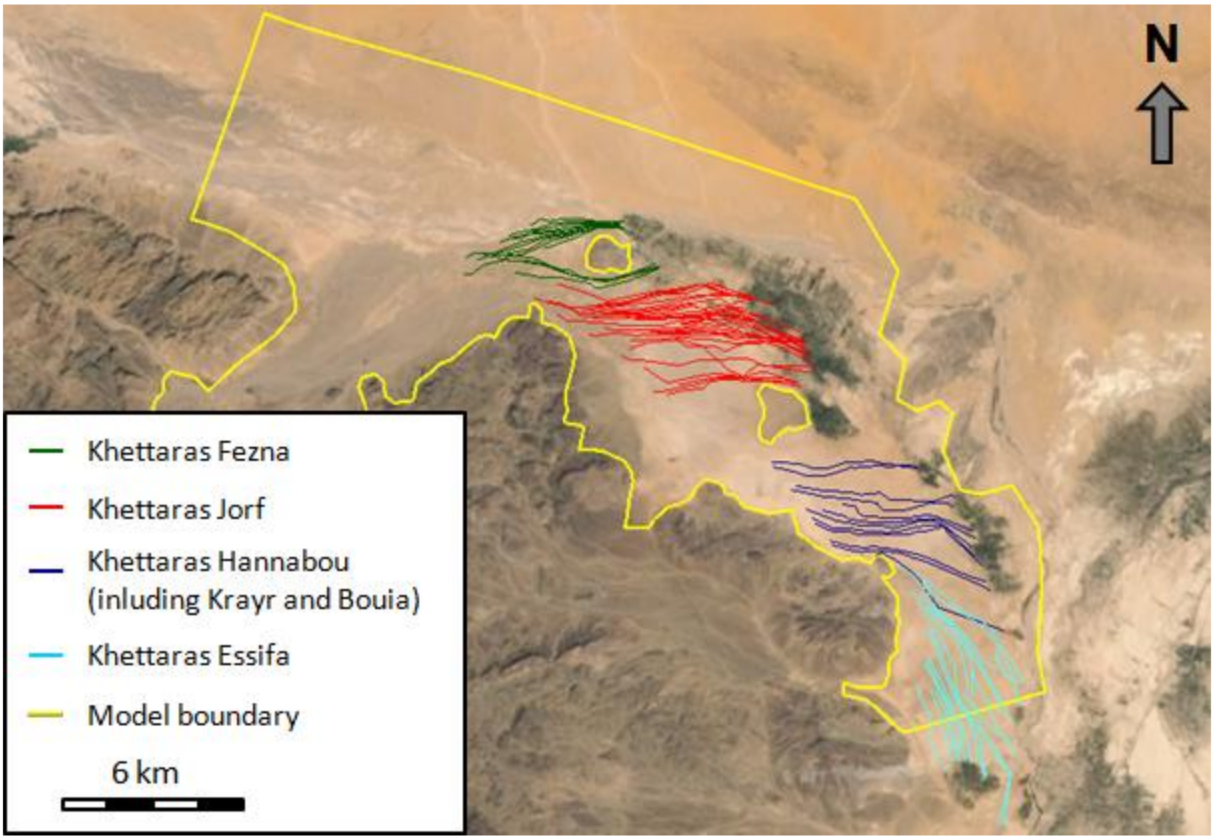


Figure 32: Locations of the modelled khettaras. Only the khettaras of Jorf and Hannabou are included in the model.

Subsequently, with *mfLab* the elevations at both sides of the khettara were extracted from the digital elevation model, followed by a linear interpolation in vertical direction. The results showed almost horizontal positioning and in some cases even negative slopes. The reason may be that the elevation information at the outlet side is influenced by the canopy elevation of palm trees present in the agricultural areas. From Google Earth it was observed that in flat regions the elevation of areas with trees (with similar height as the palm trees in the study area) is slightly higher than in open areas. Therefore, it has been decided to deepen the elevations of the khettaras at the outlet to 1.5 m below surface level. Processing again in *mfLab* resulted in slopes varying between 1/1500 and 1/7000. These slopes can be compared with the slope calculated with the Manning formula, which describes a steady-state uniform flow in a channel:

$$Q = A \cdot V = A/n \cdot R^{2/3} \cdot S^{1/2} \quad (2)$$

Q = discharge (m^3/s)
A = cross sectional area of the flow (m^2)
V = average velocity in the channel (m/s)
n = Manning's friction coefficient (-)
R = wet radius (m)
S = slope of the channel (-)

The canals of the khettaras were assumed to have the same cross-sectional shape and slopes both underground as when coming to the surface at the outlet. The measured height and the width of khettara canal at the outlet were on average 20 cm and 40 cm respectively (see figure 33), resulting in a wet radius of 0.1 m. The average flow was 20 l/s, which corresponds to a velocity of 0.25 m/s (see measured khettara discharges in appendix F). Most canals are made out of concrete that has a Manning's coefficient of n = 0.013 (Engineering Toolbox, 2014). The bottom is often covered with clean sediments (n = 0.022).

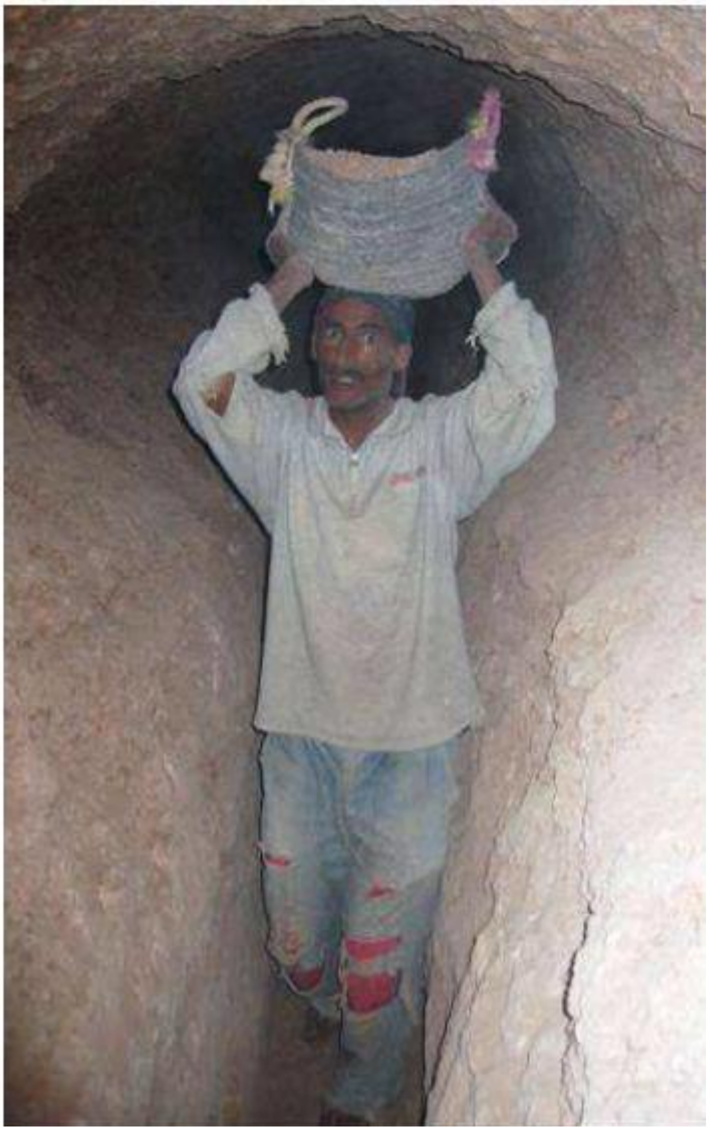


Figure 33: Maintenance work in the gallery of a typical khettara (Spoerry, 2007). The canal has on average a width of 30 to 40 cm.

Interviews revealed that some khettaras canals are not lined with concrete, but are still smoothened with fine clean soil (n = 0.018). When using an average friction coefficient (n = 0.018), the slope necessary to discharge 20 l/s becomes about 1/2500. This is of the same order of magnitude as those of the measured khettaras of Hannabou.

The mother wells of the khettaras of Jorf have not been measured. They have been given a slope of 1/5000 starting from the outlet at an elevation -1.5 m with respect to the surface level.

After all khettaras have put in the model, it was ascertained that most of the khettaras are, at the upstream end, in the conglomerate layer (see figure 34). This was also observed during fieldwork; conglomerate fragments and large pebble stones are often seen on top of the most upstream mother well hills. From geohydrological perspective this is expected; the conglomerate formation is the most favourable for groundwater flow in the aquifer.

The X, Y and Z-location of all khettaras of Jorf and Hannabou are implemented in the initial model.

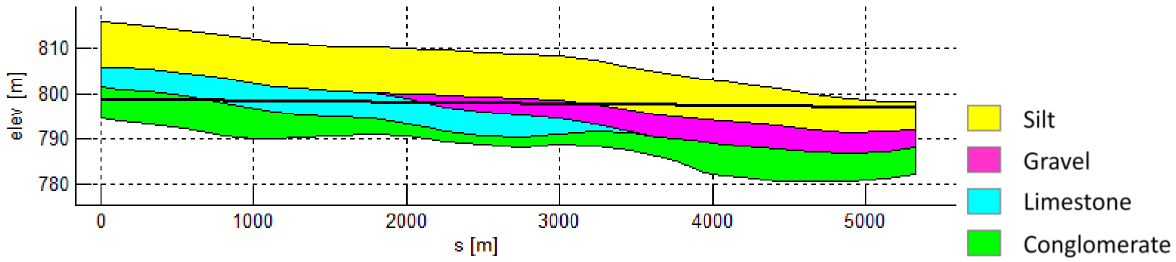


Figure 34: Cross-section of khettara Bouia Lakadima in the model (khettara of Hannabou). The black line represents the khettara, from upstream (left) to downstream (right).

The khettaras have to be specified with a certain conductance. It describes the head loss which is caused by convergence flow in the direction of the drain, the characteristics of the drain and its immediate environment (Rumbaugh, no date). The influence of the characteristics of the drain is assumed negligible, because fill material around the drain is not used. Therefore, the most relevant factor is the conductivity of the surrounding aquifer material. The conductance is presented by the following formula:

$$C = \frac{Q}{\Delta H} = \frac{2\pi k}{\ln\left(\frac{R}{r}\right)} \quad (3)$$

C = conductance (m/d)
Q = specific discharge (m^2/d)
ΔH = head minus level of the drain (m)
k = hydraulic conductivity of the surrounding aquifer material (m/d)
R = radius of influence (m)
r = radius of the khettara (m)

The khettara generally drains from the conglomerate layer, which has an average hydraulic conductivity of 22 m/d (see table 2). The radius of the khettara tunnel is equal to about half of the canal width, which is 0.2 m. Concerning the influential distance, the horizontal and vertical hydraulic conductivity of the conglomerate are assumed to be equal. As a consequence, the radius of influence can be considered to be equal to the depth of the conglomerate formation below the most upstream part of the khettara tunnel. From observing the khettaras in the model it followed that this depth is on average about 3 meters. With the above values the conductance eventually becomes circa 50 m/d.

During modelling it was observed that this value led to instability of the model. Total stability was reached with a conductance of 30 m/d. The model outcomes (khettara discharges and groundwater levels) with conductances 30 and 50 m/d were compared and they showed no significant differences. As a result, 30 m/d is applied for all khettaras in the initial model.

In chapter 5 the modelled khettara extraction rates are calibrated to the discharges obtained from literature and measurements from this research and from literature.

4.3.4 Pumping

The agricultural fields in the study area are located around the villages of Fezna, Jorf and Hannabou (including Bouia and Krayr). Only in the agricultural areas of Fezna and the northern part of Jorf pumping takes place. In Fezna the khettaras dried up in the early fifties (Ruhard, 1977). Since then this area relies more on pumping. In times of flooding, water is extracted from the oued Rheris and transported to the fields through an irrigation network. From interviewing farmers it is known that in these periods less water from pumping is required. Also the northern part of the agricultural area of Jorf only uses water supplied by pumps and floods (see also the map presented in figure 163 in appendix K). Pumping in both the areas of Fezna and Jorf was confirmed by observations during the fieldwork (see figure 135 in appendix E). The southern part of the irrigation area of Jorf is fed solely by water from khettaras.

In the irrigation area around Hannabou (including Bouia and Krayr) on the other hand, no extraction by pumping occurs. People interviewed in this area explained that the groundwater in this area is too salty for irrigation. This is confirmed by salinity data. The dry mineral residue rate of this water exceeds 10 g/l and sometimes up to 35 g/l (Ruhard, 1977). In Fezna and Jorf the dry residue rate is much lower, between 2-8 g/l. Electrical conductivity measured in 2012 shows a similar pattern: the conductivity of the groundwater in Fezna was 6330 µs/cm against 13 980, 12 100 and 8800 µs/cm in the region of Hannabou. Not many crops are entirely tolerant to such conditions. Especially vegetables are sensitive (Bischoff, 1999). Farmers in Hannabou use only khettara water for irrigation. They gain their water from other locations, far upstream of the irrigation fields, where groundwater is less saline.

The locations of the pumps were not available. As a result, the extraction by pumping has to be modelled by introducing a pumping area with a surface of 1600 ha (see figure 35). In this area, the extraction is modelled uniformly with a constant discharge per grid cell

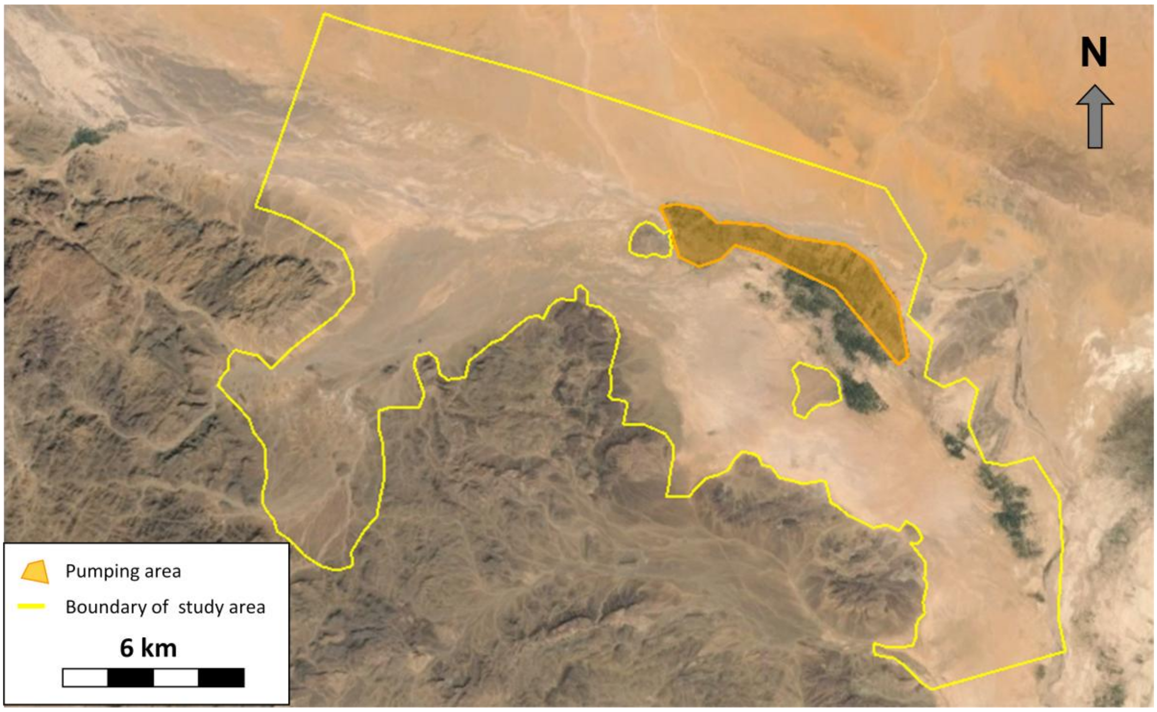


Figure 35: Location of the pumping area in the model.

In the sixties, pumping from the basin of Fezna-Jorf-Hannabou was still hardly developed compared to nowadays. Research during 1962-1965 showed that the yearly extraction by pumping was equal to 2 Mm^3/y (Ruhard, 1977; see table 3). This flux is assumed uniform in time for the initial model of period 1959-1969.

In the 1990s the pumping in the study area was estimated to be 8 million m^3 per year (Ourahou, 1998; see table 4). This is a significant increase over thirty year. More current information on pumping quantities is unavailable. However, a check was done using information on the number of wells and pumping characteristics. The number of wells in the study area is estimated to be 224 (ORMVA, 2006). Information on pumping regimes is derived by interviewing two local farmers (see table 6). Assuming that each of the 224 pumps extracts 48 000 m^3 per year, the total extraction becomes 11 Mm^3/y. This is of the same order of magnitude as the 8 Mm^3/y is estimated in the nineteen nineties (Ourahou, 1998; see table 4). Consequently, a pumping extraction of 8 Mm^3/y was applied uniformly in time for the initial model of the period 2000-2010.

Table 6: Pumping characteristics of two independent farmers in the agricultural area of Fezna and Jorf. The interviews were held in March 2013.

Parameter	Units	Farmer 1	Farmer 2
Pump capacity	m^3/h	25	20
Summer			
Pumping period		June-Aug	Mar-Oct
Pumping duration	days	91	243
Daily pumping period	hours	11	8
Winter			
Pumping period		Sep-May	Nov-Feb
Pumping duration	days	274	122
Daily pumping period	hours	8	8
Pumping/non pumping period	days	11/17	4/3
Total annual volume	m^3	46,000	50,000

4.3.5 Irrigation infiltration

The study area comprises two main agricultural areas: one between the villages of Fezna and Jorf, and one around Hannabou (see figure 36). The irrigation water in these areas is supplied by three sources: wells (pumping), khetteras and floods in the oued Rheris. A part of the irrigated water in these areas infiltrates and recharges the aquifer. This process is also known as irrigation return flow. Definition wise, however, the latter only depend on water from pumping. In this research, however, the term 'irrigation return flow' is used for the infiltration of water from all sources. The exact allocation of the irrigation water from the different sources is unknown. Therefore, for each irrigation area the irrigation infiltration is modeled as uniform plane flux; equal to the total extraction divided by the surface of the area.

The infiltration from irrigation in the areas of Fezna and Jorf in the nineteen fifties and sixties was equal to 5 Mm^3/y (Ruhard, 1977; see table 3). The agricultural area of Hannabou is not included because it lies outside of the area studied by Margat. Therefore, the irrigation infiltration in Hannabou is calculated separately.

Table 7 shows the irrigation water volumes supplied from the different sources: pumping, khettaras and flood distribution. The khettaras of Hannabou extract roughly one third of the total khettara discharge of 12 Mm^3/y (see khettara discharges in appendix F). The total irrigation water volume for the agricultural area of Fezna and Jorf becomes 22 Mm^3/y and for Hannabou 8 Mm^3/y. For calculating the irrigation infiltration in the agricultural area of Hannabou the same proportion was used resulting in 1.8 Mm^3/y. The irrigation infiltration in the entire model area becomes 6.8 Mm^3/y, which equals 22 % of the total irrigation volume.

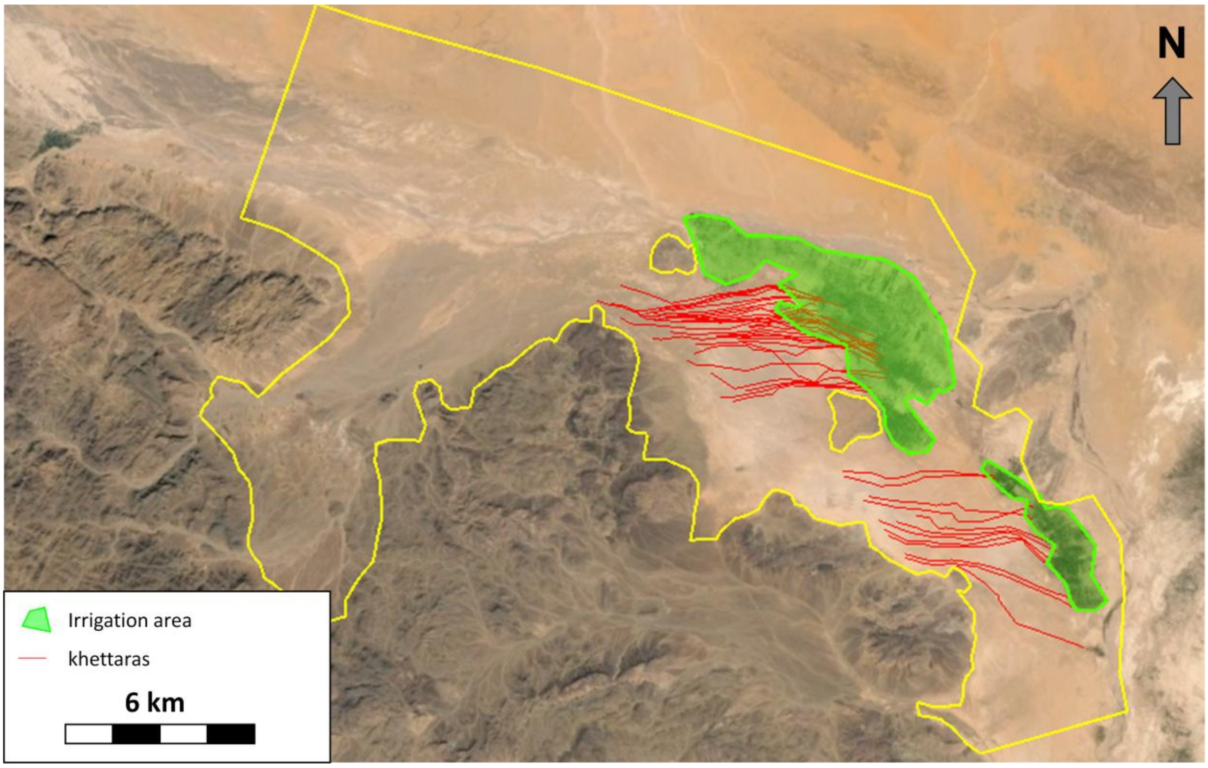


Figure 36: The areas where infiltration occurs as a result of irrigation.

Table 7: Estimated irrigation water amounts and irrigation infiltration for each agricultural area for the period 1959-1969.

flux	Fezna-Jorf (Margat area)	Hannabou	Entire model area
Irrigation water	Mm^3/y	Mm^3/y	Mm^3/y
Pumping*	2	0	2
Khettaras**	8	4	12
Floods***	12	4	16
Total	*22*	*8*	*30*
Irrigation infiltration	5	1.8	6.8

*see section 4.3.4. **see section 5.1.1. *** (Ruhard, 1977)

Ourahou (1998) estimated the irrigation infiltration in Margat's study area at 11 Mm^3/y. This is twice the estimation in the nineteen fifties and sixties (Ruhard, 1977; see table 3). This difference will be checked by considering the irrigation volumes.

Table 8 shows the irrigation volumes estimated for the period 2000-2010. Only the amount of flood water used for irrigation is not available. For convenience, the same amount is used as for the period 1959-1969. The estimated total irrigation volume in 2000-2010 was equal to 32 Mm^3/y.

Table 8: Estimated irrigation water amounts and irrigation infiltration for each agricultural area for the period 2000-2010.

	Fezna-Jorf (Margat area)	Hannabou	Entire model area
Irrigation water	Mm^3/y	Mm^3/y	Mm^3/y
Pumping*	8	0	8
Khettaras**	5.3	2.7	8
Floods	12	4	16
Total	25.3	6.7	32
Irrigation infiltration	5.8	1.3	7.1

*see section 4.3.4. **see section 5.1.1.

This is checked by comparison of the water required for the total production of agricultural products in the area of Fezna, Jorf and Hannabou. The water use per unit of ton production of crop is expressed in terms of water footprint (see table 9). The water footprint of a product is the total volume of freshwater used to produce it, summed over the various steps of the production chain. The water footprints used are based on worldwide average conditions. The resulting total required water is around 50 Mm^3/y, which is of the same order of magnitude as the estimated total supplied irrigation volume.

Table 9: The estimated water usage based on the production and water footprint of crops cultivated in Fezna, Jorf and Hannabou. The production is averaged over the period 1996-2005.

Parameter	Unit	Cereals	Lucerne	Horticulture	Vegetables	Dates	Olives
Total production*	ton	3318	30358	321	39	683	252
Water footprint**	m^3/ton	1644	1500	1000	322	2277	3015
Water usage	Mm^3	5.46	45.54	0.32	0.01	1.56	0.76

*(ORMVA, 2006) **(Hoekstra, 2010)

The research of Margat is performed during a long period of about eight years. Therefore, the estimated irrigation infiltration of 5 Mm^3/y is considered to be more reliable than that of Ourahou (1998), of which the duration is unknown. Consequently, for the initial model of period 2000-2010, also an infiltration percentage of 22 % was applied. This results in a total irrigation infiltration of 7.1 Mm^3/y. However, the found variations in literature allow to improve the estimation during the calibration of the model (see chapter 5).

4.3.6 River infiltration

The oued Rheris is the main wadi in the study area. Most of the infiltration from surface water occurs in the bed of the Rheris. Water in the Rheris originates dominantly from the High Atlas and Anti-Atlas, the Hamada system north of the study area and from precipitation in the study itself.

The groundwater tables in the study are generally 10 to 20 m below ground level. Therefore, groundwater discharge into the Rheris is rare. Consequently, solely river infiltration was applied to the model, in the form of a flux. The course of the Rheris was digitized in Google Earth (see figure 37). Upstream of Fezna, the Rheris is wider and follows multiple channels in a braided wadi system. For practical reasons only one route in this area was chosen in the form of the largest wadi. The assigned width is 100 m, which is the average width of the Rheris in the study area. Furthermore, the river infiltration was applied uniformly along the river route, because no specific preferential infiltration zones could be determined from literature or during fieldwork.

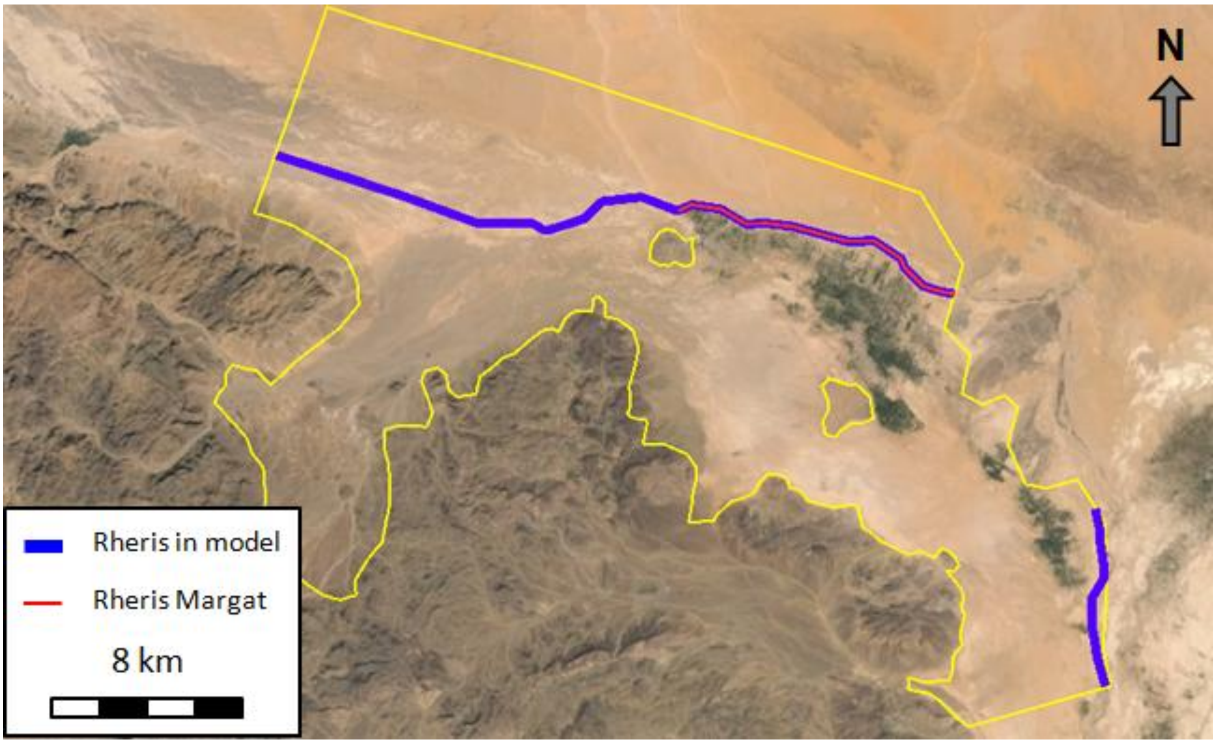


Figure 37: Location of the Rheris, where river infiltration takes place in the model, and the part of the Rheris which is focussed on by Margat.

The discharge of oued Rheris is on average 30 Mm^3 per year (ABHGZR, 1997; ORMVA JICA, 2005). Floods occur on average 4 to 5 times a year (Spoerry, 2007). Margat estimated the river infiltration in his study area in the nineteen sixties to be 5 Mm^3/y (Ruhard, 1977; see table 3). The river recharge in the remaining part of the model area was obtained by using the same flow per unit length. The total river infiltration in the model area thus becomes about 14 Mm^3/y, which was applied to the initial model of period 1959-1969.

The average precipitation in the periods 1959-1969 and 2000-2010 are about equal: 101 mm and 111 mm per year respectively (see aggregated precipitation in appendix B). Consequently, the same amount of river infiltration (14 Mm^3/y) was applied to the initial model of the period 2000-2010.

In the model the total yearly infiltration of 14 Mm^3/y was distributed over the months with more than 20 mm rainfall as a method to the fact that the Rheris only carries water during floods.

5 Calibration

5.1 Calibration data

The model was calibrated by comparing model outcomes with measured and estimated data. This applies for the discharges of the khettaras, the incoming and outgoing groundwater flows and the groundwater levels.

5.1.1 Khettara discharges

Because khettara data are incomplete and because the depth and course of the khettaras are only approximately known, partly due to uncertain ground-level elevations, it was decided to only evaluate the total discharge of the khettaras in the area.

In the nineteen fifties and sixties, the average total discharge was estimated to be 12 Mm3 per year (Ruhard, 1977; see table 3), which was also applied for the calibration of the period 1959-1969. Ourahou (1998; see table 4) estimated the total extraction by the khettaras at 3.7 Mm3/y. In the period 2005-2007, measurements showed that the khettara discharges increased substantially to approximately 8 Mm^3/y (ORMVA, 2006; ORMVA JICA, 2005; Spoerry, 2007; see table 10). Own measurements in 2013 showed a total estimated discharge of around 14 Mm^3/y. However, the total discharge of the khettaras of the different sources can not be compared, because not the same khettaras are measured. Nevertheless, the khettaras of Hannabou, of which most are measured except of Guedima, show an increase of 30 % in total discharge between 2005-2006 and 2013.

The significant rise in the khettara discharges can be first explained by the period of measuring. The measurements done in the end of the nineteen nineties and the period 2005-2007 could be performed in dry years, for example in 1998/1999, 2000/2001 and 2002/2003 (see figure 10). In general, this period is relatively low in precipitation. Another argument is the canalisation of numerous khettaras with concrete, which took place between 2003 and 2005 (ORMVA JICA, 2005). This work was part of a rehabilitation performed by the Japan International Cooperation Agency (JICA), a governmental organisation that coordinates official development cooperation. The lining prevents leakage from khettara tunnels, which was estimated by Ruhard (1977) on 50 %, leading to higher khettara discharges. Users of the khettaras declared, during interviews, that the khettara flows increased after they were lined.

The average estimated khettaras discharge for the period 2000-2010 is about 8 Mm^3/y. However, due to the large variation during the period, this value is not being strictly conformed to during the calibration.

Table 10: Discharges of the khettaras of Hannabou and Jorf from literature (ORMVA[1], 2006; ORMVA JICA[2], 2005; Spoerry[3], 2007) and obtained by own measurements during fieldwork in 2013 (Q_m). Information on the location of the measured khettaras and the date of the measurements can be found in appendix F.

Place	Name	Q_l^1 (l/s)	Q_l^2 (l/s)	Q_l^3 (l/s)	Q_m (l/s)
Hannabou	Lakadima Kryar	11.7	10.9	-	30.0
	Gadida Kryar	11.7	14.0	-	13.3
	Mustaphia	7.2	5.3	-	14.6
	Khtettera	18.4	21.0	-	30.8
	Aloria	7.5	8.2	-	10.5
	Grenia	4.6	6.4	-	5.1
	Guedima	13.8	-	-	-
	Auctania	17.2	6.4	-	10.3
	Fougania	30.0	50.2	-	42.7
	Sayed	16.0	11.7	-	16.6
	Gadida Bouia	19.4	16.5	-	21.9
	Lakdima Bouia	19.4	28.2	-	22.2
Jorf	Aisawia	4.0	-	-	16.2
	Assaouia Monkara	5.9	2.3	20.0	31.0
	Alboishabia	0	6.4	-	10.6
	Abrika	0	-	23.6	8.6
	Lahoua Monkara	11.5	21.5	35.5	54.2
	Lakbira	0	9.1	-	4.4
	Mbarkia Monkara	15.1	-	15.0	18.8
	Rozia Monkara	0	-	6.5	5.5
	Saidia	0	3.9	12.3	10.5
	Saihla	4.0	13.6	19.0	28.6
	Soihlat'de Alhaiyen/Lambarkia	-	19.7	19.7	21.0
	Zanoihia	0	-	10.0	13.9
	El Aissaouia	0	6.4	15.3	-
	Boshabia	0	-	30.0	-
	Zarguia	0	-	10.0	-
	Souihla O.Gh.	0	-	49.5	-
	Jdida	0	-	10.0	
Total (l/s)		**217.4**	**261.7**	**276.4**	**441.3**
(Mm^3/y)		**6.9**	**8.3**	**8.7**	**13.9**

5.1.2 Incoming and outgoing groundwater flows

To compare the model outcomes with the estimations of Margat, the flow across the upstream and downstream boundaries of the area studied by Margat are considered.

The incoming groundwater flow occurs along the outcrop of Gara Gfifate (see figure 20). This water originates from the Anti-Atlas, the High Atlas or from infiltration in the area just upstream of Fezna. For the period of 1959-1969 the incoming groundwater flow was estimated to be 16 Mm^3/y (Ruhard, 1977; see table 3). For the period of 2000-2010 it is estimated to be 12 Mm^3/y (Ourahou, 1988; see table 4).

Groundwater leaves the Margat area near the village of Krayr and the Anti-Atlas (see figure 14 and figure 19). For both periods 1959-1969 and 2000-2010 this flow is estimated to be 11 Mm^3/y (see table 3 and table 4).

The above presented estimated incoming and outgoing groundwater flows were used to calibrate the model. The methods by which these flows were determined are not known in detail. The flows have probably been estimated using the Darcy method for which information on the groundwater slope, geological formations and hydraulic conductivities are required. Most of this information is quite uncertain. Therefore, during the calibration, the model outcomes are allowed to deviate from the estimated fluxes.

5.1.3 Groundwater levels

Direct and indirect information on the groundwater levels was used to constrain the model during the calibration. This information consists of piezometric data, khettara depths, surface levels and available geological cross sections.

Piezometers
Several piezometers are present in and near the study area for which monthly groundwater data are available (see appendix C). Most piezometer data are recent (2011-2013), which implies a bias of the calibration of the simulation period 2000-2010. Furthermore, all piezometers are inside the agricultural areas, and are, therefore, potentially influenced by pumping from the many wells that exist in the same areas. Because neither the location of the wells nor their actual use are known, calibration does not force equality of the model and the available piezometric data.

Ground-surface deviation
Groundwater levels are usually 10-20 m below ground surface. Therefore, it was ascertained that the average groundwater tables do not exceed the surface level.

Cross sections
Ruhard (1977) provides various geological cross sections in which, besides of geological formations, also water levels are presented (figure 139 and figure 140 in appendix H).

The cross sections are made in the nineteen fifties and sixties. Hence, the groundwater information from the cross sections is used for the calibration of the period 1959-1969. The groundwater tables are observed only one shortly after drillings, thus this information is not very decisive during the calibration.

Khettaras of Fezna
The khettaras of Fezna (see figure 32) provided also useful information on groundwater levels; they have fallen dry during the 1950s as a consequence of pumping that commenced in that period (Ruhard, 1977). This means that the groundwater levels must be below the level of the khettaras. Consequently, the khettara elevations indicate the maximum level of the groundwater table. The khettara elevations of Fezna were determined in the same way as the khettaras of Jorf (see section 4.3.3). This information was used for the calibration of both the period 1959-1969 and that of 2000-2010.

The observed groundwater levels, used to calibrate the models for both periods, can be seen in respectively figure 38 and figure 39.

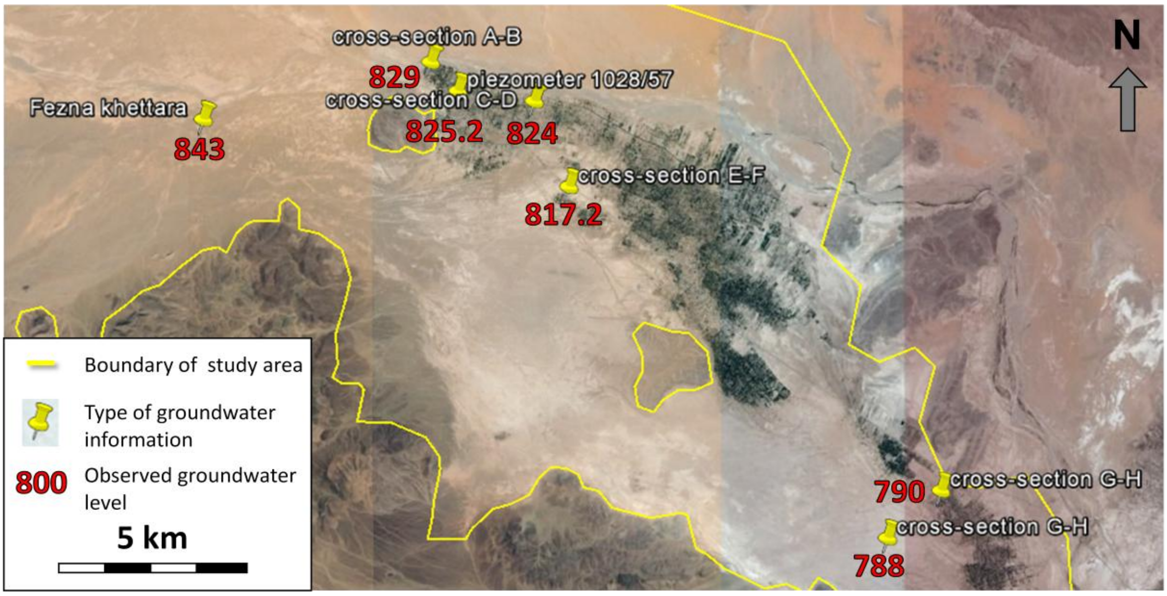


Figure 38: Observed groundwater levels used for the calibration of period 1959-1969. In addition, the type of groundwater information is presented. The geological cross sections can be found in appendix H. Appendix C shows the water levels observed at the piezometers.

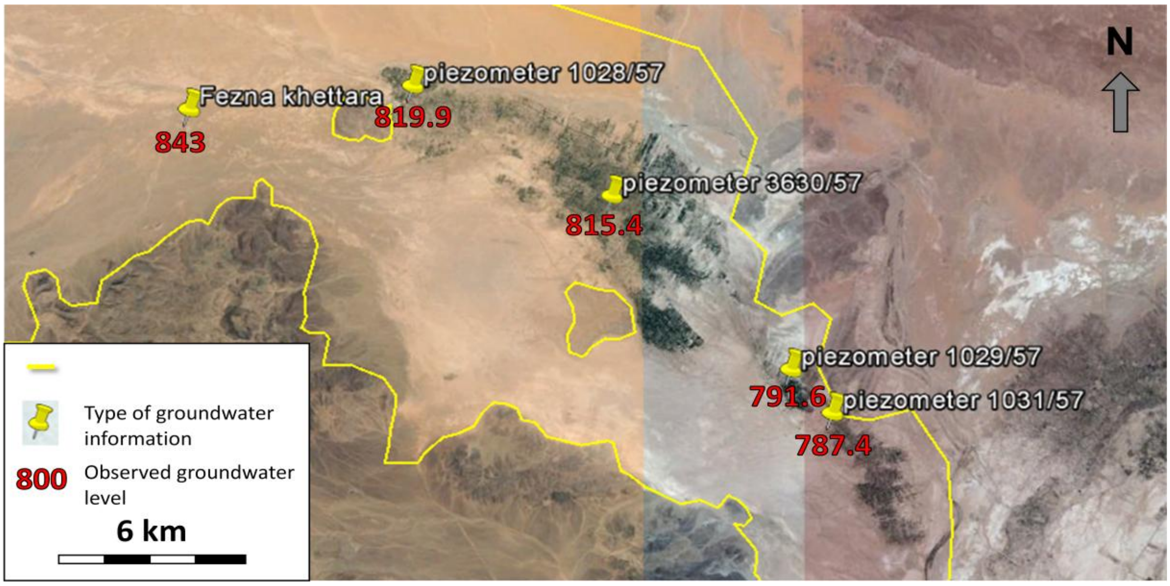


Figure 39: Observed groundwater levels used for the calibration of period 2000-2010. Appendix C shows the observed water levels at the piezometers.

5.2 Calibration process

This section discusses the steps undertaken during the calibration of the model. Various obstacles were encountered which led to new insights into the behaviour of the groundwater system of Fezna-Jorf-Hannabou. The model was first calibrated for the period 1959-1969 (section 5.2.1 – 5.2.3), followed by a combined calibration, including the period 2000-2010 (from section 5.2.4).

5.2.1 Initial model

The calibration started for the period 1959-1969. The more the natural situation is approached, the fewer variables have to be considered during the calibration. During the 1959-1969 period the groundwater system was less influenced by human activities than today, because the extractions by pumping were still small compared to the period 2000-2010.

To make a first estimation of the general flow capacity of the model, the calibration process started with only the fixed head boundaries (see section 4.3.1). Mean hydraulic conductivity values of the range presented by Margat were used (see set 1 in table 11).

The model calculates a groundwater flow through the model that equals about 1.5 Mm^3/y. This flow is very low compared to the estimated flows by Margat (Ruhard, 1977; see table 3).

Table 11: The hydraulic conductivities sets presented by Margat (Ruhard, 1977) and other sets used during the calibration process.

Soil type	Hydraulic conductivity				
	Margat*	Set 1	Set 2	Set 3	Set 4
	m/d	m/d	m/d	m/d	m/d
Silt	0.1 - 1	0.5	1	3	1
Sand & gravel	90 - 260	175	260	780	260
Limestone	1 - 43	21	43	129	43
Conglomerate	1 - 43	21	43	129	86
Bedrock (schist & sandstone)	Impermeable				

*Ruhard (1977)

The second step was to include all hydraulic boundaries described in chapter 4. The hydraulic conductivities are set to the upper boundaries presented by Margat, to enlarge the groundwater flows (see set 2 in table 11).

Figure 40 shows the modelled average groundwater levels and the differences with the observations. The modelled groundwater levels are too high, especially near and upstream of the outcrop of Gara Gfifate (see figure 40 and figure 41). The groundwater level here is even up to 5 m above the surface level. Also in the northeast of the model area the computed groundwater levels exceed ground surface. Ruhard (1977) describes a bedrock peak near Bouia which functions as a threshold, which is visible at a distance of 2600 m in figure 42. This causes the groundwater to come close to ground surface which causes formation of salt crusts as a result of enhanced evaporation. Another source, Linarès (1932), speaks about groundwater drainage of salt water in the oued Rheris just downstream of H'mida, which is just east of the Paleozoic outcrops and near the site where the modelled water levels are above ground surface (see figure 12 and figure 19).

Evaporation is not modelled separately due to instability of the model as a consequence of too many simultaneous non-linear processes. However, evaporation is indirectly included in the recharge in the plain and the river infiltration in the oued Rheris, which follows from the Anti-Atlas catchment algorithm (see section 4.3.2 and 4.3.6).

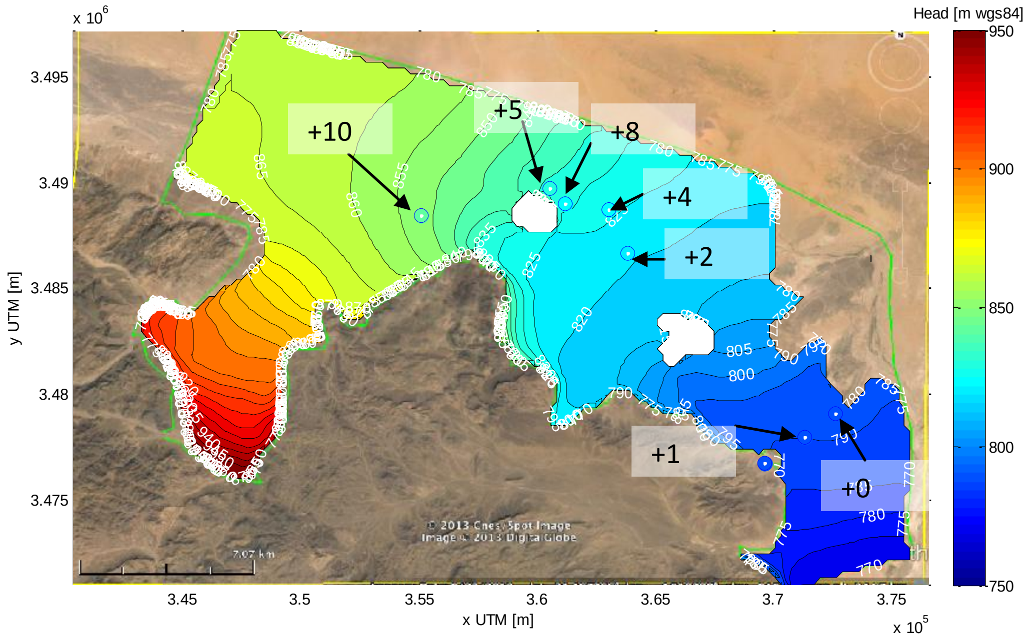


Figure 40: The simulated groundwater levels with the initial model for period 1959-1969. The modelled groundwater levels are compared to the observed levels. Positive values indicate that the modelled groundwater levels are higher than observed.

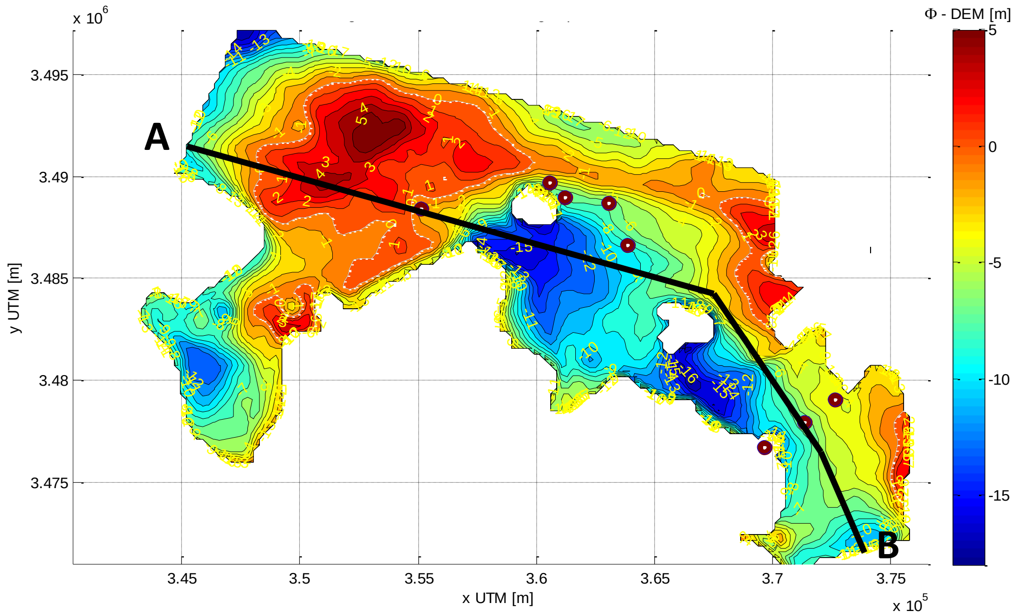


Figure 41: Average groundwater levels with respect to the surface level, simulated with the initial model of period 1959-1969.

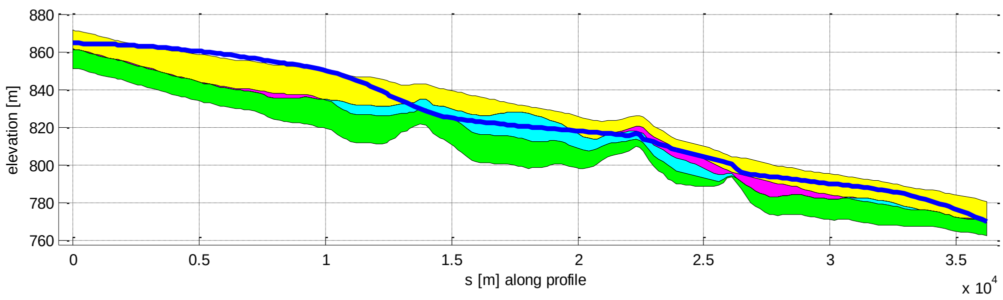


Figure 42: Longitudinal cross section of the groundwater system including the groundwater table (blue line) simulated with the initial model of period 1959-1969. The location of the cross section can be found in figure 41, see line AB.

Table 12 shows the groundwater balance for the area studied by Margat (Ruhard, 1977). The modelled khettara extraction reasonably matches with the estimated values. However, the incoming and outgoing groundwater flows, respectively 8.0 and 3.2 Mm^3/y, are too low. So, even with hydraulic conductivities at the upper limit of Margat's values, the general flow capacity of the model is too low to make the estimated flows of Margat (Ruhard, 1977) physical possible.

In conclusion, the initial model did not generate satisfactory results. Its outcomes deviated too much from the estimated and observed values. It was, therefore, necessary to explore alternative ways to make the model work properly with respect to what is known about the groundwater system

Table 12: Groundwater balances of the initial model of period 1959-1969 compared to other estimations. The small difference between the modelled total inflow and outflow is caused by the large spin up time of the model.

Flows	**Margat***	**Initial estimation**	**Modelled**
IN	Mm^3/y	Mm^3/y	Mm^3/y
Groundwater inflow along outcrop Gara Gfifate	16	16	**7.3**
Infiltration in the plain	2	0.9	**0.9**
Lateral groundwater inflow from Anti-Atlas		0.2	**0.2**
River inflow Fezna-Jorf	5	5	**5.0**
Irrigation infiltration Fezna-Jorf	5	5	**4.7**
Total	*28*	-	***18.1***
OUT			
Groundwater outflow near Krayr	11	11	**1.6**
Pumping	2	2	**2.0**
Khettaras	12	12	**13.8**
Total	*28*	-	***17.5***

*Ruhard (1977)

5.2.2 Alternative calibration pathways

To improve the initial model, various potential solutions were assessed. They can be divided in two categories: geology and hydrology. Concerning geology, options will be presented that increase the transmissivity. The hydrological solutions are related to adjustments of the hydraulic boundaries.

5.2.2.1 Geology

Hypothesis 1: Extra gravel channel

The critical region restricting groundwater flow is the passage along the outcrop of Gara Gfifate. The groundwater is passes this outcrop north and south. The geological structure of the subsurface on the northern side is known from geological cross sections (see figure 139 in appendix H). On the southern side, however, the geological structure is uncertain, which enables a wider interpretation of the geology.

One possibility is that the gravel formation is also present in the southern passage, although the few drillings do not support this. An NE-SW ancient gravel channel is present north of the outcrop Gara Gfifate (Ruhard, 1977). The rounded shape of the Gara Gfifate outcrop may be an indication of past erosion and suggests that the former Rheris also flew along the south of the outcrop, and, thus may have deposited gravel beds as well as on the north. If this is the case, then the very high hydraulic conductivity of the gravel will provide the transmissivity required to enable sufficient groundwater flow, so that the model will agree better with the observations, especially in the area where the groundwater levels are extremely high in the initial model.

The model was used to assess this hypothesis; the channel was given overestimated dimensions with an average width of 1 km and a thickness of 5 m (see figure 43). This is done to verify the hypothesis has the expected impact on the groundwater flow and head.

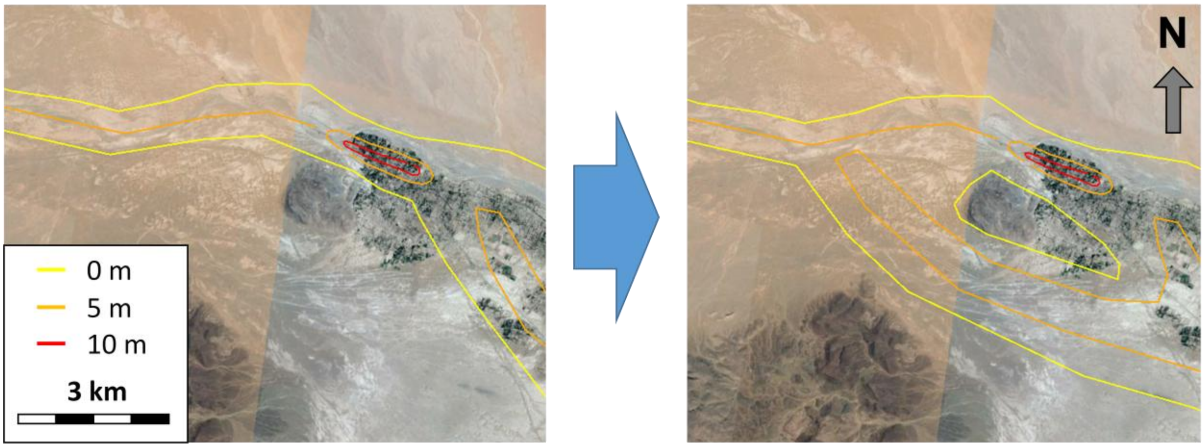


Figure 43: Contours of the gravel thickness in the initial model (left) and the adapted (right) situation. An extra gravel channel has been added between the outcrop Gara Gfifate and the Anti-Atlas.

The simulation results did not show a significant effect. In the critical area upstream of Fezna the groundwater levels were still substantially above surface level (see figure 44); the differences in flows (total khettara discharge, incoming and outgoing discharge) are minor as well.

It was concluded that the impact of extra gravel is negligible, even if the presence of the gravel formation is exaggerated. Based on this and the uncertain presence of gravel south of the outcrop of Gara Gfifate, it was decided to not apply this change in the model.

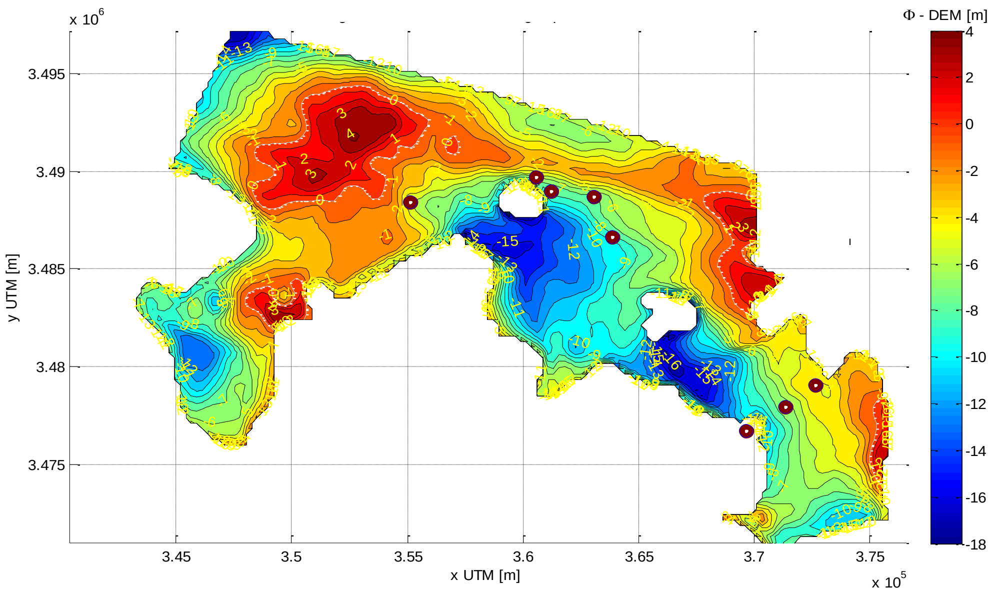


Figure 44: Average groundwater levels with respect to the surface level simulated with the initial model after the introduction of gravel formation in the passage between the outcrop of Gara Gfifate and the Anti-Atlas.

Hypothesis 2: Increased hydraulic conductivities

Another way to enlarge the transmissivity of the model is by increasing the permeability of the formations. The hydraulic conductivities of the formations were increase proportionally to the values of Margat (Ruhard, 1977) among the formations until the modelled flows matched the estimated ones. This target was reasonably reached when applying hydraulic conductivities three times the upper limit presented by Margat (see set 3 in table 11). Particularly the incoming and outgoing groundwater flows improved (see table 13). Also, the calculated groundwater levels decreased to (almost) below ground surface as they should (see figure 45).

Table 13: Groundwater balance of the initial model for the period 1959-1969 in which the hydraulic conductivities are increased to three times the upper limit of Margat.

Flows	Margat*	Initial estimation	Modelled
IN	Mm^3/y	Mm^3/y	Mm^3/y
Groundwater inflow along outcrop Gara Gfifate	16	16	**14.6**
Infiltration in the plain	2	0.9	**0.9**
Lateral groundwater inflow from Anti-Atlas		0.2	**0.2**
River inflow Fezna-Jorf	5	5	**5.0**
Irrigation infiltration Fezna-Jorf	5	5	**4.7**
Total	*28*	-	***25.4***
OUT			
Groundwater outflow near Krayr	11	11	**6.9**
Pumping	2	2	**2.0**
Khettaras	12	12	**14.9**
Total	*28*	-	***23.8***

*Ruhard (1977)

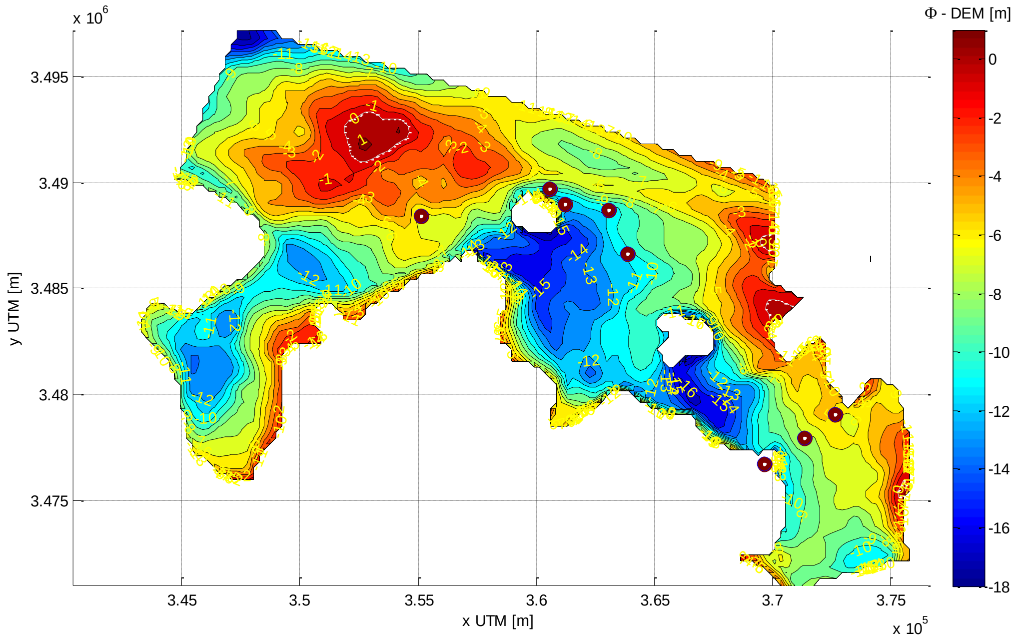


Figure 45: Average groundwater levels, with respect to surface level, modelled with the initial model of the period 1959-1969, in which the hydraulic conductivities are increase to three times the upper limit presented by Margat.

However, the hydraulic conductivities were assumed not credible. The ranges presented by Margat were derived from independent pumping tests and hence reliable. Nevertheless, Margat (Ruhard, 1977) states that the conglomerate layer locally can have a higher permeability due to less cementation. However, it is first tried to try other hypothesis in the continuation of the calibration process. Therefore, the hydraulic conductivities were set back to the upper limits of Margat (set 2 in table 11).

5.2.2.2 Hydrology

Until now the focus has been predominantly on increasing the transmissivity of the model. Alternatively, the model could be improved by adjusting its flows. The most critical one is the incoming groundwater passing the outcrop of Gara Gfifate. This flow causes the too high groundwater levels upstream of Fezna. The two most important fluxes generating the incoming groundwater are infiltration from the oued Rheris during floods and the flows from the Anti-Atlas catchments adjacent to the study area. Both fluxes recharge the aquifer upstream of the outcrop Gara Gifate.

Hypothesis 3: Reduced river infiltration

The river infiltration in the oued Rheris upstream of the outcrop Gara Gfifate equals 6 Mm^3/y in the initial model; it is responsible for a significant part of the incoming groundwater flow of 8 Mm^3/y. This also follows from the modelled monthly variation of the groundwater levels. Figure 46 shows the modelled groundwater level in the region of the khettaras of Fezna. The peaks are caused by floods in the oued Rheris, which on their turn are generated by excessive precipitation events. However, these peaks were unrealistically high, even up to 80 m above ground surface.

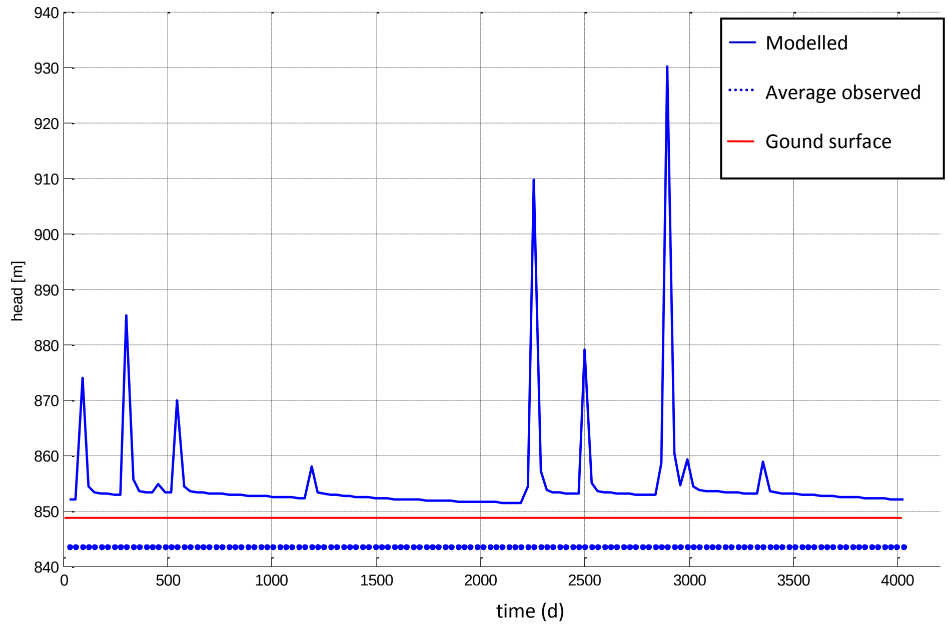


Figure 46: The groundwater level upstream of the outcrop of Gara Gfifate near the khettaras of Fezna (for location khettaras of Fezna see location figure 32), simulated with the initial model.

These extreme computed groundwater levels suggest that the river recharge estimated by Margat (Ruhard, 1977; see table 3) is too high. It is unknown how this value is obtained. River recharge is obviously one of the most complicated flows to quantify as it cannot be measured directly. Therefore, an alternatively method is applied to estimate this flux.

It was tried to model the river recharge in the oued Rheris during a single flood event. This was done using the River package in MODFLOW. The purpose of the River (RIV) package is to simulate the effects of flow between surface water features and groundwater systems. To accomplish this purpose, terms representing seepage to or from the surface features must be added to the ground-water flow equation for each cell affected by the seepage. For the River package the following information is provided:

<u>Riverbed width</u>
From satellite images from Google Earth it is determined that the width of the riverbed in the study area is on average 100 m.

<u>Riverbed resistance</u>
UWM (n.d.) states the resistance for sand is 1 day and that for silt 1-10 days. Generally, the riverbed of the oued Rheris exists of gravelly alluvium; a mixture of sand and gravel. For the River Package a resistance of 1 to 2 days is applied.

<u>Riverbed bottom</u>
The riverbed bottom is equal to the elevation obtained from the DEM.

<u>River stage during event</u>
No data is available on the river stage in the oued Rheris during flood events. During fieldwork it is observed that the river edges at both sides are not exceeding 1 m (see figure 122 and figure 121 in

appendix D). This is confirmed by the elevation obtained from the digital elevation model. Consequently, maximum river stages of 0.5 and 1.0 m are used in the model.

To simulate a flood event stress periods of one day are used. Spoerry found (2007) that the average flood duration is two days (see figure 47), which is also applied to the model.

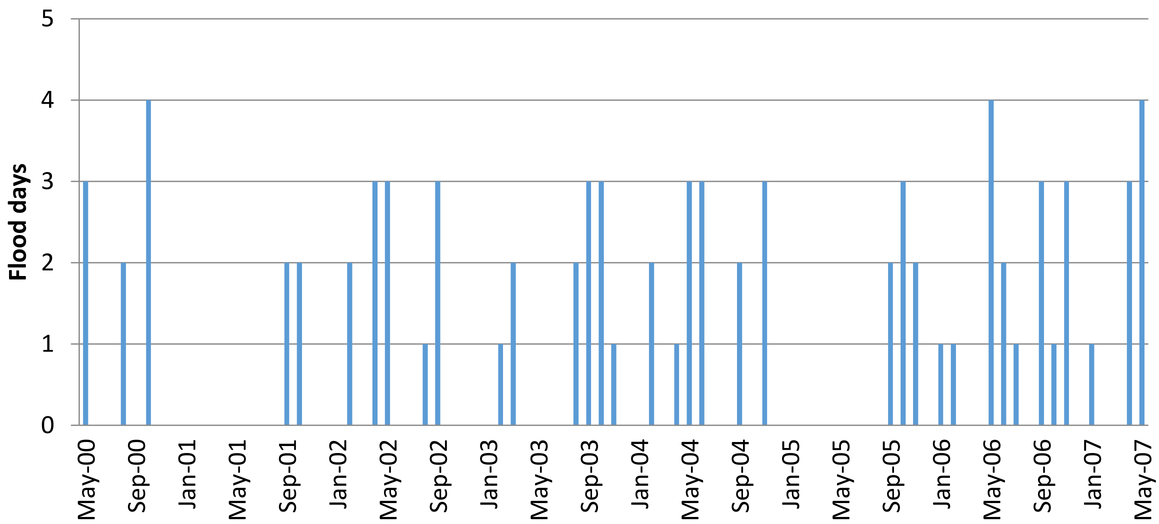


Figure 47: Flood events, and their duration in days, for the period 2000-2007 (Spoerry, 2007).

<u>Geological structure along the river</u>
A typical geological layout along the oued Rheris can be seen in figure 48. The river bed exists predominantly of sands and gravels, underlain by conglomerate. Next to the river, the top layer exists of silt. The schematisation in the model can be seen in figure 49.

<u>Groundwater table</u>
The groundwater table near the Rheris is generally present in the conglomerate layer (see figure 48). The same is applied to the model (see figure 49).

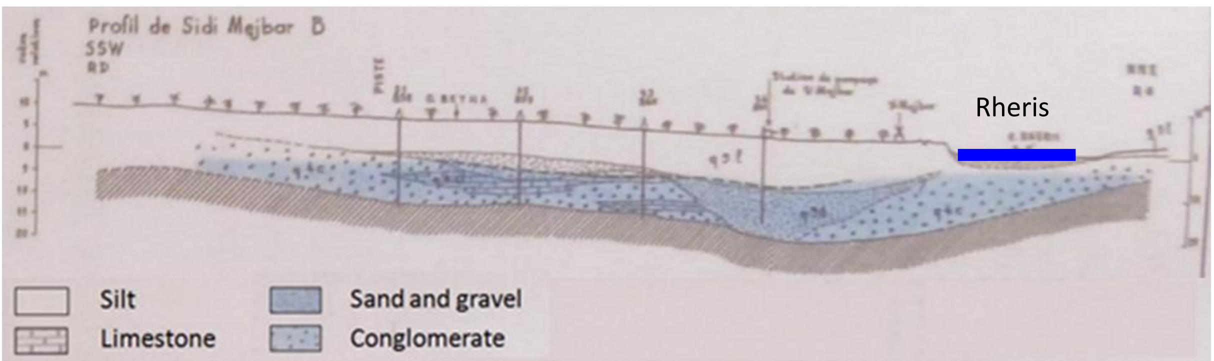


Figure 48: Cross section of a typical geological layout along the oued Rheris.

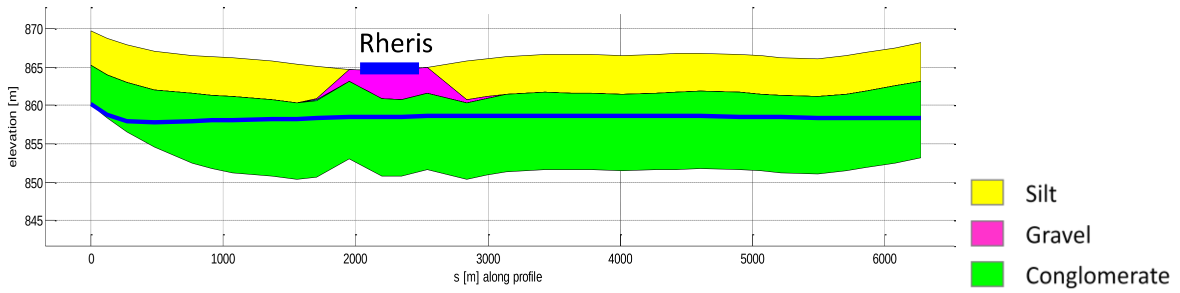


Figure 49: Geological cross section along the oued Rheris in the model.

On average, annually four flood events occurred in the period 2000-2007 (see figure 47). For the period 1959-1969 the same frequency was applied, because the precipitation in both periods is about equal. The total annual infiltration in the oued Rheris was obtained by multiplying the river recharge of one flood event by four.

Table 14 shows the results of four different flood event scenarios. A minimum river infiltration of 0.9 Mm^3/y in the area studied by Margat occurs in the scenario with a river stage of 0.5 m and a conductance of 2 days. The scenario with a river stage of 1.0 m and a conductance of 1 day produced a maximum infiltration of 5.4 Mm^3/y. This is almost similar to the estimation of Margat (5 Mm^3/y). The mean infiltration of the four scenarios is 2.7 Mm^3/y, which is similar to 180 $m^3/m/y$.

Table 14: River infiltration results of different modelled situations.

Parameter	Unit	S_1	S_2	S_3	S_4
Stage day 1	m	1.0	1.0	0.5	0.5
Stage day 2	m	1.0	1.0	0.5	0.5
Width	m	100	100	100	100
Conductance	d	1	2	1	2
V_{total}*	Mm^3/y	17.9	8.9	5.7	2.8
$V_{Margat\ area}$**	Mm^3/y	5.4	2.7	1.7	0.9
$V_{estimated\text{-}Margat\ area}$***	Mm^3/y	5			

* Modelled river infiltration in the entire model
** Modelled river infiltration in the Margat area
*** River infiltration in the Margat area estimated by Margat

The river infiltration may also be determined analytically. Unrestricted infiltration from a river of which the water level is raised by Δh_0 and kept constant for t days after which the level returns to its original value can be described by the following formula (Marsily, 1986; see figure 50):

$$h(x) = \Delta h_0 \cdot \operatorname{erfc}\left(x \cdot \sqrt{\frac{S}{4 \cdot kD \cdot t}}\right) \tag{3}$$

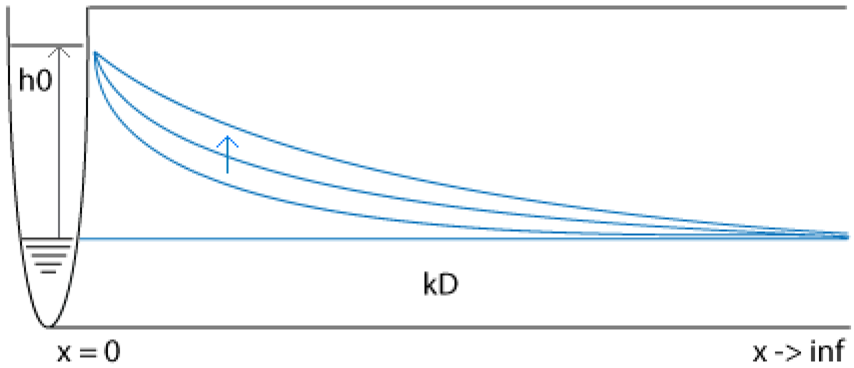


Figure 50: A schematisation of the change of the groundwater table after changing the stage of the river.

Substitution of equation 3 in the equation of Darcy becomes:

$$q(x,t) = -kD \cdot \Delta h_0 \cdot \frac{d}{dx}\left(\frac{2}{\sqrt{\pi}}\int_a^\infty e^{-u^2} du\right) \qquad a = \sqrt{\frac{x^2 \cdot S}{4 \cdot kD \cdot t}} \qquad (4)$$

$$= \Delta h_0 \cdot \frac{kD}{\sqrt{\pi}} \cdot 2e^{-u^2}\sqrt{\frac{S}{4 \cdot kD \cdot t}} = \Delta h_0 \cdot e^{-u^2}\sqrt{\frac{kD \cdot S}{\pi \cdot t}}$$

$$q(0,t) = \Delta h_0 \cdot \sqrt{\frac{kD \cdot S}{\pi \cdot t}} \qquad (5)$$

And the infiltrated volume for one side of the river becomes:

$$V(t) = \int_0^t q(0,t) \cdot n = 2\Delta h_0 \cdot \frac{\sqrt{kD \cdot S \cdot t}}{\pi} \cdot n \qquad (6)$$

h(x) = phreatic groundwater table change (m)
h_0 = change in river stage (m)
x = distance to the river (m)
kD = transmissivity (m^2/d)
S = specific yield (-)
t = time (d)
q(t) = discharge (m^3/d)
V(t) = infiltrated volume (m^3)
n = yearly number of floods (-)

The transmissivity of the aquifer below the oued Rheris is about 500 m^2/d. The specific yield of silt, the formation in which the water is expected to rise, is 0.11 (Fitts, 2002). The average duration of a flood is 2 days, which occur on average 5 times a year (see figure 47figure 1). During floods, the stage in the Rheris is assumed to be about 1 m above the river bed, because this is the depth of the river bed with respect to the surrounding area (see figure 122 and figure 121 in appendix D). This information leads to:

V(2) = 33 m^3/m/year

The total length of the Oued Rheris in the area studied by Margat is about 15 km. The total yearly river infiltration volume then becomes:

$V(2) \quad = 33 \cdot 15{,}000 \approx 500{,}000\ m^3/year = 0.50\ Mm^3/year$

The average of the river infiltration computed by the model (2.7 Mm^3/y) and analytically calculated (0.50 Mm^3/y) is 1.6 Mm^3/y. Therefore, an average value of eventually 2 Mm^3/y was, equal to 133 $m^3/m/y$, applied to the model.

The results of the model including the adjusted river recharge show a significant lowering of the groundwater levels upstream of Fezna (see figure 51). The maximum drop has been 4 m compared to the outcomes of the initial model (see figure 41). Furthermore, the groundwater peaks during floods also declined (see figure 52). However, the total khettara discharge of 8 Mm^3/y deviated still significantly from estimated (12 Mm^3/y). Moreover, the groundwater levels upstream Fezna are still above ground surface. Consequently, additional adjustments in the model were required.

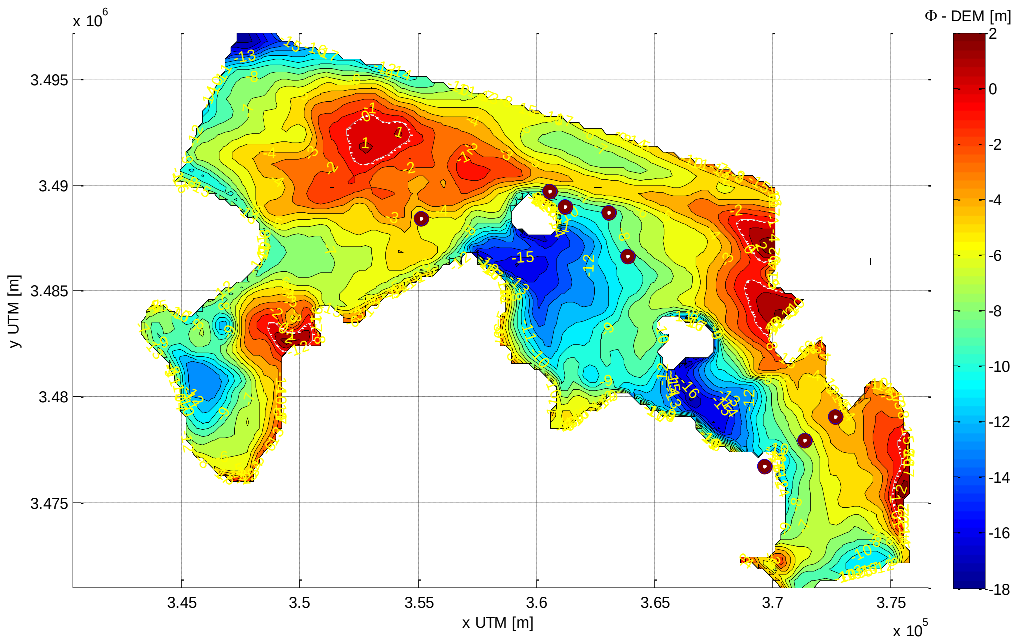


Figure 51: Average groundwater levels, with respect to the surface level, after reducing the river infiltration.

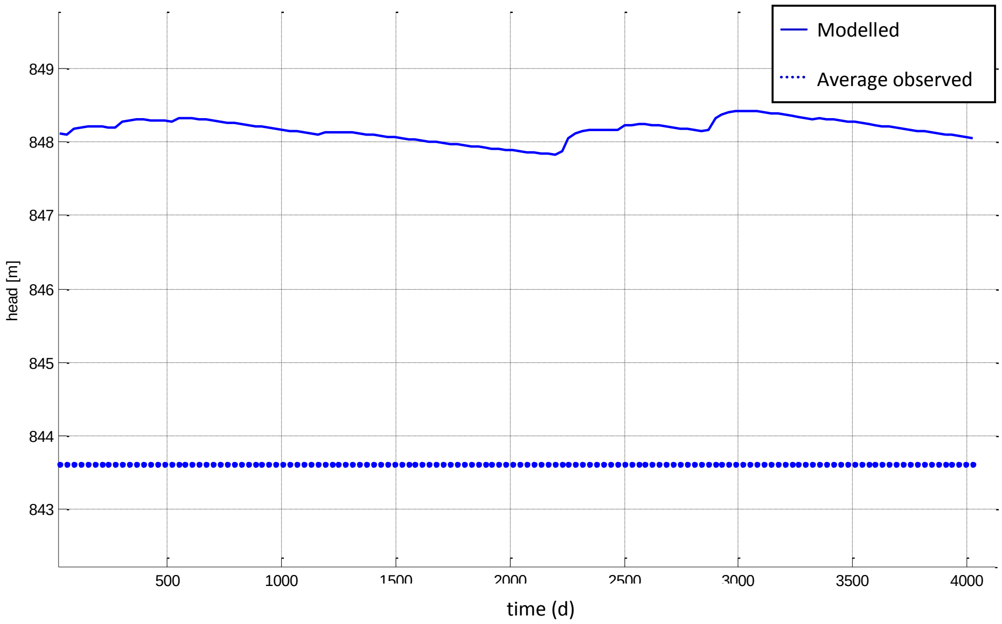


Figure 52: Modelled groundwater levels over time at the location of the khettaras of Fenza after reducing the river infiltration (for location see figure 38).

Hypothesis 4: Surface water passing south of outcrop Gara Gfifate

In the initial model, most of the water originating from the Anti-Atlas catchments infiltrates in front of the bottleneck that causes the extreme groundwater levels upstream of Fezna. In reality, the water passes the bottleneck, possibly as surface water instead of groundwater, which then infiltrates in the plain downstream of the outcrop of Gara Gfifate and feeds wells and khettaras there.

Many wadis, including the oued Batha, are present in the passage between the outcrop of Gara Gfifate and the Anti-Atlas in the south (see figure 53 and figure 54). Floods in these wadis transport sediments as can be seen from the dark-coloured fan. The dark colour indicates that the deposits originate from the Anti-Atlas. The formations of the High Atlas, and the sediments coming from there, have a lighter colour. The fan indicates the spreading of the surface water as the topography becomes more flat downstream (see the cross sections in figure 55). The average slope of the flow route in the catchments upstream Fezna is 1.7 %. The slope in the plain is much smaller, about 0.5 %. This reduces flow velocities and promotes sedimentation and infiltration. The spreading of surface water in the plain, supplied by the oued Batha, is also suggested by the map presented in figure 144 in appendix I. A local farmer representative stated during fieldwork in the plain that during extreme floods, water in the plain occasionally reaches up to a depth of several decimetres. The ABH Guir-Ziz-Rheris (see section 3.4.1.) constructed a small dam at the Anti-Atlas side at the level of Krayr, visible at the new imaginary of Google Earth (lat: 31.427823°, lon: -4.394423°)(WAMAN, 2007). These dams are intended to store surface water to stimulate the groundwater recharge. However, the Anti-Atlas catchments downstream of outcrop Gara Gfifate are relatively small, suggesting that a significant part of the surface water must originate from the more upstream located catchments, which have a larger surface area (see figure 30).

The above given arguments make it likely that substantial amounts of surface water flow through the passage and infiltrate downstream where topography becomes more flat.

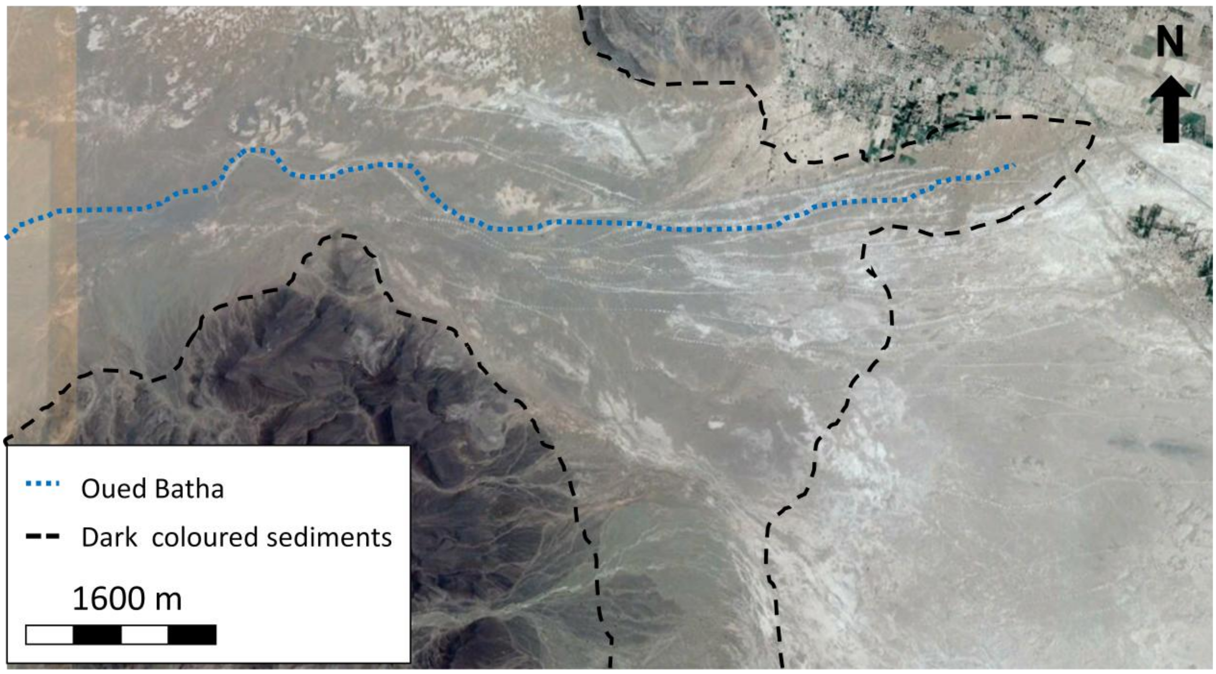


Figure 53: Satellite image of the passage between the outcrop of Gara Gfifate and the Anti-Atlas (see location Y in figure 55). The dark coloured fan consists of sediments deposited by floods originating from the Anti-Atlas.

Figure 54: Satellite image of many wadis near the town of Oukhit (see location X in figure 55), indicating substantial amounts of flood water.

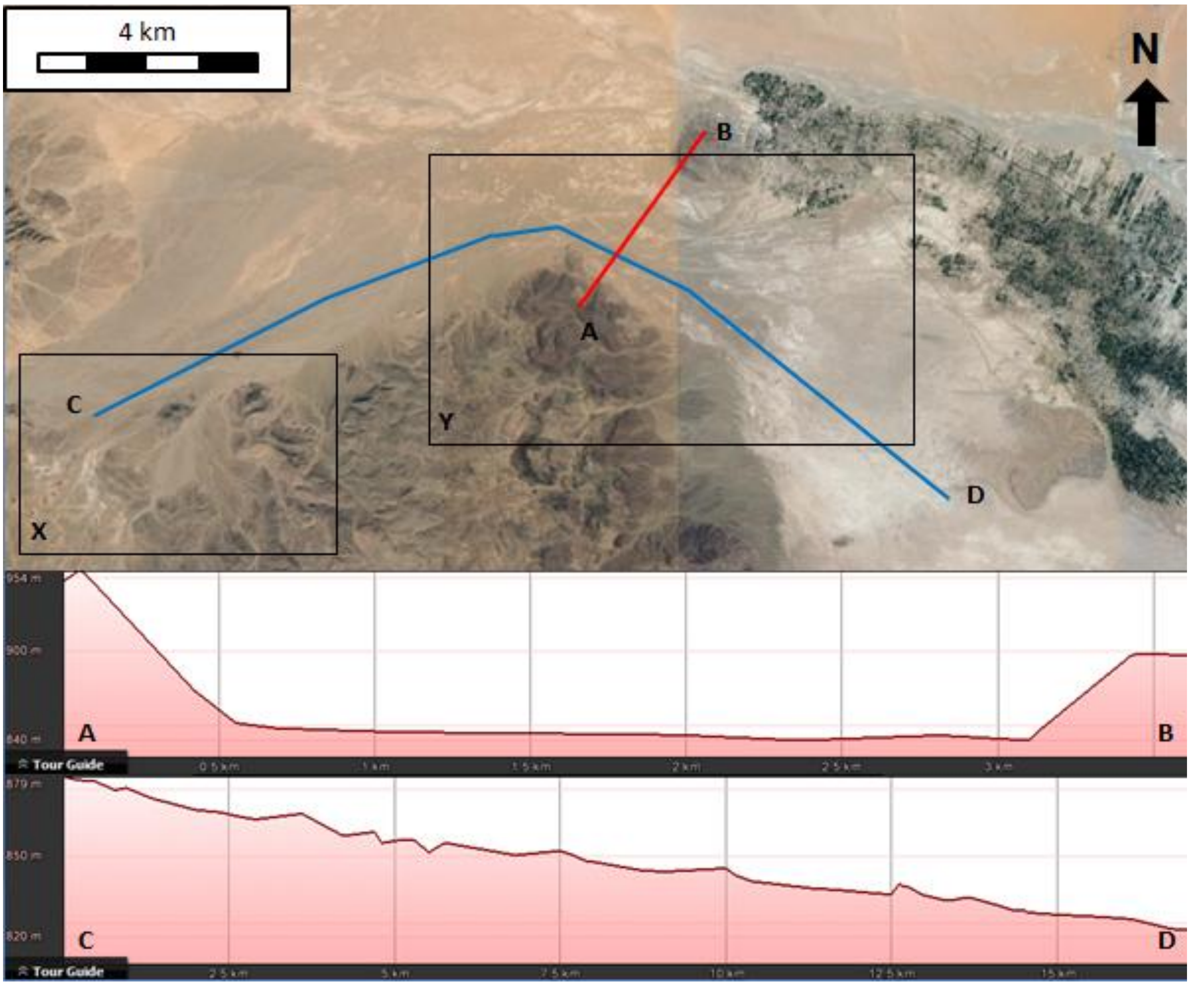


Figure 55: Lateral (AB) and longitudinal (CD) elevation cross sections of the surface water flow paths from the Anti-Atlas mountains (southwest of C) into the plain of Fezna-Jorf (D).

To adapt the model to the hypothesis, the Anti-Atlas catchment algorithm (see section 4.3.2) was adjusted to make the recharge upstream smaller and the infiltration in the plain larger. The runoff factors of the primary and secondary catchments were increased from 0.8 to 0.9, while that of the tertiary catchment is lowered from 0.8 to 0.5. Table 15 shows the recharge per catchment level before and after the adjustments. The recharge in tertiary catchment increased substantially at the expense of that in the primary and secondary catchments, mainly located upstream of the outcrop of Gara Gfifate. The fact that with the adjusted model the total recharge becomes larger is because less surface water flows out the tertiary catchment (see figure 30).

Table 15: Catchment recharge calculated by the algorithm for both the initial and the adjusted model.

Catchment level	Recharge			
	Initial		adjusted	
	Entire model area	Margat Area	Entire model area	Margat Area
	Mm^3/y	Mm^3/y	Mm^3/y	Mm^3/y
Primary	1.5	0.2	0.7	0.1
Secondary	1.2	0.2	0.5	0.1
Tertiary	1.2	0.9	3.5	2.7

The model results are as expected with the groundwater table upstream of Fezna being lowered significantly (see figure 56). The groundwater system behaves more locally because the infiltration downstream in the plain increased from 0.9 (initial model) to 2.8 Mm^3/y at the expense of the incoming groundwater flow which reduced from 7.3 to 5.3 Mm^3/y (see table 16). The modelled total extraction by khettaras was 10.5 Mm^3/y, which is more close to the estimated value.

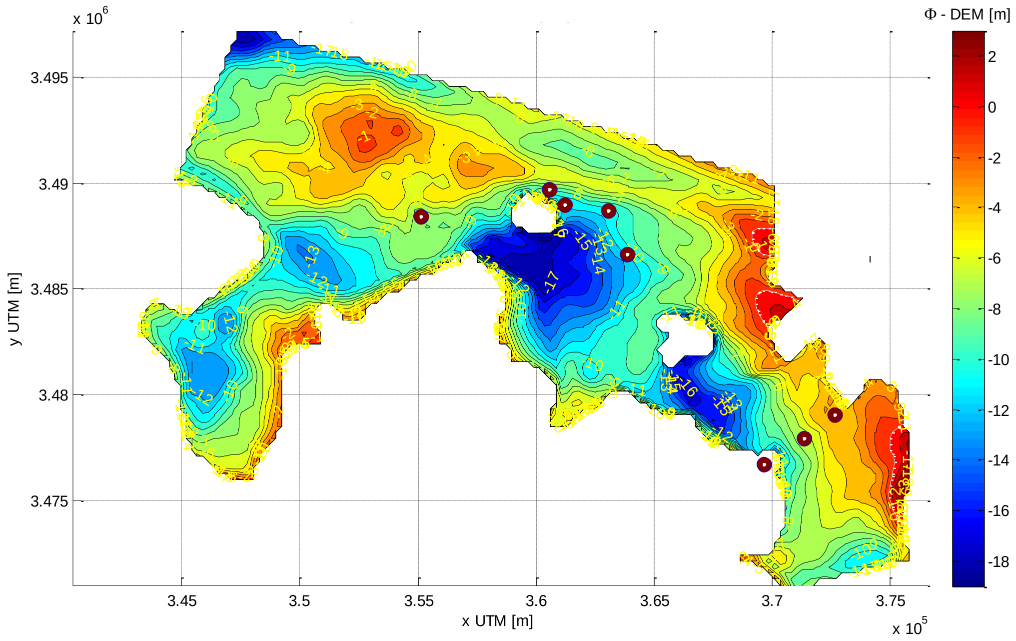


Figure 56: Average simulated groundwater levels, with respect to surface level, after adjusting the Anti-Atlas catchment algorithm.

Table 16: Modelled groundwater balance after adjusting the Anti-Atlas catchment algorithm.

Flows	**Margat***	**Initial estimation**	**Initial model**	**Modelled**
IN	Mm^3/y	Mm^3/y	Mm^3/y	Mm^3/y
Groundwater inflow along outcrop Gara Gfifate	16	16	7.3	**5.3**
Infiltration in the plain	2	0.9	0.9	**2.8**
Lateral groundwater inflow from Anti-Atlas		0.2	0.2	**0.1**
River inflow Fezna-Jorf	5	5	5.0	**2.0**
Irrigation infiltration Fezna-Jorf	5	5	4.7	**4.7**
Total	-	-	*18.1*	***14.9***
OUT				
Groundwater outflow near Krayr	11	11	1.6	**2.0**
Pumping	2	2	2.0	**2.0**
Khettaras	12	12	13.8	**10.5**
Total	-	-	*17.5*	***14.5***

*Ruhard (1977)

The model improved significantly after the adjustments to the river recharge and the Anti-Atlas catchment algorithm, as groundwater levels decreased upstream of Fezna. As a result, the incoming groundwater flow was lowered, while more water infiltrates downstream. For the rest of the calibration process, only the adjusted estimations were considered instead of the initial estimations.

The problem of the extreme groundwater levels upstream of Fezna thus being solved, more attention could be given to groundwater levels in more detail at the locations of the measurements. Figure 57 shows that the differences between calculated and observed heads are smaller compared to the initial model (see figure 40). The model outcomes of the period 1959-1969 are considered to be within acceptable margins.

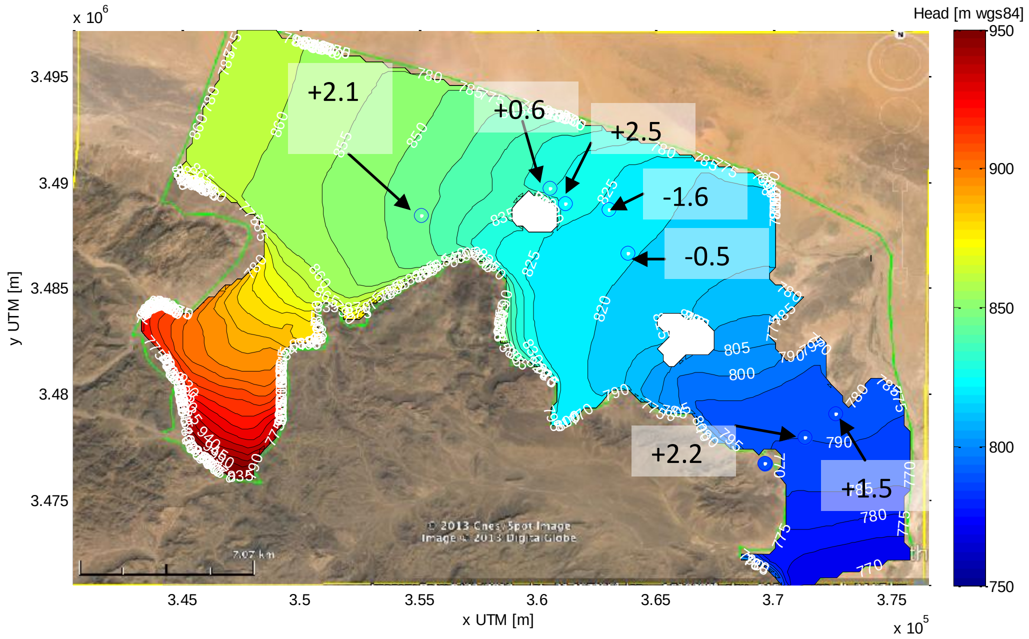


Figure 57: The differences in head between the modelled and the observed groundwater levels with the model including adjustments to river infiltration and the Anti-Atlas catchment recharges.

5.2.3 Shifting the downstream boundary

The modelled groundwater levels in the area of Krayr and Hannabou were fairly stable during the calibration process. This is in accordance to Ruhard (1977), who states that the maximum fluctuation in the 1950s and 1960s in this area was only 0.8 m. For the period 1980-2012, the groundwater level in piezometer 1029/57, near Krayr, varied about 1.5 m, when excluding the outliers (see figure 58 and figure 59). These fluctuations are very small compared to the groundwater tables near Fezna and Jorf. These small fluctuations may be explained by the large distance between this piezometer and the oued Rheris. As a result, the groundwater table in this piezometer is less influenced by river recharge pulses during floods than piezometers closer to the Rheris. The change of the groundwater level after a change in stage in a river can be described by equation 3 (see section 5.2.2.2).

The groundwater level in piezometer 1029/57 is usually about 7 m below ground surface (see figure 59). The river bed is usually 2 m lower than the surrounding area. During floods, the stage in the Rheris is assumed to be about 1 m above the river bed (see section 5.2.2.2), which makes: h_0 = 7-2+1

= 6 m. The transmissivity of the aquifer at piezometer 1029/57 is about 800 m^2/d. The specific yield of silt, the formation expected to store most of the infiltrated water, is 0.11. The distance between piezometer 1029/57 and the oued Rheris is about 5000 m. The average duration of a flood is about 2 days (see figure 47), however, an overestimated duration of 50 days was used to see the impact. With the above information the change of the phreatic groundwater table in piezometer 1029/57 becomes $2.7 \cdot 10^{-8}$ m. Hence, the impact of flooding in the oued Rheris on the groundwater table in piezometer 1029/57 is non-existent.

The stable water levels permit shifting of the downstream fixed-head boundary in upstream direction towards Krayr (see figure 58). Advantages are that several uncertainties can be left out of the model, which are:

- The khettara of Essifa, of which the discharges are unknown.
- The oued Rheris just east of Hannabou, of which no exact information is available on the amount of infiltration.
- The value of the current downstream fixed-head boundary, which is extrapolated over a considerably distance (5 km from the most downstream piezometer 1048 in Hannabou).

Placing the downstream fixed-head boundary towards Krayr has the disadvantage that it is considerably close to the extraction points of the khettaras of Hannabou, and consequently, can influence their model outcomes. However, it is expected not to outweigh the uncertainties regarding the khettaras of Essifa, the infiltration in the oued Rheris and the level of the former downstream boundary. Therefore, it is decided to implement the new downstream boundary.

The value of the head of the new downstream fixed-head boundary is based on the measurements of piezometer 1031/57 (see figure 26), located exactly on this boundary. An average groundwater level of 787 m above mean sea level is used in the model. This value is applied to the full length of the boundary, lateral to the general groundwater flow.

The new downstream fixed head boundary reduces the model area, excluding the area downstream of Krayr.

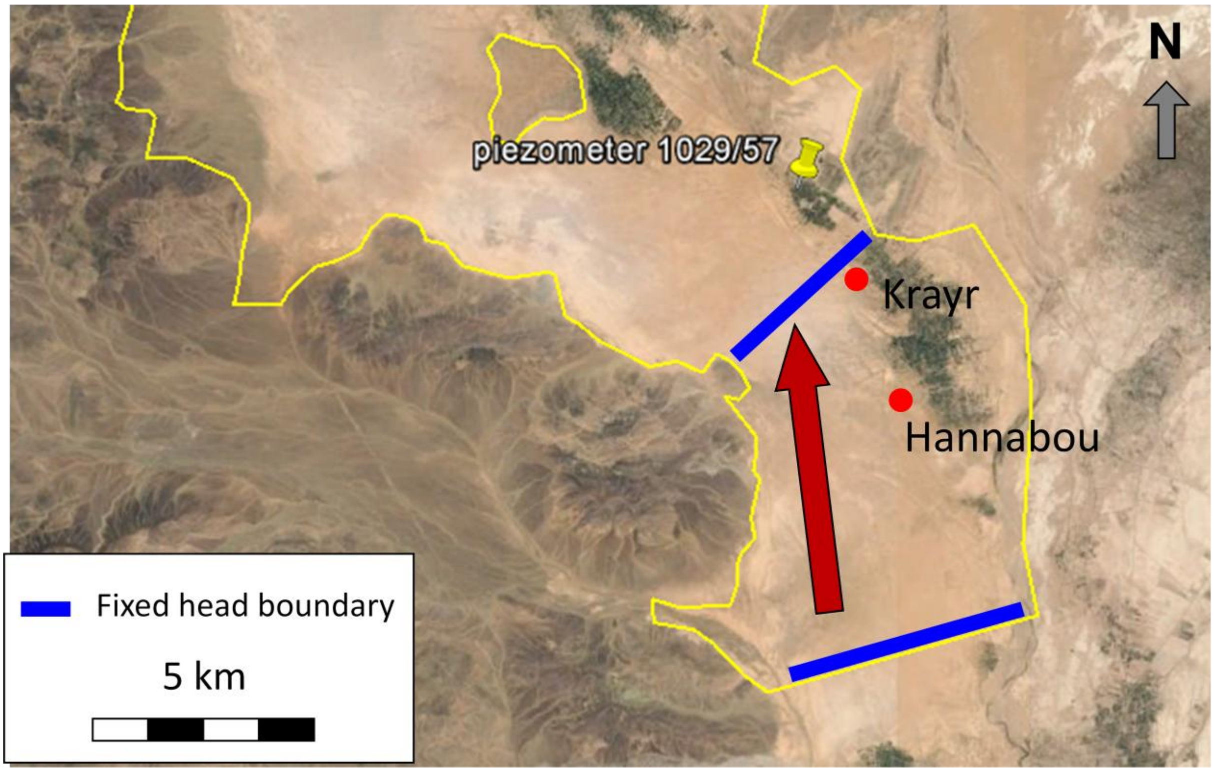


Figure 58: Shifting the downstream fixed head boundary from its initial location to the area near the town of Krayr.

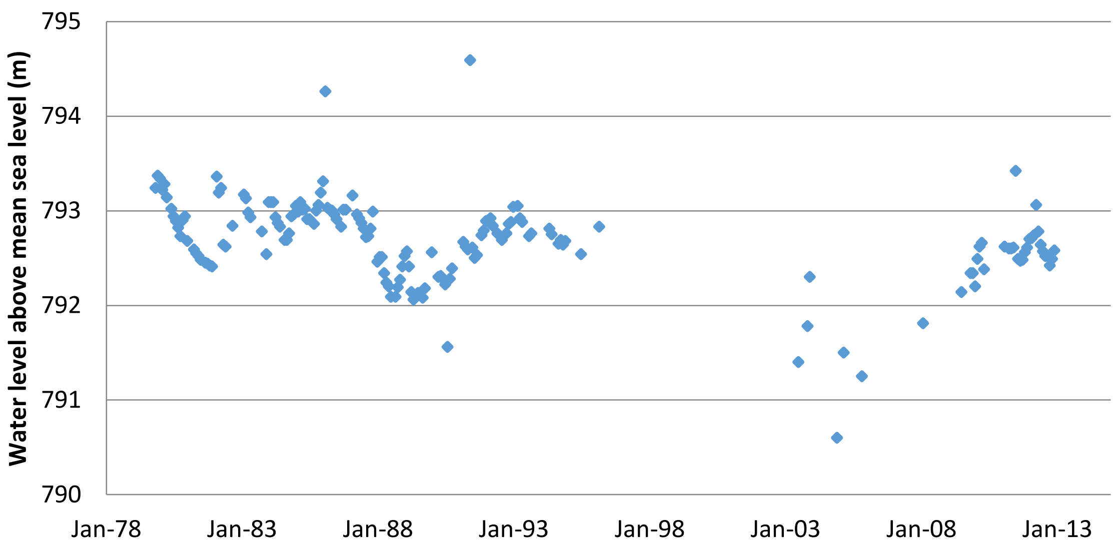


Figure 59: Water levels at piezometer 1029/57 (for the location see figure 110 in appendix C). The ground surface has an elevation of 800 m.

Table 17 shows the modelled groundwater computed balance after shifting the downstream boundary north to Krayr. The calculated total khettara discharge is 7.5 Mm^3/y, which is far below the estimated value of Margat (Ruhard, 1977). This can be explained by the groundwater levels at the changed downstream fixed-head boundary being lower than the levels in the previous model at the same location (see figure 57).

The modelled groundwater levels were not significantly influenced; they stayed within acceptable margins compared to the observed groundwater levels (see figure 60).

Table 17: Modelled groundwater balance after moving the downstream fixed head boundary to the north.

Flows	Margat*	Initial estimation	Adjusted estimation	Modelled
IN	Mm^3/y	Mm^3/y	Mm^3/y	Mm^3/y
Groundwater inflow along outcrop Gara Gfifate	16	16	-	**5.1**
Infiltration in the plain	2	0.9	2.8	**2.8**
Lateral groundwater inflow from Anti-Atlas		0.2	0.1	**0.1**
River inflow Fezna-Jorf	5	2	2	**2.0**
Irrigation infiltration Fezna-Jorf	5	5	5	**4.7**
Total	-	-	-	***14.7***
OUT				
Groundwater outflow near Krayr	11	11	-	**4.3**
Pumping	2	2	2	**2.0**
Khettaras	12	12	12	**7.5**
Total	-	-	-	***13.8***

*Ruhard (1977)

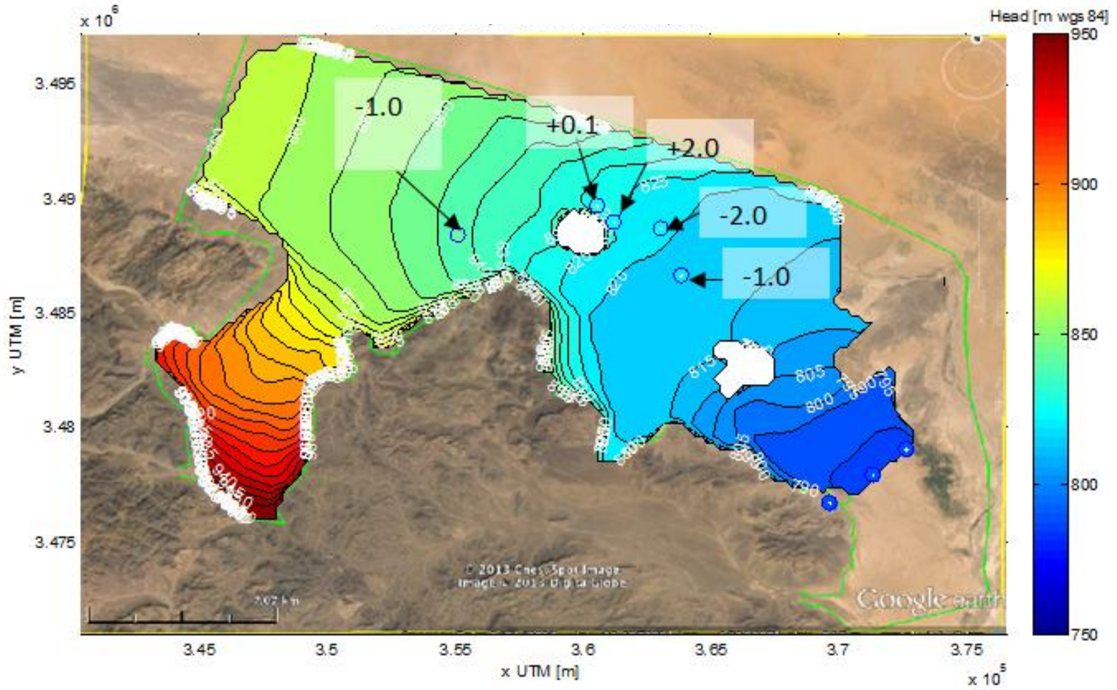


Figure 60: Modelled average groundwater levels after moving the downstream fixed head boundary. Positive values mean that the modelled groundwater levels are higher than the observed levels.

5.2.4 Introducing model period 2000-2010

As the calibration of the model of period 1959-1969 approaches its completion, the model of period 2000-2010 is included in the calibration. The setup of this model was explained in chapter 4. Similar adjustments are applied as to the model of period 1959-1969, which are the following:

- Decrease the river infiltration to 2 Mm^3/y, the same as for the period 1959-1969. This is done because the average annual rainfall of both periods is about equal: 101 mm (period 1959-1959) against 111 mm (period 2000-2010).
- Increase of the infiltration of surface water from the Anti-Atlas catchments downstream the outcrop Gara Gfifate and lowering the recharge upstream. The same adjusted runoff factors for the Anti-Atlas algorithm are applied. The resulting recharge volumes can be seen in table 18.
- Shift of the downstream fixed-head boundary to Krayr. The same head of 787 m is applied, because the water table in this region is very stable, even during a period of several decades (see figure 59).

Table 18: Recharge for each catchment level for the adjusted model of period 2000-2010, calculated by the Anti-Atlas catchment algorithm.

Catchment level	**Recharge**			
	Initial		Adjusted	
	Entire model area	Margat Area	Entire model area	Margat Area
	Mm^3/y	Mm^3/y	Mm^3/y	Mm^3/y
Primary	1.7	0	1.0	0.1
Secondary	1.3	0.3	0.2	0.1
Tertiary	1.4	1.1	4.2	3.1

The groundwater balance of the model for period 2000-2010 shows, just like for the period 1959-1969, that the incoming and outgoing groundwater flows were substantially lower than initially estimated (see table 19). This can also be explained by the adjustment of the water overhead passing the outcrop of Gara Gfifate. Furthermore, the modelled total khettara discharge of 4.8 Mm^3/y was lower than the estimated flow of 8 Mm^3/y. Hence, for both the models of period 1959-1969 (see table 17) and 2000-2010 the khettara discharges were low.

The modelled groundwater levels reasonably match the observed ones (see figure 61). The adjustments made to the Anti-Atlas algorithm are considered to be desirable for the model of period 2000-2010. The groundwater levels upstream outcrop of Gara Gfifate stay below the elevation of the khettaras of Fezna (-2.2 m) as they should.

Table 19: Modelled groundwater balance of the period 2000-2010.

Flows	Ourahou (1998)	Initial estimation	Adjusted estimation	Modelled
IN	Mm^3/y	Mm^3/y	Mm^3/y	Mm^3/y
Groundwater inflow along outcrop Gara Gfifate	12.2	12	-	**5.3**
Infiltration in the plain	-	1.1	3.5	**3.5**
Lateral groundwater inflow from Anti-Atlas	-	0.3	0.1	**0.1**
River inflow Fezna-Jorf	2.2	5	2	**2.0**
Irrigation infiltration Fezna-Jorf	11	5.8	5.8	**5.3**
Total	-	-	-	***16.2***
OUT				
Groundwater outflow near Krayr	11	11	-	**3.2**
Pumping	8	8	8	**7.7**
Khettaras	3.7	8	8	**4.8**
Total	-	-	-	***15.7***

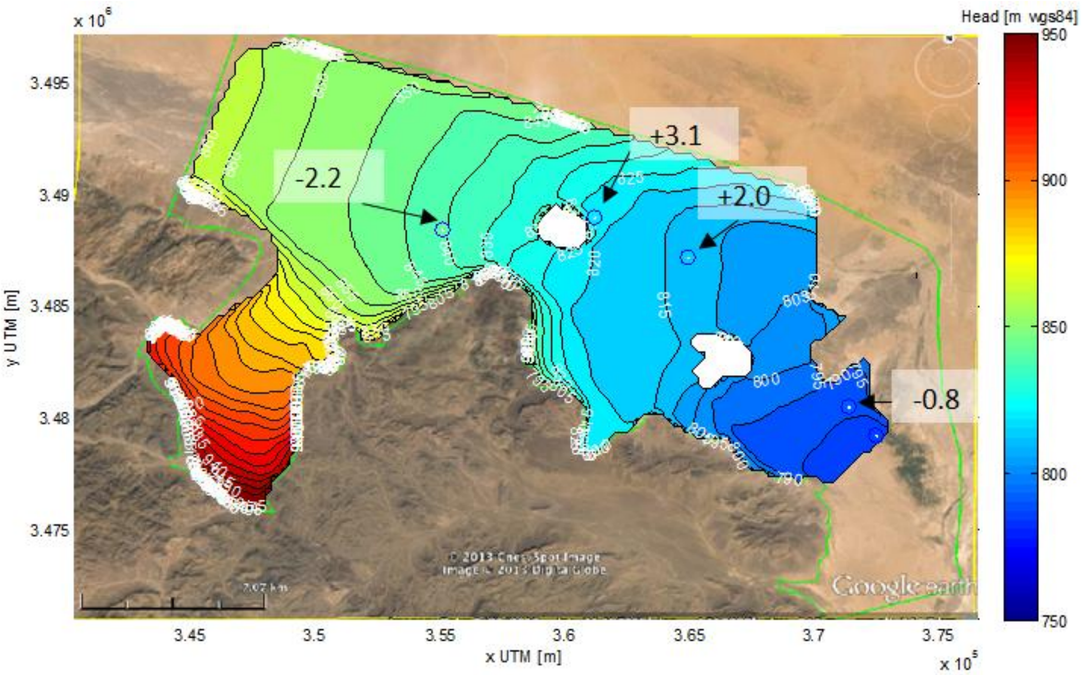


Figure 61: Average groundwater levels simulated with the model of period 2000-2010. Positive values mean that the modelled groundwater levels are higher than the observed levels.

5.2.5 Final models

The models of both periods 1959-1969 and 2000-2010 are still not correct as the calculated total khettara discharges are too low. With the few possibilities left to improve the models, the remaining flow to adjust is the irrigation return flow. Increasing the irrigation return flow may enlarge the khettara discharges. Margat (Ruhard, 1977) estimated the average division of flood water from the oued Rheris in the agricultural for irrigation in the 1950s and 1960s on 12 Mm^3/y. With an average infiltration percentage of 30-50%, derived from observed groundwater rise of the aquifer in Jorf, the infiltration from irrigation was estimated on 5 Mm^3/y. Irrigation is also from khettaras and pumping by means of tube wells which yielded about 14 Mm^3/y (see table 7), which is more than was provided by floods. However, this water was not included in the estimation of the irrigation return flow, of which the reasons are unkown. The infiltration of water from floods might infiltrate in larger percentages because it comes in a much smaller time frame, on average 8-12 days per year (see figure 47), which does the crops not allow to evaporate the total incoming amount 12 Mm^3/y. This is in contrast to the water supplied by khettaras and pumps, which is more or less continuous. Nevertheless, it seems unlikely that none of the khettara and pump water infiltrates and, therefore, the irrigation infiltration was increased by 20 % for both periods.

However, increasing the irrigation infiltration probably causes the groundwater levels near Fezna and Jorf to deviate largely from the observed ones, especially in the model for 2000-2010 (see figure 61). Hence, there was no other choice than to still increase the transmissivities.

The hydraulic conductivities are considered reliable because they are based on pumping tests (Ruhard, 1977). However, Margat states (Ruhard, 1977) that the conglomerate can have all degrees of cementation. It is possible that the conglomerate in the groundwater system of Fezna-Jorf-Hannabou is less cemented than in other parts of the Tafilalet aquifer. Less cemented conglomerate was also generally observed during fieldwork where loose gravels and pebbles where found on the top of the khettara hills, which are made of excavation material from the tunnel (see figure 62 and figure 63). Cementation may perhaps be more dominant near the lower parts of the Tafilalet plain, where surface water infiltrated, especially originating from the High Atlas side, with a relatively high concentration of calcite due to longer exposure to evaporation (see figure 64). Loose pebble formations can have high hydraulic conductivities, between 80 - 80,000 m/d (see figure 164 in appendix L). Therefore, the hydraulic conductivity of conglomerate in the model was increased as needed by a factor of two to 86 m/d (see set 4 in table 11), making it twice the upper limit of the range presented by Margat. Of course, an unconsolidated pebble layer should not be called conglomerate, however we keep this name to prevent confusion.

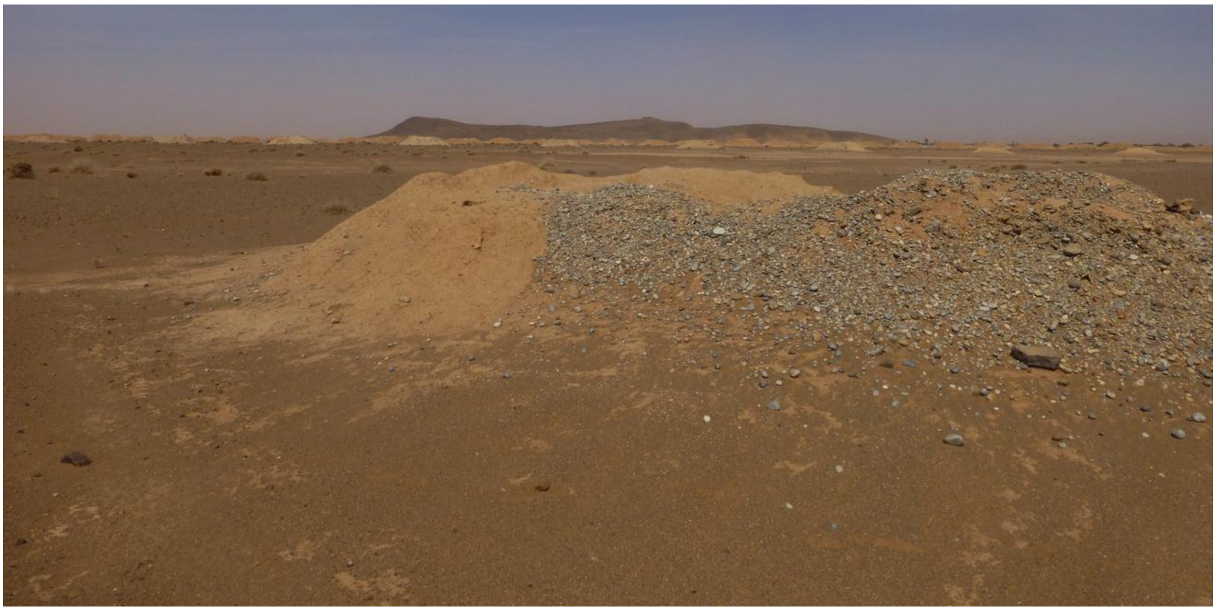


Figure 62: Hill near Krayr with pebbles from the water-bearing, most upstream, part of the khettara tunnel.

Figure 63: Uncemented pebbles, id est not conglomerate (same location as figure 62).

Figure 64: Conglomerate existing of cemented rounded pebbles (same location as figure 62).

Table 20 gives the groundwater balance of the period 1959-1969 after implementing the new adjustments. The incoming and outgoing groundwater flows increased compared to the model before the adjustments, but they remain less than the values estimated by Margat (Ruhard, 1977). The total extraction by khettaras matches reasonably well with the estimated value.

Also the calculated groundwater levels reasonably matched the observed ones (see figure 65). Upstream the outcrops of Gara Gfifate, the modelled groundwater levels are below the dry khettaras of Fezna as they should. In most of the model area, the modelled groundwater levels are below surface level (see figure 66), except of in the northeast. This can be attributed to the bedrock threshold near Bouia generating an evaporation flux (Ruhard, 1977).

Table 20: Modelled groundwater balance of the final model for the period 1959-1969, after increasing the irrigation return flow and the hydraulic conductivity of the conglomerate formation.

Flows	Margat*	Initial estimation	Adjusted estimation	Modelled
IN	Mm^3/y	Mm^3/y	Mm^3/y	Mm^3/y
Groundwater inflow along outcrop Gara Gfifate	16	16	-	**7.4**
Infiltration in the plain	2	0.9	2.8	**2.8**
Lateral groundwater inflow from Anti-Atlas		0.2	0.1	**0.1**
River inflow Fezna-Jorf	5	2	2	**2.0**
Irrigation infiltration Fezna-Jorf	5	5	6	**6.0**
Total	-	-	-	***18.3***
OUT				
Groundwater outflow near Krayr	11	11	-	**4.6**
Pumping	2	2	2	**2.0**
Khettaras	12	12	12	**11.7**
Total	-	-	-	***18.3***

*Ruhard (1977)

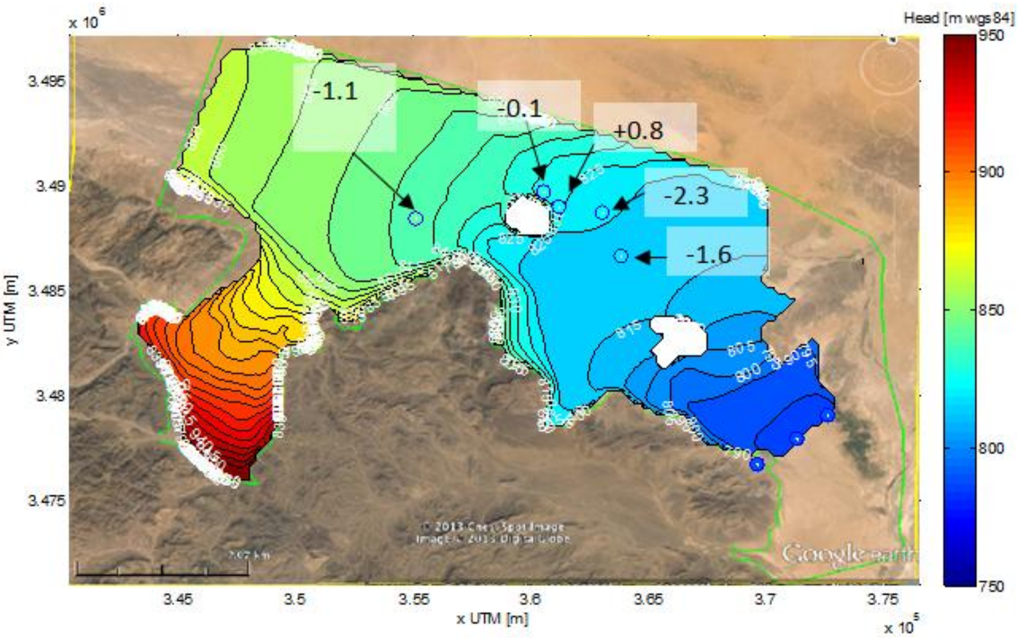


Figure 65: The modelled groundwater levels of the final model for the period 1959-1969, after increasing the irrigation return flow and the hydraulic conductivity of the conglomerate formation.

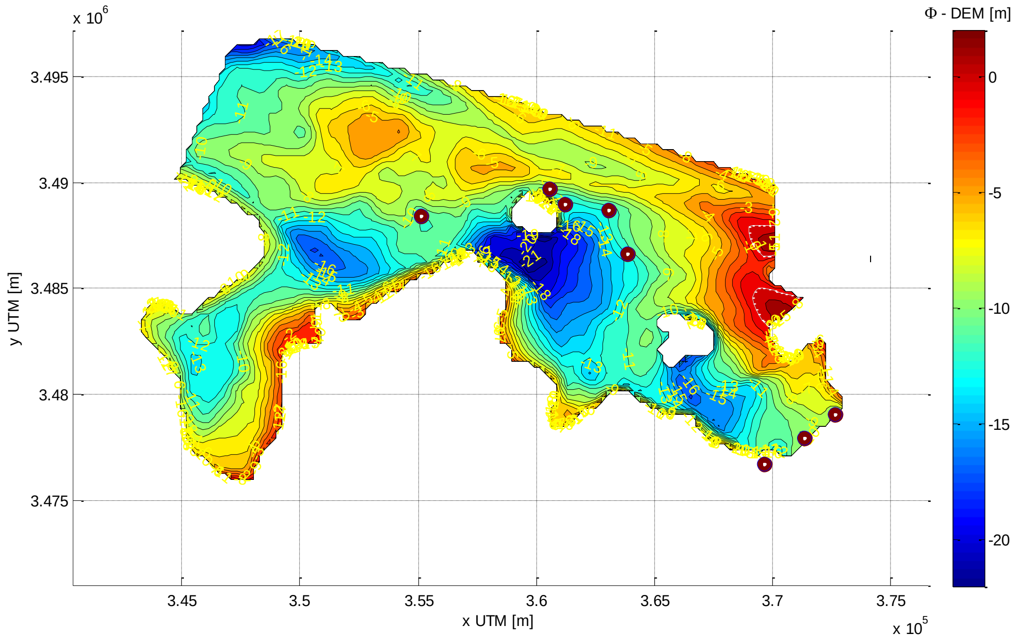


Figure 66: The modelled groundwater levels, in relation to the surface, of the final model for the period 1959-1969, after increasing the irrigation return flow and the hydraulic conductivity of the conglomerate formation.

Table 21 gives the modelled groundwater balance of the period 2000-2010. The incoming and outgoing groundwater flows increased compared to the previous model. The modelled total khettara discharge increased to 8.3 Mm3/y, almost matching the values estimated by Margat.

Figure 67 shows the modelled groundwater levels. They are essentially within acceptable margins compared to the observed levels. Only the modelled groundwater levels near the outcrop of Gara Gfifate differs substantially from the near-by piezometer. However, this can be explained by the fact that the observed groundwater data are related to ground surface. This causes inaccuracies near outcrops and mountains. Due to thelocally large slope of the terrain, large errors can arise by averaging the elevation of the cells used here. Finally, figure 68 shows that the groundwater levels are below ground surface for the entire model area, as they should.

Table 21: Modelled groundwater balance of the final model for the period 2000-2010, after increasing the irrigation infiltration and the hydraulic conductivity of the conglomerate formation.

Flows	Ourahou (1998)	Initial estimation	Adjusted estimation	Modelled
IN	Mm^3/y	Mm^3/y	Mm^3/y	Mm^3/y
Groundwater inflow along outcrop Gara Gfifate	12.2	12	-	**8.1**
Infiltration in the plain	-	1.1	3.5	**3.5**
Lateral groundwater inflow from Anti-Atlas	-	0.3	0.1	**0.1**
River inflow Fezna-Jorf	2.2	5	2	**2.0**
Irrigation infiltration Fezna-Jorf	11	5.8	7.0	**7.0**
Total	-	-	-	***20.7***
OUT				
Groundwater outflow near Krayr	11	11	-	**4.6**
Pumping	8	8	8	**7.8**
Khettaras	3.7	8	8	**8.3**
Total	-	-	-	***20.7***

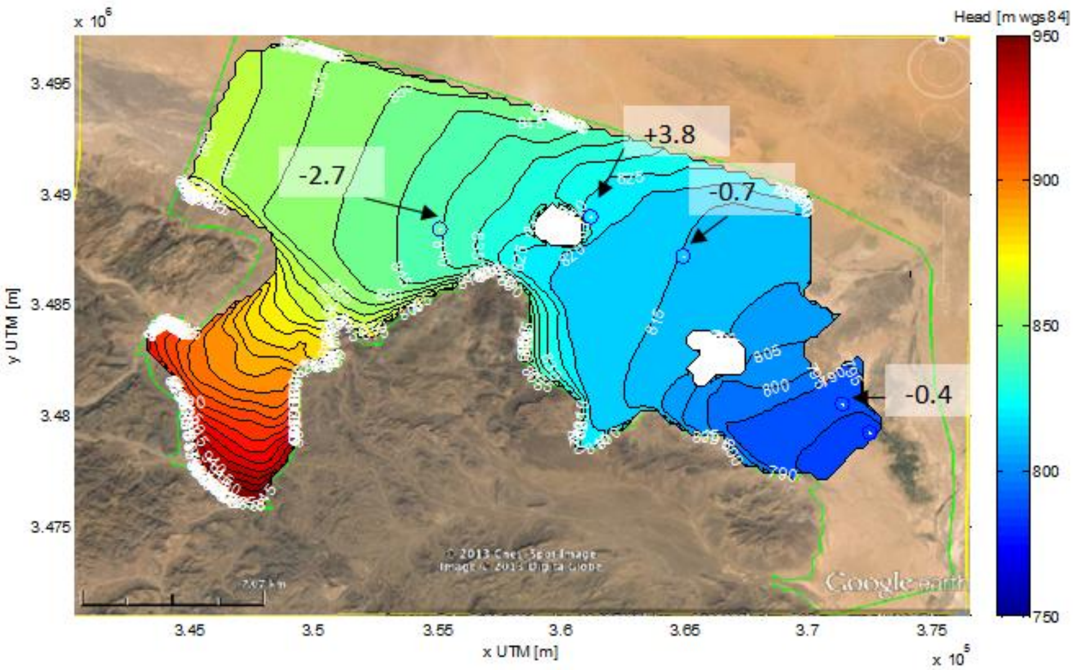


Figure 67: The modelled groundwater levels of the final model for the period 2000-2010, after increasing the irrigation return flow and the hydraulic conductivity of the conglomerate formation.

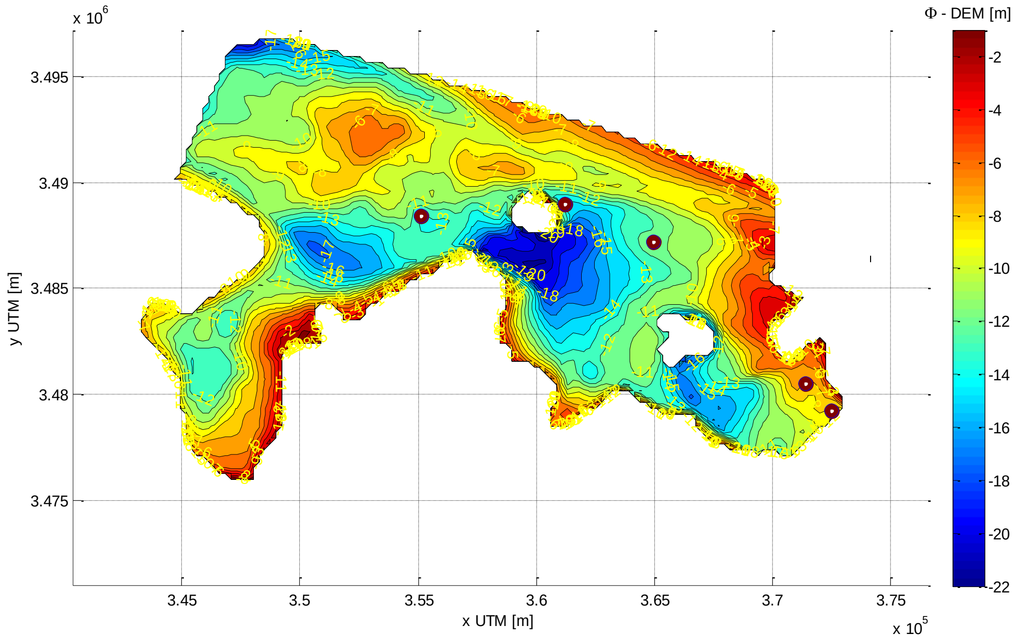


Figure 68: The modelled groundwater levels, in relation to the surface, of the final model for the period 2000-2010, after increasing the irrigation return flow and the hydraulic conductivity of the conglomerate formation.

5.3 Conclusions

During the calibration process several hypothesis were proposed and evaluated step by step to improved the model. Given the available data and information, the presented models in section 5.2.5 are currently considered to be a fair representation of the groundwater system of Fezna-Jorf-Hannabou.

Table 22 gives a summary of the calibration process including the problems faced and the adjustments at each step, their results, their likelihood and whether they are applied or not.

Table 22: Summary of the calibration process.

Period	Problem	Adjustment	Result	Likely	Applied
1959-1969	Initial model: extremely high groundwater levels upstream of the outcrop of Gara Gfifate	Adding gravel in the bottleneck	Effect on the levels is minor	No, presence in passage is not so likely	No
		Increasing hydraulic conductivities of the present formations	Enlarged flows, almost matching the estimated flows	No, conductivities are not likely to be higher than those presented by Margat	No
		Lowering river recharge	Substantial drop of the groundwater levels upstream Fezna	Yes, a lower river recharge is supported by model calculations	Yes
		Increasing recharge of surface water from the Anti-Atlas in plain and lowering the infiltration upstream of Fezna	Lowering of the groundwater levels upstream of Fezna and higher khettara discharges	Yes, many wadis are present near the area of Oukhit and in the passage. And large infiltration in the downstream area is possible due to the flatness	Yes
	Uncertainties of hydraulic boundaries in downstream area	Moving the downstream fixed head boundary upstream to the town of Krayr	Smaller model area, realistic groundwater tables and very low khettara discharges	Yes, the groundwater levels near Krayr are relatively stable	Yes
1959-1969 & 2000-2010	Too low total khettara discharge	Increased irrigation infiltration	Realistic groundwater tables and khettara discharges	Yes, difficult to determine this flux. And fits in the idea of local hydrological processes	Yes
		Higher hydraulic conductivity of the conglomerate formation		Yes, although the hydraulic conductivities are considered to be reliable, the conglomerate formation in study area could be relatively less cemented and hence more permeable	Yes

6 Scenarios

This chapter analyzes the behaviour of the groundwater basin of Fezna-Jorf-Hannabou in different times and/or under changed stresses.

The starting point for the scenarios is the model for period 2000-2010, which was calibrated in the previous chapter. The same precipitation data set is used, which is considered to be representative for the last fifty years (see rainfall data in appendix B).

6.1 Historical evolution

Several historical situations are considered that are hydrologically different, predominantly caused by human intervention. The scenarios are the following (in chronological time order):

Natural situation

The natural situation represents the period before any human intervention in the water system, i.e. before the thirteenth or fourteenth century. There were human activities in the Tafilalet region though, especially near the medieval city of Sijimassa, which played an important role as a caravan crossroad and trading centre (Lightfood, 1996). Irrigation was already practised in this period, but at a very minor scale (Lightfood, 1996). Furthermore, it is known that khettaras didn't appear yet in the Sijimassas time.

Introduction of khettaras

It was not until the in the late fourteenth century, when the Sijimassa dynasty fell and the Tafilalet became to be ruled by the Alaouiets, that the people started to spread and settle all over the Tafilalet plain and shortage of water commenced to appear (Spoerry, 2007). This drove the people to expand the infrastructure through a large-scale irrigation network of small dams and division works off the oueds Ziz and Rheris (Lightfood, 1996). Simultaneously, the excavation of khettaras started in the late fourteenth century (Lightfood, 1996), although the first khettaras in Morocco were built in the twelfth century in the Haouz plain around Marrakech and the technique was probably known by the Sijimassa (Lightfood, 1996). It is likely that these water related technological developments also occurred in the area of Fezna, Jorf and Hannabou, which makes up the northern part of the Tafilalet plain.

Current situation

Groundwater pumping by means of tube wells started by the French, who built several collective stations in the early last century (Ruhard, 1977). From the sixties, more and more private pumps were installed by farmers. Today, groundwater pumping by tube wells is a major source of water for irrigation, next to khettaras and floods.

6.1.1 Natural situation

A period of seven hundred years is small in comparison with the scale of glacial periods. The last ice age occurred more than ten thousand years ago. Since then, average global temperatures fluctuate with several degrees Celsius (see figure 69), with the little ice age as most recent extreme. These fluctuations probably had its effects on the precipitation, however, the exact quantities are unkown. It is, therefore, difficult to simulate the situation before the 14th century. Consequently, this scenario can better be seen as an evaluation of the current situation without human intervention.

In this scenario, the hydraulic boundaries related to human intervention, such as khettaras, pumping, infiltration in irrigation areas, are excluded from the model. The heights of the upstream and downstream fixed head boundaries may have to be adapted for the "natural" system. But by lack of independent information it is not clear to what extent. Therefore these two head boundaries remain unchanged.

Finally, drainage in the oued Rheris is implemented in the model, because first model results showed that the groundwater levels increased far above surface level.

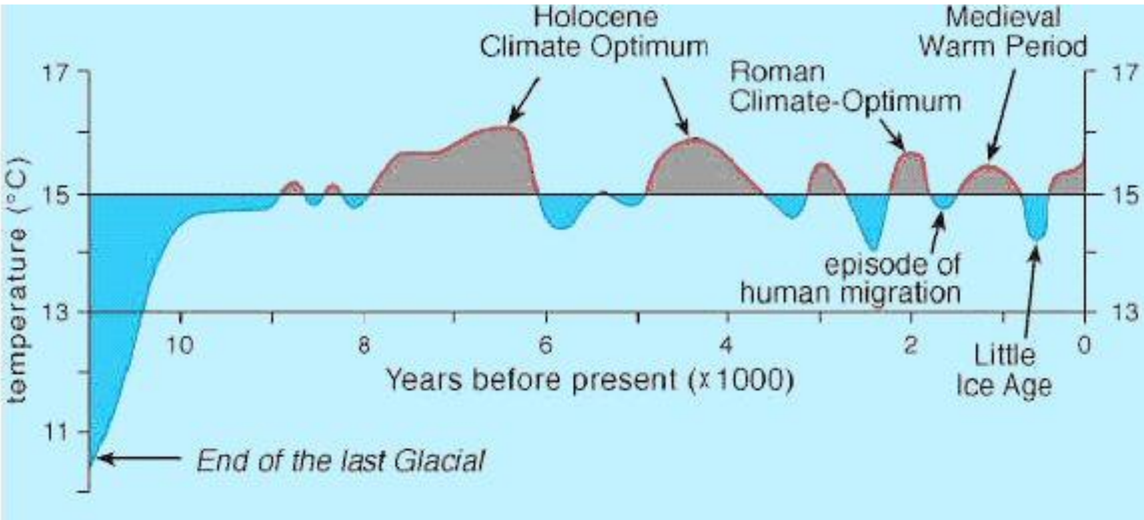


Figure 69: Average near surface temperature of the northern hemisphere during the past eleven thousands years (lwHancock, 2012).

Table 23 shows the groundwater balance for the model for the "natural situation". The total groundwater flow through the model is about 11 Mm^3/y, which is less than in the model of the current situation (20 Mm^3/y). This can be explained by the absence of infiltration from irrigation, i.e. river diversion. Figure 70 shows that the groundwater levels are close to ground surface. Lightfoot (1996) describes that in the Tafilalet groundwater has always been shallow enough to support the large oasis. This groundwater has accumulated by the supply of seasonal runoff from the Atlas Mountains through the oueds Rheris and Ziz. In the northwest of the model area the groundwater level is even computed above surface level, which is caused by the geological threshold of the bedrock near Bouia (see section 4.1.3).

The drainage by the oued Rheris is about 2.4 Mm^3/y (see table 23). The model suggests that water flowed continuously in the oued Rheris. This might be true because the groundwater was also shallow in the downstream part of the Tafilalet plain (Lightfood, 1996). On the other hand, it is not so likely because one started constructing khettaras, which would not have been necessary with an abundance of surface water.

Table 23: Modelled groundwater balance of the natural situation in the area presented by Margat.

Flows	Modelled
	Mm^3/y
IN	
Groundwater inflow along outcrop Gara Gfifate	6.9
Infiltration in the plain	3.5
Lateral groundwater inflow from Anti-Atlas	0.2
River inflow Fezna-Jorf	-
Total	*10.6*
OUT	
Groundwater outflow near Krayr	8.3
Drainage Rheris	2.4
Total	*10.7*

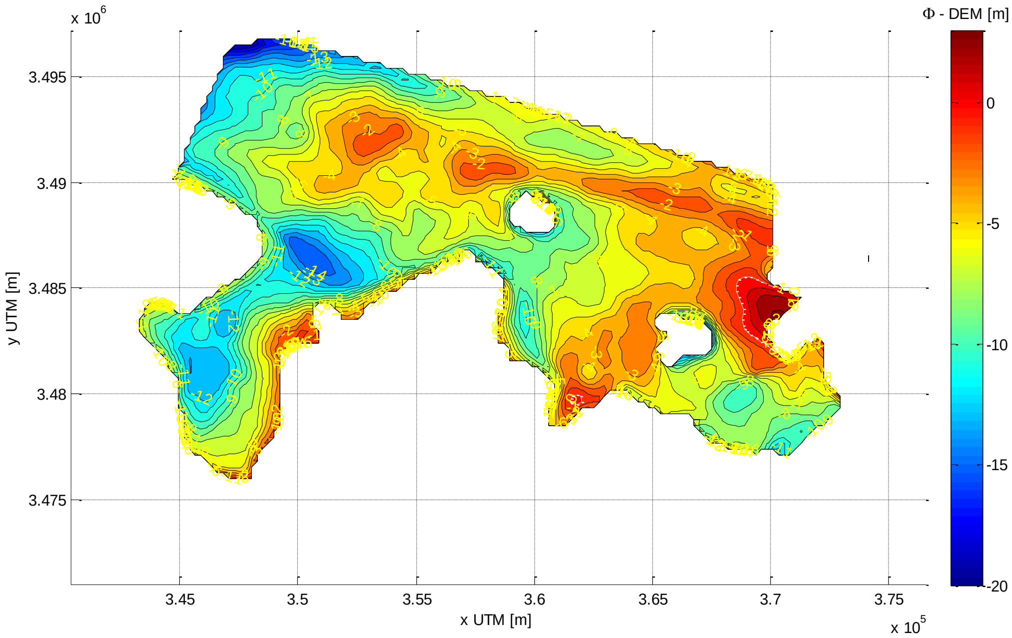


Figure 70: The calculated groundwater level with respect to the surface level for the natural situation.

6.1.2 Introduction of khettaras

The khettaras and infiltration from irrigation in the agricultural areas are now introduced in the model. The same khettaras are activated as used for the model for the periods of 1959-1969 and 2000-2010, i.e. all khettaras of Jorf and Hannabou visible from satellite images. It is known that some of them are currently not functioning. But due to the absence of pumping in this sub scenario, it is assumed all of them were working. The khettaras of Fezna were used actively before pumping started in the early twentieth century (Ruhard, 1977). However, in this scenario they are not included, because the impact of pumping alone wants to be evaluated by comparison with the current situation (see 6.1.3).

Furthermore, an extended network of irrigation canals was constructed from the 14th century, which probably differed from the current system, at least because the canals were originally made of soil instead of concrete. Nevertheless, the same flood amounts are used in the model for the periods 1959-1969 and 2000-2010. It is likely that the khettara discharges increase as a result of not pumping. The irrigation return flow depends (partly) on the khettara extraction, which is calculated by the the model. On the other hand, the khettara extractions depend on the amount of irrigation return flow. Therefore, the model is adjusted until the return flow is 40 %, determined during the calibration, of the total irrigation water volume, including the khettara supply.

Table 24 shows the groundwater balance computed by the model for this situation. The Khettaras extract a large amount of 13.2 Mm^3/y, more than half of the incoming groundwater. Their discharges almost equals that of of the khettaras in the period 1959-1969 in which pumping just started (see section 5.2.5). The incoming and outgoing groundwater flows are less compared to the previous case, before the 14th century. Both the khettara discharges and the irrigation infiltration are significant.

The influence of the khettaras on the groundwater system is substantial. The groundwater levels lowered in the entire model area, especially near the extraction locations of the khettaras of Jorf and Hannabou (see figure 72 and figure 73).

Table 24: Calculated groundwater balance of the historical situation after the introduction of the khettaras.

Flows	**Modelled**
	Mm^3/y
IN	
Groundwater inflow along outcrop Gara Gfifate	6.5
Infiltration in the plain	3.5
Lateral groundwater inflow from Anti-Atlas	0.2
River inflow	2.0
Irrigation infiltration	6.6
Total	*18.8*
OUT	
Groundwater outflow near Krayr	5.4
Khettaras	13.2
Total	*18.6*

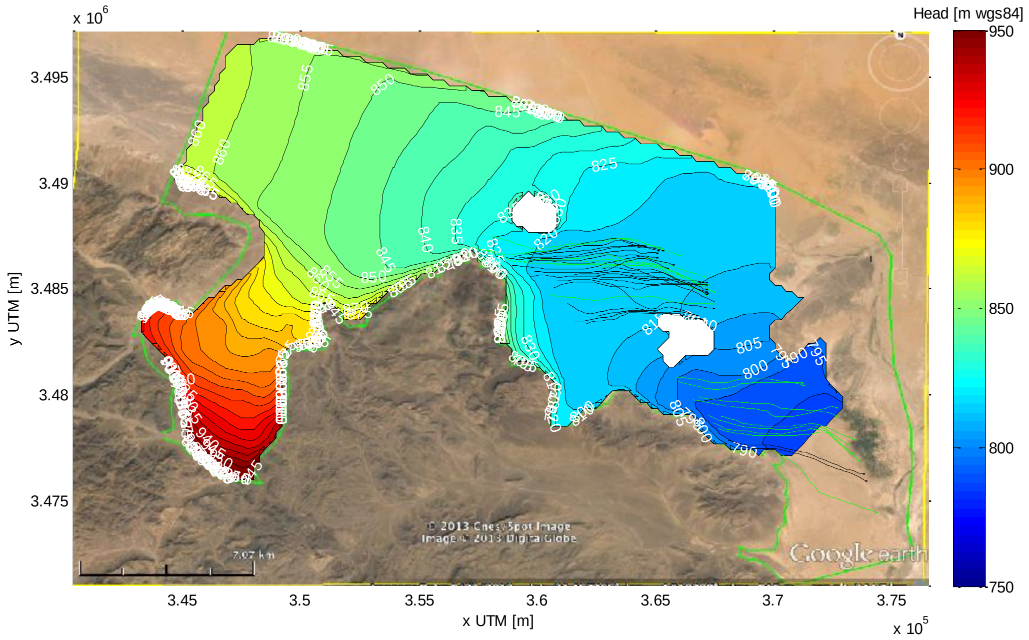


Figure 71: The modelled groundwater level for the situation after introducing the khettaras. The functioning khettaras are presented in green and the not functioning khettaras in black.

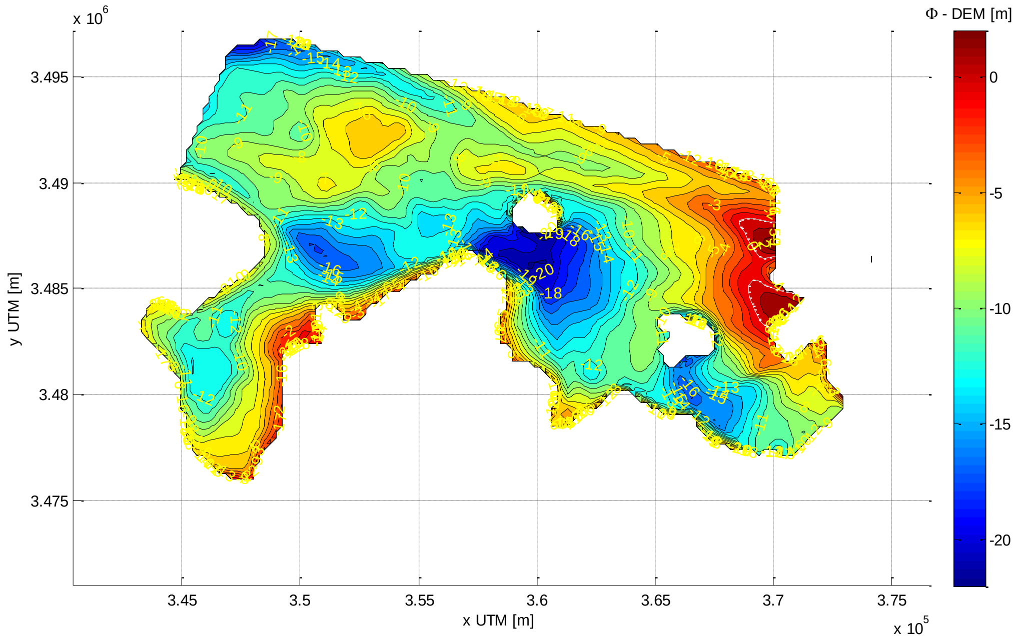


Figure 72: The modelled groundwater level with respect to surface level for the historical situation after introduction of the khettaras.

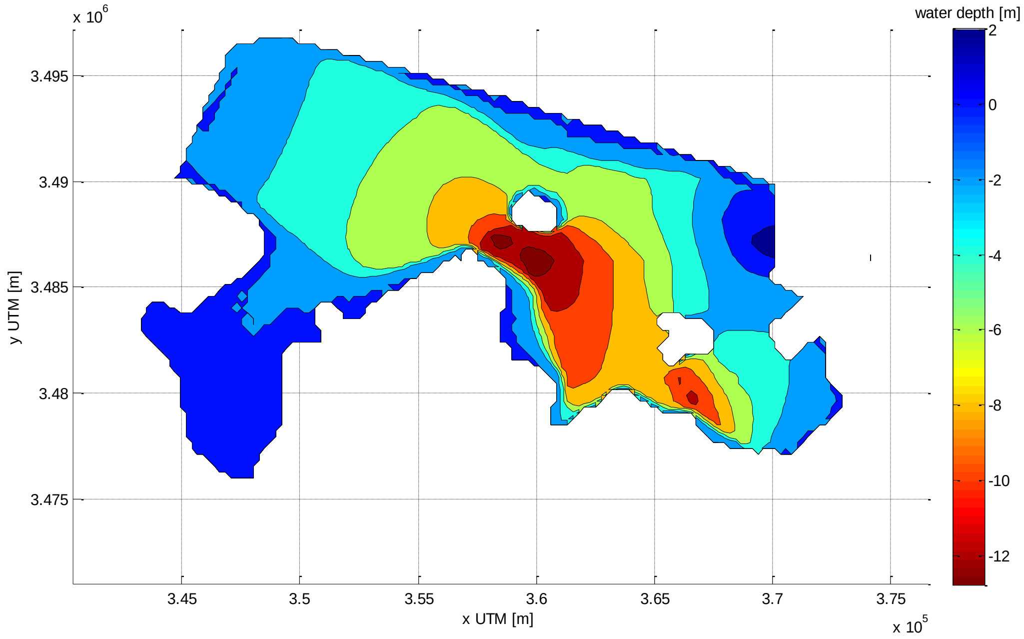


Figure 73: The differences in modelled groundwater level of the situation after the introduction of khettaras compared to the natural situation. The functioning khettaras are presented in green and the not functioning khettaras in black.

6.1.3 Current situation

In the current scenario groundwater pumping by means of tube wells occurs. The khettara discharge decreased substantially, which is entirely caused by the pumping in the area (see table 25). Figure 74 shows the calculated groundwater levels with respect to the surface. Figure 75 shows the differences in modelled groundwater level between the current situation and the previous situation, before pumping. The groundwater levels dropped significantly near the pumping area. The influence zone of the pumping reaches to the area where the mother wells of the khettaras of Jorf and Hannabou and, hence, it affects their discharges. Figure 76 shows the differences in modelled groundwater level between the current situation and "natural situation". The total impact of extraction by khettaras and pumping by tube wells is significant.

Table 25: Modelled groundwater balances of current situation compared to the other historical situations.

Flows	Natural situation	After introduction khettaras	Period 2000-2010
	Mm3/y	Mm3/y	Mm3/y
IN			
Groundwater inflow along outcrop Gara Gfifate	6.9	6.5	8.1
Infiltration in the plain	3.5	3.5	3.5
Lateral groundwater inflow from Anti-Atlas	0.2	0.2	0.1
River inflow Fezna-Jorf	-	2.0	2.0
Irrigation infiltration Fezna-Jorf	-	6.6	7.0
Total	*10.6*	*18.8*	*20.7*
OUT			
Groundwater outflow near Krayr	8.3	5.4	4.6
Khettaras	-	13.2	7.8
Pumping	-	-	8.3
Drainage Rheris	2.4	-	-
Total	*10.7*	*18.6*	*20.7*

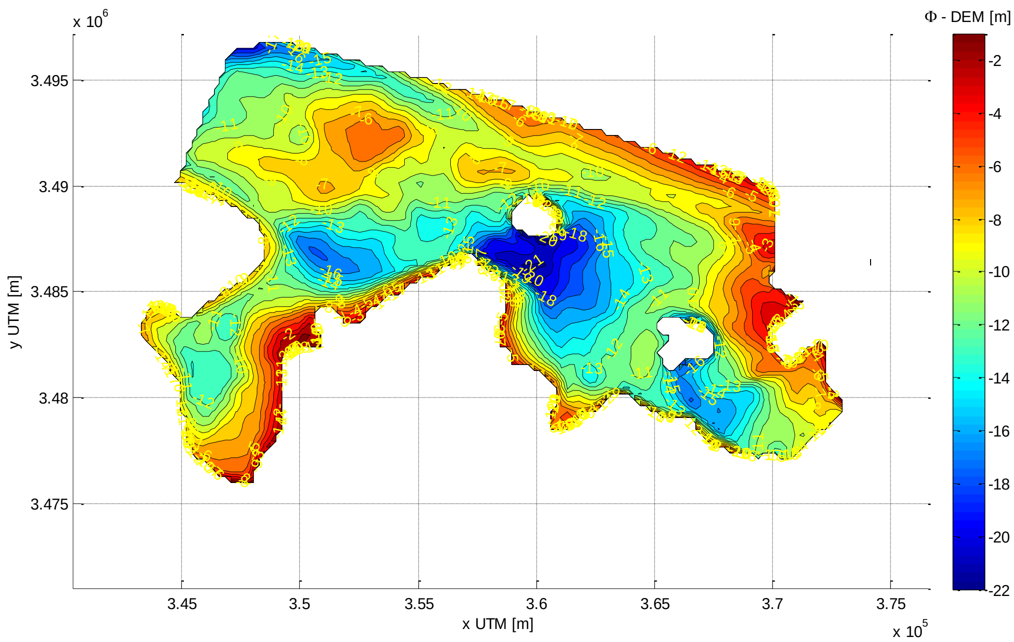


Figure 74: The modelled groundwater level with respect to surface level of the current situation.

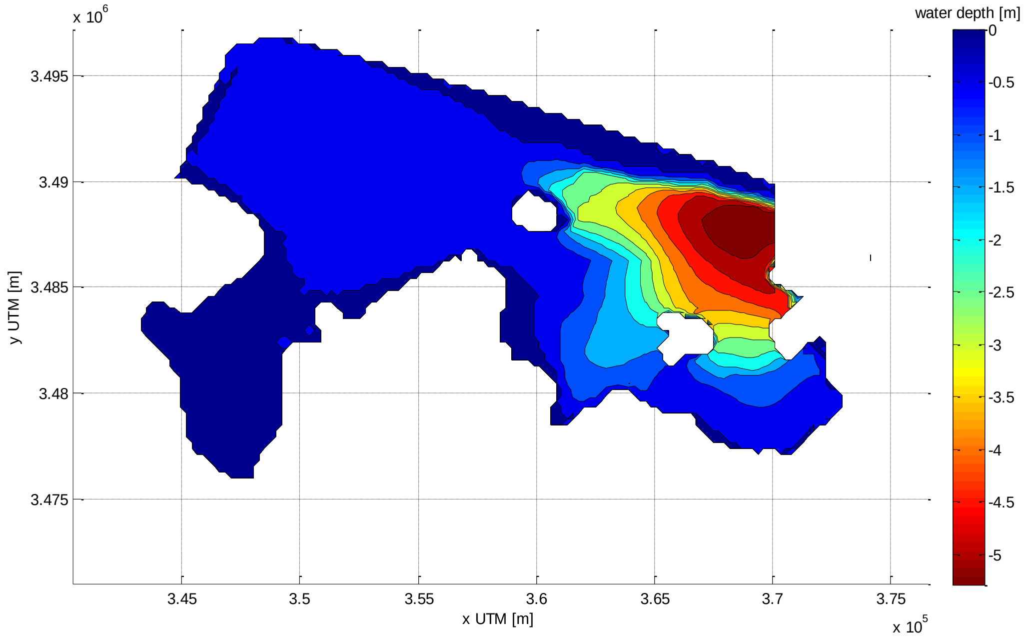


Figure 75: The differences in modelled groundwater level between the current situation and situation after the introduction of khettaras.

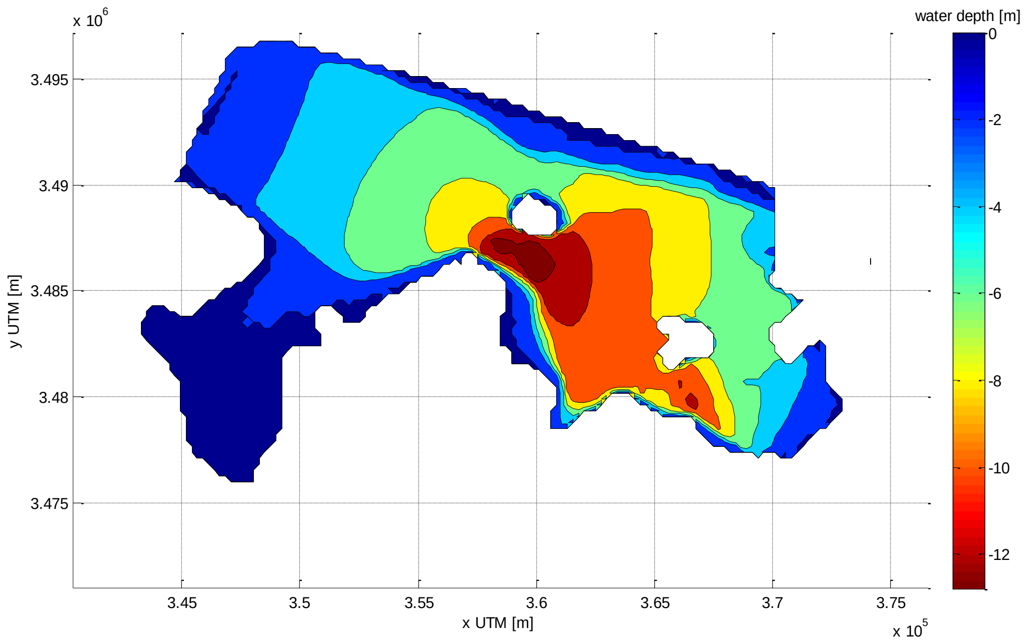


Figure 76: The differences in modelled groundwater level between the current situation and "natural situation".

6.2 Future threats for sustainable water supply

6.2.1 Increased pumping

From the 1930's, the use of pumping in the agricultural areas of Fezna and Jorf intensified, from zero to 2 Mm^3/y in the nineteen sixties (Ruhard, 1977) growing to 8 Mm^3/y around 2000 (Ouharou, 1998). This trend is likely to continue, especially with the increased use of solar panels providing energy to pumps. As stated by CEDTOD (see section 3.4.1), currently 40 out of 220 pumps in the area of Fezna and Jorf make use of solar energy. More solar energy installations are expected to be used as the government stimulates the use of solar panels through subsidies. These new energy source allow the farmers to extract groundwater whenever the sun is shining, which in arid regions such as the Tafilalet is nearly continuous during daytime, without any other restrictions. This is in contrary to pumps that use fossil energy or electricity, to which costs are related per unit of use. A calculation is done to determine the groundwater volumes that could be pumped with solar energy, which is done through the following formula:

$$V \cdot \rho \cdot g \cdot h = \eta_s \cdot I \cdot (3.6 \cdot 10^6) \cdot \eta_p \cdot A \qquad (6)$$

Through conversion it becomes:

$$V = \frac{\eta_s \cdot I \cdot (3.6 \cdot 10^6) \cdot \eta_p \cdot A}{\rho \cdot g \cdot h} \qquad (7)$$

V = water volume (m^3)
ρ = specific weight (kg/m^3)
g = gravitational acceleration (m/s^2)
h = height (m)
η_s = energy conversion efficiency of the solar panel (-)
I = yearly average daily insolation (kWh/m^2/day)
h_p = energy conversion efficiency of the pump (-)
A = surface of the solar panel (m^2)

Groundwater has to be moved from an average depth of 10 m. The energy conversion efficiency of commercially available solar panels (PV) is about 15% (Energy Independence, n.d.). The yearly average daily insolation equals about 5.5 kWh/m^2/day (see figure 77). The energy conversion efficiency of small pumps as used in the study area is about 70 %. Information from CEDTOD states that each farmer with a solar installation used for pumping has on average 10 panels with an average area of 1.5 m^2. With this information the groundwater volume which can be extracted by solar energy extracted becomes:

$$V = \frac{0.15 \cdot 5.5 \cdot (3.6 \cdot 10^6) \cdot 0.7 \cdot 15}{1000 \cdot 10 \cdot 10} = 312 \text{ m}^3/\text{d}$$

This means that a pump with a capacity of 25 m^3/h can easily operate more than 10 hours. And as there are no costs related to the use of solar energy, they will be used as much as possible.

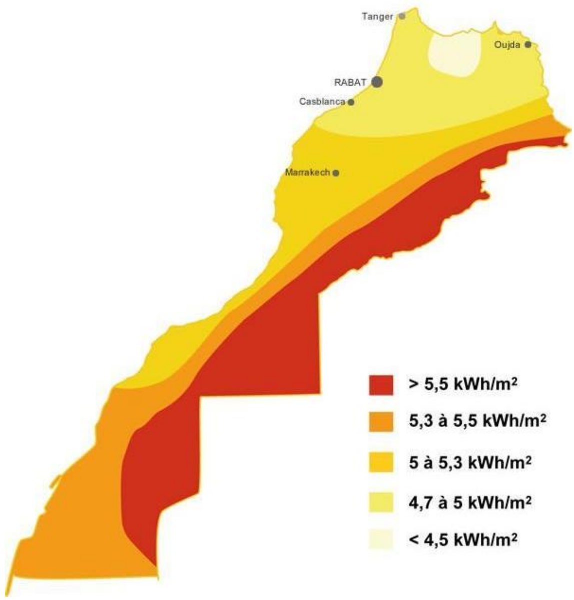


Figure 77: Yearly average daily insolation figures for Morocco (http://www.mctsolaire.ma/qui-sommes-nous/).

This scenario evaluates the impact when the trend of increased pumping is extrapolated. In this situation pumping has doubled from 8 to 16 Mm^3/y. Consequently, the irrigation infiltration increases along with the increase pumping to 9.4 Mm^3/y. The rest of the model is the same as the model of the period 2000-2010.

The model calculated that the increase of pumping is at the expense of the discharge of the khettaras and the groundwater outflow (see table 26). The khettaras discharge about 3.5 Mm^3/y less than in the current situation, because the groundwater level becomes lower than the bottom of several khettaras, especially those of Hannabou (see figure 78). Most of the khettaras of Hannabou stop functioning, while in the current situation eighty percent of them are functioning. Furthermore, the groundwater flow to the downstream areas is almost halved.

The decrease in khettara discharge is mainly caused by the lowering of the groundwater levels, which takes place in almost the entire model area (see figure 79). The most severe lowering up to 10 m occurs within the pumping area.

Nonetheless, the increase in pumping does not seem to create depressions in the groundwater table, a hazard which is stated by Olsthoorn (2013) as a 'vicious trap'. Depressions generate an inward groundwater flow, carrying with it the salt that this groundwater contains. Part of the groundwater evapotranspirates as pure H_2O, while the salt accumulates with each irrigation cycle. In the long run, the groundwater extraction is not sustainable as the salt content of the groundwater will eventually exceed the salinity tolerance of the crops. This process, though, does not occur with the use of khettaras, because they capture their groundwater upstream. The absence of groundwater level depressions in the model could be explained by the following factors:

- The pumping is uniformly over the area, whereas in reality extractions by pumps create point extractions with individual cones of depression.
- The general gradient of the groundwater level in the study area. In more flattened areas, the risk of depressions is higher.
- There is still a significant irrigation infiltration from water supply by floods and khettaras in the agricultural areas, which consequently lowers the net groundwater extraction.

The first reason is analyzed in more detail. Figure 80 and figure 81 show that cones of depression do arise when point extractions of 2 Mm^3/y are introduced, representing a large pumping station or a small area in which many wells are concentrated, instead of an area extraction. The model shows that the maximum drawdown of the groundwater can be more than 10 m.

Table 26: Modelled groundwater balance of the scenario with increased pumping.

Flows	**Period 2000-2010**	**Increased pumping**
	Mm^3/y	Mm^3/y
IN		
Groundwater inflow along outcrop Gara Gfifate	8.1	8.0
Infiltration in the plain	3.5	3.5
Lateral groundwater inflow from Anti-Atlas	0.1	0.2
River inflow	2.0	2.0
Irrigation infiltration	7.0	9.4
Total	*20.7*	*23.1*
OUT		
Groundwater outflow near Krayr	4.6	2.1
Pumping	7.8	15.9
Khettaras	8.3	5.5
Total	*20.7*	*23.5*

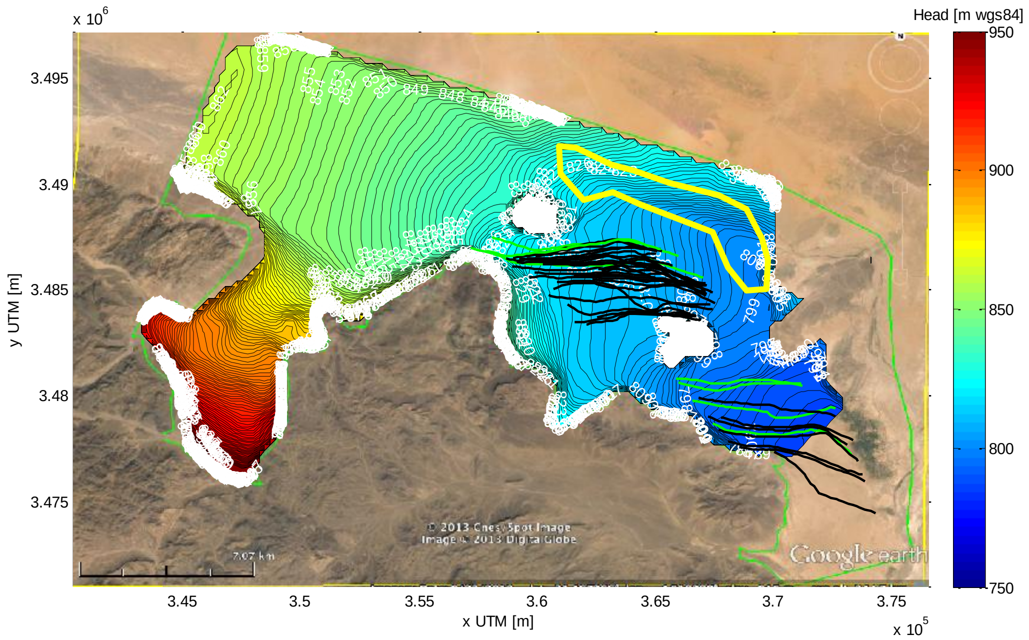


Figure 78: Modelled groundwater level of the scenario with increased pumping, including functioning (green) and not functioning khettaras (black). The yellow line represents the boundary of the pumping area.

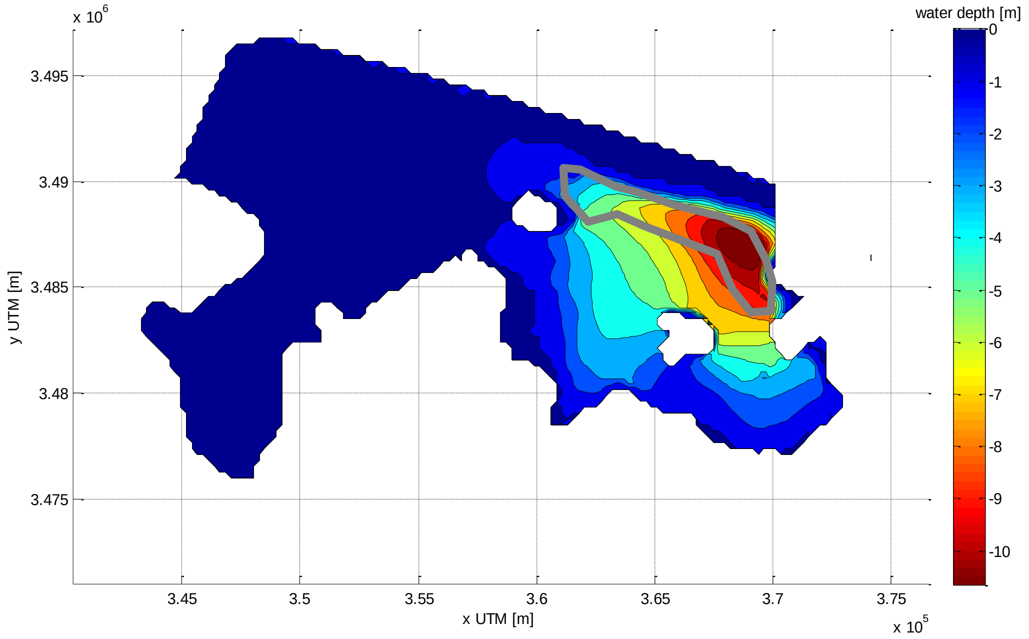


Figure 79: Modelled groundwater level differences of the scenario with increased pumping compared with the current situation. The grey line represents the boundary of the pumping area.

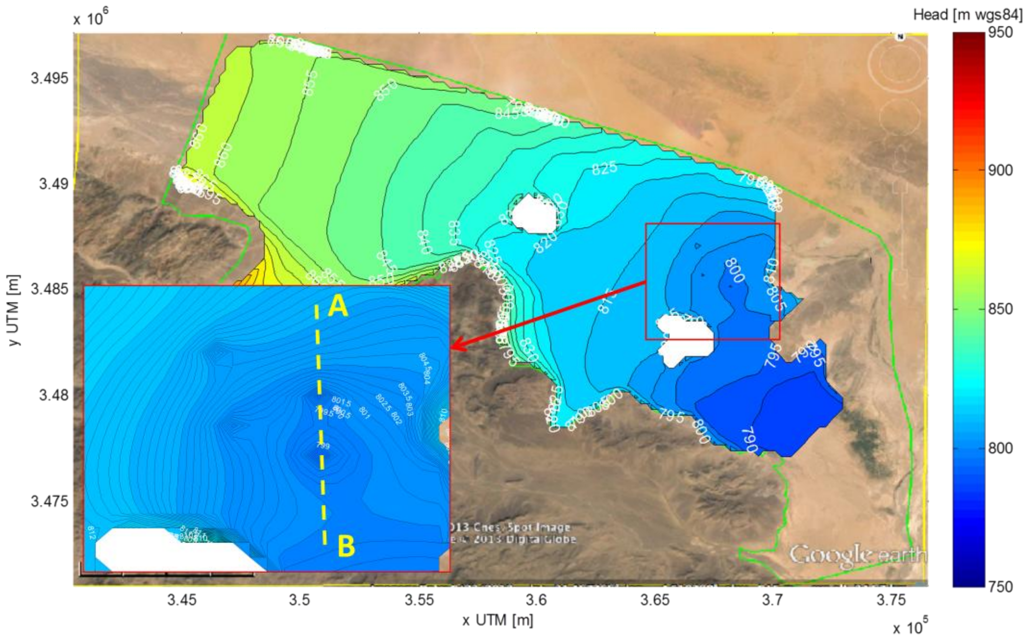


Figure 80: Calculated groundwater level contours in which cones of depression are visible due to extractions by individual pumps. Cross section AB can be seen in figure 81.

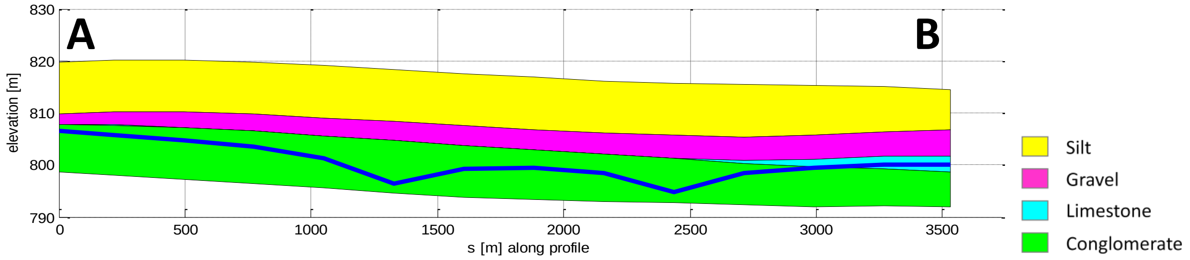


Figure 81: Cross sectional view of the cones of depression in the groundwater table due to pumping of wells. The location of the cross section can be seen in figure 80.

In conclusion, the model shows that the trend of the past half century of lower khettaras discharges and less groundwater outflow will continue when pumping intensifies. Consequently, an expansion of pumping in the agricultural areas is expected to impact the livelihoods of the people depending on local agriculture due to salinization. Salinization of the agricultural areas is a potential risk as cones of depression can arise due to withdraws by pumping stations. Of course, the risk depends on the number, distribution and magnitudes of the extractions.

6.2.2 Drought

Morocco has been facing a noteworthy change in climate the last decades. From the beginning of the twentieth century until 1990, 20 % of the years were dry against 50 % in the last decade of the same century (Karrou, 2006). In the Tafilalet area this continued in the period 2000-2005; this period was characterized low precipitation in 2000/2001 and 2002/2003 (see figure 82). These were tangible in the agricultural activities near Fezna, Jorf and Hannabou as, for example, some khettaras fall completely dry for a short period (Spoerry, 2007). The period 2000-2010, used for the model, was eventually in its totality modest in precipitation, due to the substantially wet circumstances in the last five years.

In the future, Morocco is among the countries that are threatened by climatic change (Karrou, 2002). Temperatures in Morocco will increase combined with a reduction in precipitation: 10 % for the period 2021-2050 and 20 % for the period 2070-2100 (Karrou, 2002). It is assumable that this trend will be accompanied by an increase in frequency and duration of droughts, which may severely threatening for livelyhoods in the arid area of the Tafilalet.

In this scenario, a dry period of ten years is modelled using the precipitation data of 2000-2005 twice in a row. The annual average precipitation of this period is equal to 68 mm (see the aggregated precipitation data in appendix B), which is 40 % less compared to the period of 2000-2010. The recharge from floods in the Anti-Atlas catchments, having precipitation as input, also declines by about 40 %. The other flood-related fluxes in the model are assumed to decrease with the same proportion. These are the infiltration in the oued Rheris and the flood water used for irrigation, which partly infiltrates.

Farmers are expected to mitigate effects of droughts by an increase of pumping amounts. It is assumable that the decrease of flood water and khettara discharge lead to a compensation by more groundwater extraction from wells. A similar situation occurred in the oasis of Ferkla, approximately 60 km west of Jorf. In Ferkla, dry years and an increase in pumping by tube wells led to the degradation of the oasis and destabilizing the local population by also stimulating (Kabiri, 2006). Nevertheless, no adjustments are done to the pumping in this scenario because it is hard to estimate the degree of the increase of this extraction.

The simulated dry period of ten years follows a moderate hydrological period, for which the period of 2000-2010 is used. The final groundwater levels of the latter period are used as initial heads for this scenario.

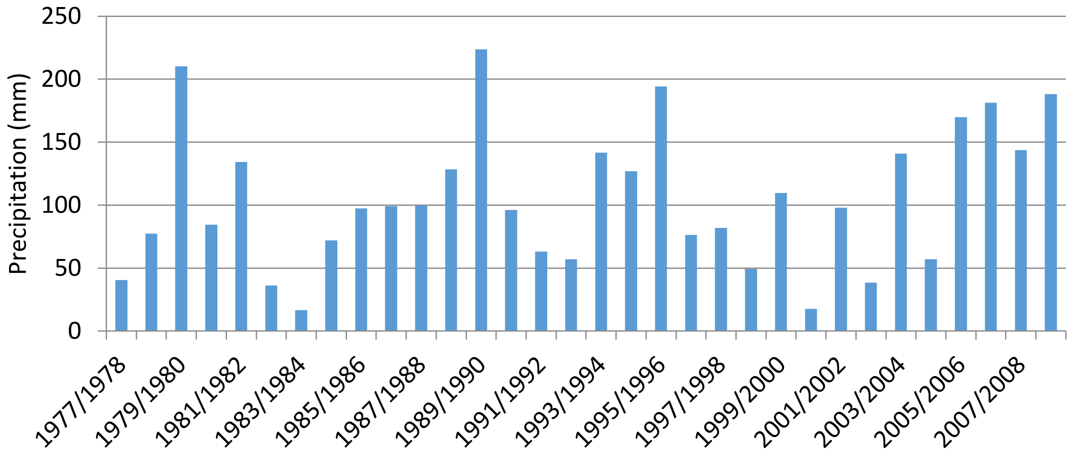


Figure 82: Annual precipitation in Merroutcha, located about 25 km west of the study area. The years run from September until August. It should be noticed that monthly values, which are the base for the annual values, are sporadically missing (see also the data set in appendix B).

The groundwater levels decline throughout the entire model area in this scenario (see figure 83). The most extreme lowering takes place in the agricultural areas near the oued Rheris as well as in the areas receiving flood water from the Anti-Atlas in the southwest. The most upstream and downstream areas are less affected by the changes. This can be easily explained by the fact that the levels of the fixed head boundaries are the same as those used in the period 2000-2010. In reality, they too will lower along with the groundwater levels in the rest of the model area, which will cause the levels in the centre of the model area to decrease even more.

The effects of the groundwater level changes can also affect the discharge of the khettaras (see figure 84). These discharges gradually decline from about 10 Mm^3/y at the start of the dry period to 7 Mm^3/y at the end. However, the actual progress of the khettara discharges is more uncertain as it mainly depends on the transmissivity and the specific yield of the aquifer, for which assumptions are made in this model (see equation 3 in section 5.2.2.2).

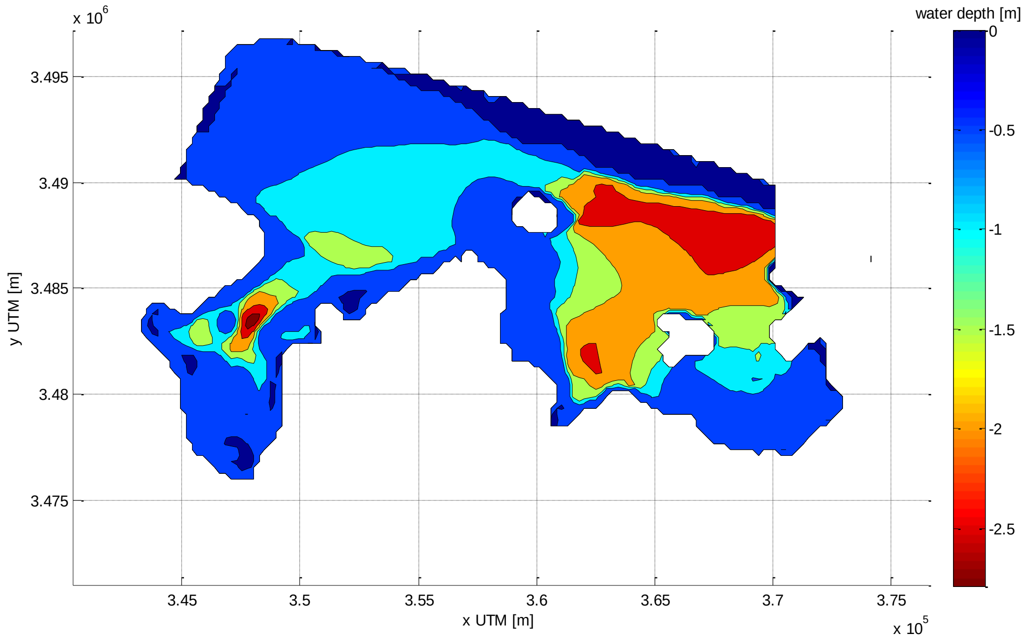


Figure 83: Calculated groundwater difference between the situation before and after the drought.

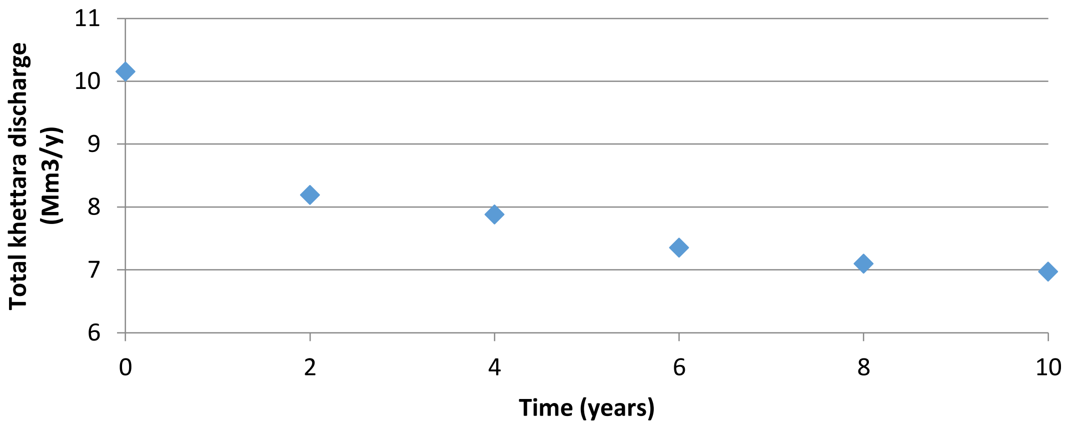


Figure 84: The calculated total khettara discharge in the model area during the entire drought period.

To conclude, the impact of a dry period of ten years is large as the groundwater levels drop in the major part of the model area and the total discharge of the khettaras decreases by 30 %. The effect is even underestimated because consequences of the drought, like the increase of pumping as well as the lowering of the groundwater levels at the upstream and downstream boundary, are not included.

6.3 Preservation of khettaras

In the area of Fezna, Jorf and Hannabou, the groundwater extraction by pumping has substantially increased since the 1930's. Pumping is considered an easy way to obtain fresh water. Pumping enables farmers to irrigate their fields independently of floods and khettaras and requires little time and effort in maintenance. However, this trend is deemed to fail as a long-term solution for the water shortage problem, in contrary to the more traditional not regular regulatable but indefinitely sustainable khettaras.

Pumping easily leads to a general depletion of the groundwater resources because motor pumps can empty the aquifer. Groundwater levels have decreased substantially in the study area since the introduction of motor pumps in the first half of the last century (see figure 15). The modelling results confirm groundwater pumping as a cause of drying up of the khettaras (see section 6.1.3 and 0.1). The dried up khettaras of Fezna forced even more farmers to switch to pumping from wells (Ruhard, 1977).

Other severe effects are visible in the downstream part of the Tafilalet plain where many palm groves are today in a disastrous condition due to a lack of water (Olsthoorn et al., 2013). The pumping in the agricultural areas of Fezna, Jorf and Hannabou is most probably at least partly responsible for this. Groundwater flow to the downstream Tafilalet plain has likely diminished, as is suggested by the simulated scenarios described in section 6.1.3 and 0.

Furthermore, pumping enhances the risk of salinization and is a potential danger for sustaining present agricultural activities. In section 6.2.1 this process is explained in more detail and demonstrated by simulation of point extractions. Salinization with by khettaras, on the other hand, is impossible, because khettaras gain groundwater from upstream of the irrigation fields and, hence, do not create groundwater depressions within the irrigation areas.

Next to hydrological consequences, cultural inheritage of the agricultural areas is affected. The development of privately owned wells changed the interaction between society and the environment fundamentally (Dvoran, 2012); it enabled farmers to irrigate individually and break out of rigid traditional community rule. The tube well irrigation therefore, can be understood as a symbol of individual freedom, with as negative side effect the undermining of social cohesiveness of khettara-based communities.

Also, the khettaras play an important role in the sustainability of the oases, which are ecologically sensitive and of great biological interest due to their confirmed role in the fight against desertification (Benqlilou, 2013).

The scenarios presented in the following sections are meant to show which actions can be taken to preserve khettaras, also against khettara-related threats, and what the consequences are for the groundwater system.

6.3.1 Super khettaras

Emigration of young adults from the Tafilalet has already led to a shortage in labour (De Haas, 2006), with villages like Fezna, Jorf and Hannabou suffering the most. A census carried out in 2004 indicated that 25 % of the population contributes to the labour force, which is far below the national average of 36 % (Spoerry, 2007). This development has severe effects on maintenance in agricultural areas, including khettaras (Benqlilou, 2013).

Emigrants send money to support their families still living in the rural areas. This money is spent on households, building new houses, and in modern agricultural activities: producing quality crops like premium dates and olives (Spoerry, 2007). The latter is often accompanied by the investments in electricity and diesel driven pumps for extracting groundwater from wells. Little money is spent on khettaras, mainly because the maintenance of khettaras is complex, dangerous, labour and time intensive. Cleaning the gallery of the khettara alone, for example, takes about 180 days executed per year, done by four to eight persons (Spoerry, 2007).

An imaginable solution of maintenance of khettaras on the one hand and the overdraft of ever more local pumping on the other, could be the construction of modern khettaras, that combine the capacity of a larger number of old ones, while required maintenance is reduced to almost nil while being sustainable indefinitely. We call these “super khettaras”.

Such modern khettaras will else guarantee a better water quality, which reduces health risk for humans and cattle. Khettaras are known to carry pathogens (Scott, 2009). Increased discharge combined with fewer oppurtinity to enter the tunnel, due to fewer shafts, favors water quality.

At least one modern khettara already was constructed near Marrakech (see figure 85), and functioned without maintenance between about 1928 ans 2003 when it too became victim to overpumping.

In this section two situations are simulated:

- The replacement of the individual khettaras of Jorf and Hannabou, each by a super khettara.
- The implementation of a super khettara upstream of Fezna, while sustaining the individual khettaras of Jorf and Hannabou.

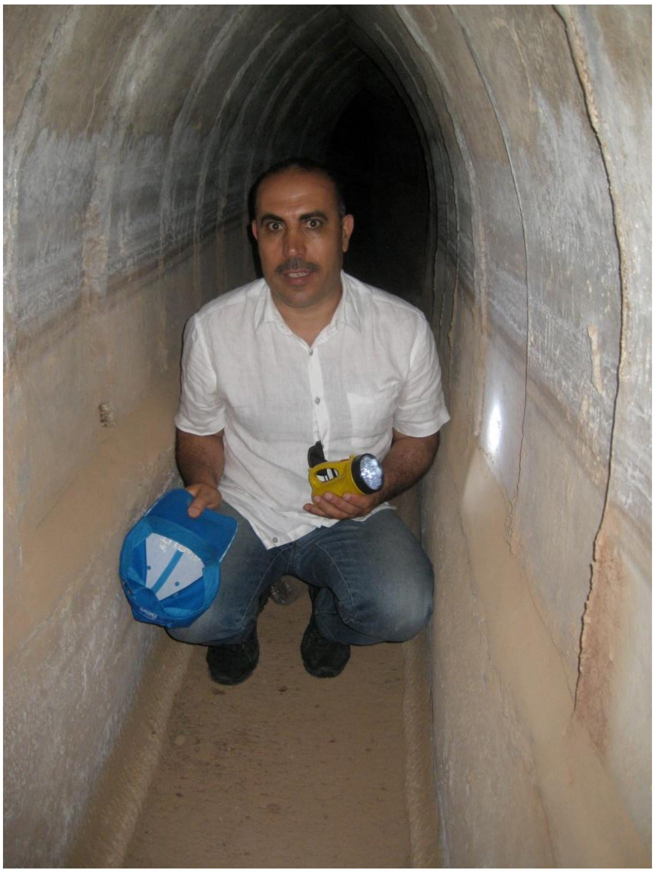


Figure 85: The interior of a modern khettara near the area of Marrakech. It was built by the French around 1928 and became the property of ONEE since it felt dry around 2003.

Super khettaras Jorf & Hannabou

This scenario explores to what extent the khettara groups of Jorf and Hannabou might eventually replace super khettara (see figure 86). The head of the super khettara each have two branches to extract the same amount of water as all of the individual khettara. Their outlets are placed in the agricultural areas as upstream as possible. In this way, they can feed most irrigation areas by gravity. Furthermore, the same slope of 1/5000 is used as with the current khettaras. With this slope, both super khettaras extract from the conglomerate layer (see figure 87).

The dimensions of the khettara drainage tunnel in combination with the water height can be calculated with equation 2 (see section 4.3.3). Concrete is assumed as construction material, which has a Manning's friction coefficient of 0.013. The total discharge of the super khettaras should be about the same as the combined extraction of all individual khettaras: 8-10 Mm^3/y or 250-320 l/s. For each super khettara the expected discharge becomes on average 140 l/s. With a water height of 30 cm in the canal, the canal width becomes about 50 cm, which is a reasonable size (see figure 85).

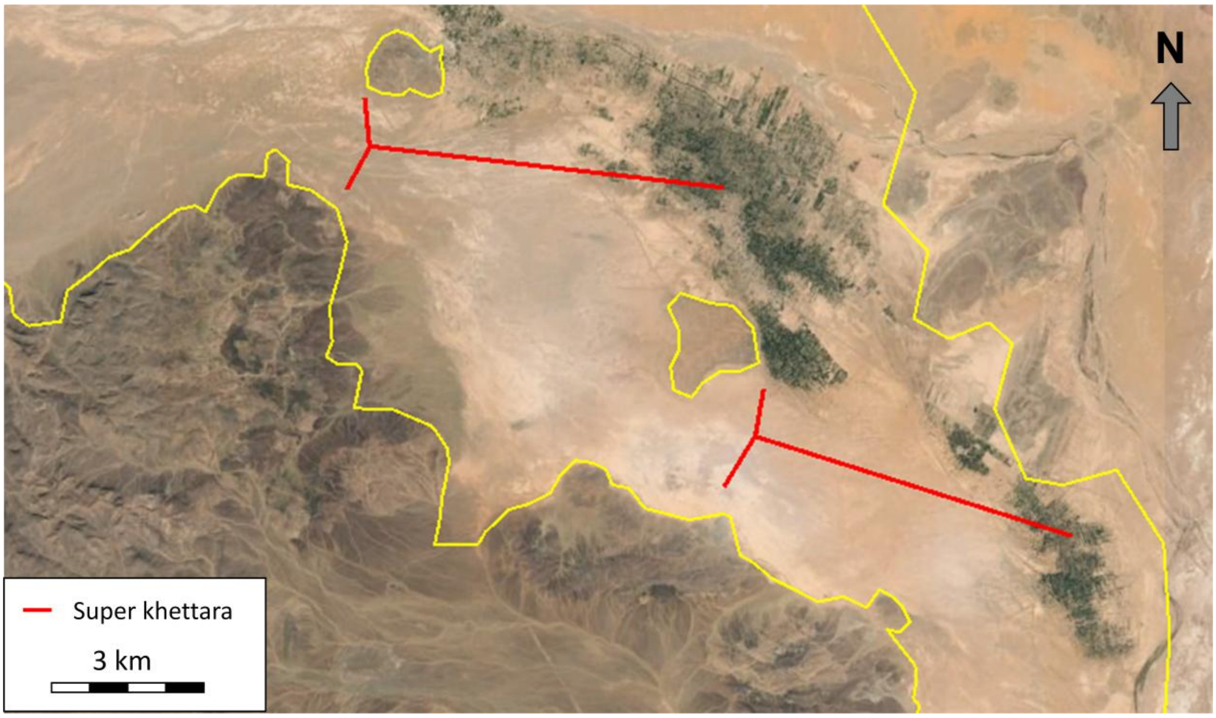


Figure 86: Locations of the super khettaras in the model.

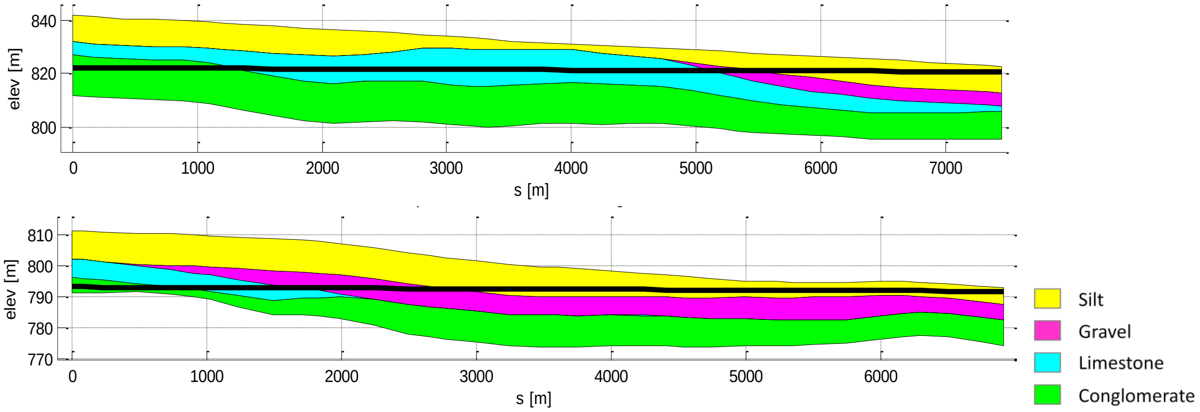


Figure 87: Geological cross section along the super khettaras (black line) of Jorf (up) and Hannabou (down).

The model calculates that the super khettaras extract about the same amount as all current khettaras combined (see table 27). The water budgets hardly changes when current khettaras would be replaced by super khettaras from which we conclude that it should work.

Figure 88 shows that the super khettaras lower the groundwater table near their branches. The super khettara of Jorf is shallow because it is located high in the conglomerate layer (see figure 87), shallower than the current khettaras and, therefore, groundwater levels near the extraction section are higher. The opposite is true for the super khettara of Hannabou. Nevertheless, for the major part of the model area, the groundwater levels are not significantly different.

Table 27: Modelled Groundwater balance of the scenario including super khettaras Jorf & Hannabou.

Flows	**Period 2000-2010**	**Super khettaras Jorf and Hannabou**
	Mm^3/y	Mm^3/y
IN		
Groundwater inflow along outcrop Gara Gfifate	8.1	8.2
Infiltration in the plain	3.5	3.5
Lateral groundwater inflow from Anti-Atlas	0.1	0.2
River inflow	2.0	2.0
Irrigation infiltration	7.0	7.0
Total	*20.7*	*20.9*
OUT		
Groundwater outflow near Krayr	4.6	4.6
Pumping	7.8	7.8
Khettaras	8.3	8.4
Total	*20.7*	*20.8*

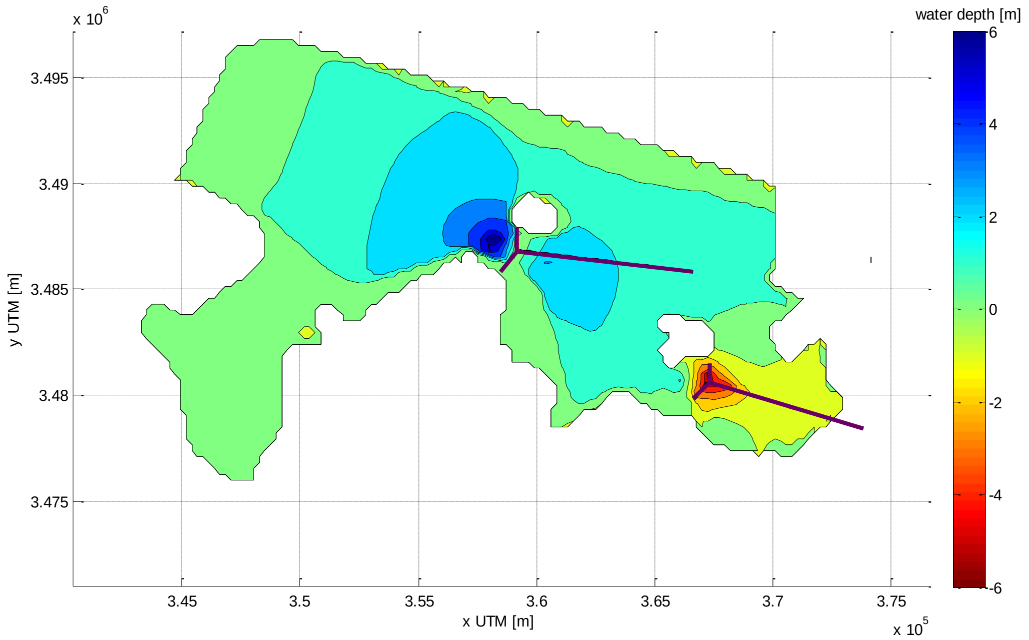


Figure 88: The groundwater level difference of the scenario including the super khettaras compared to the current situation including individual khettaras. The super khettaras are indicated in purple.

It can be concluded that the two super khettaras would supply the same amount of water as the current khettaras. In theory they could replace all current khettaras without a disturbing effect on the groundwater system. With the use of super khettaras less or hardly any maintenance is needed. Of course, the irrigation systems in both Jorf and Hannabou would have to be adapted to connect at one point instead of multiple points.

Super khettara Fezna

This scenario covers the construction of a super khettara upstream of Fezna, while preserving the individual khettaras of Jorf and Hannabou. Because the khettaras of Fezna have been dry since the 1950's, their replacement by a new super khettara might meet fewer objections. The outlet of the projected super khettara is just north of the outcrop of Gara Gfifate, which is the same location as the outlets of the current dry khettaras of Fezna (see figure 89). The upstream branches lie partly below the oued Rheris, north of the former individual khettaras of Fezna. This is done to prevent the 'stealing' of groundwater from the present khettaras of Jorf and Hannabou. Moreover, this super khettara is positioned straight against the slope of the valley and, hence, will reach the conglomerate layer after 4 or 5 km (see figure 90). In this way, the groundwater table is reached, in contrary to the individual khettaras of Fezna. A slope of 1/5000 is used for the gallery of the super khettara, the same as for the other khettaras.

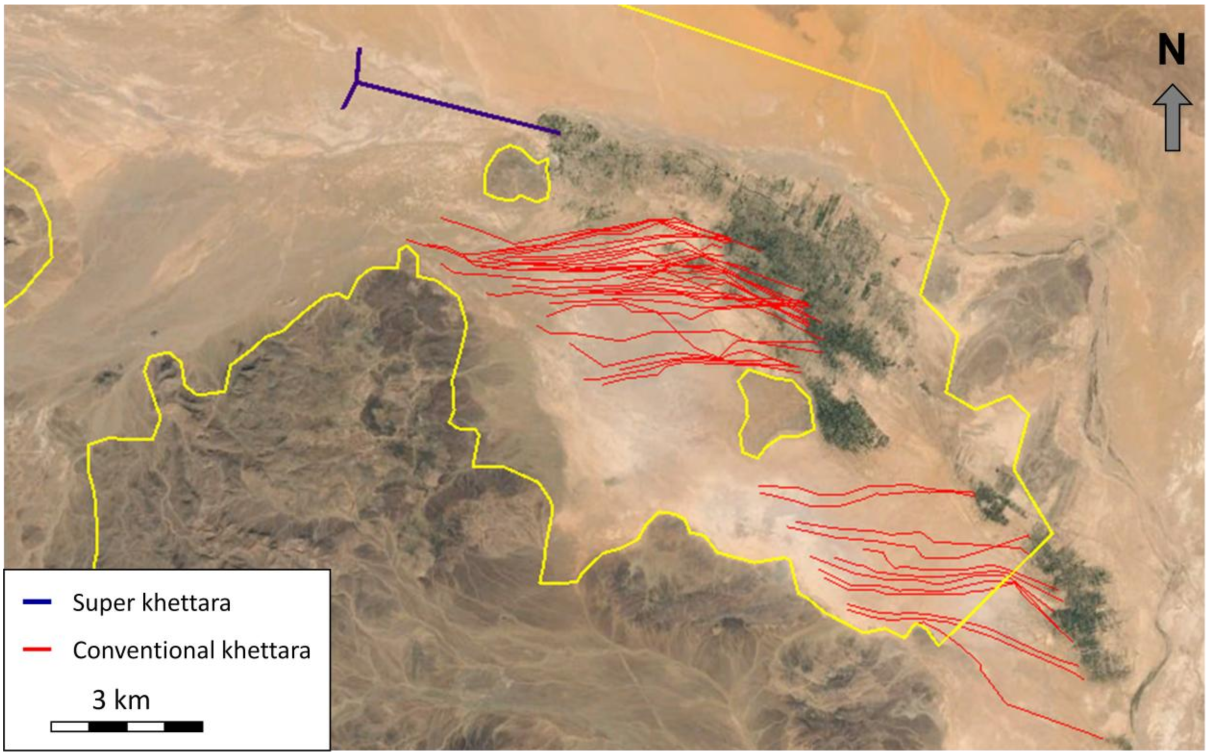


Figure 89: The super khettara of Fezna in addition to the existing individual khettaras of Jorf and Hannabou.

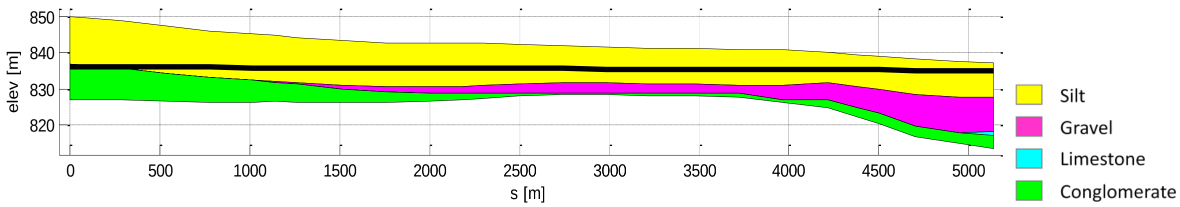


Figure 90: Cross section of the super khettara of Fezna in the model.

With the model it is calculated that the super khettara of Fezna extracts a relative small amount of about 2 Mm^3/y. Table 28 lists the modelled groundwater balance of the area researched by Margat, in which the super khettara of Fezna is not included as it is located more upstream. The combined discharges of the current khettaras of Hannabou and especially those of Jorf would loose 2 Mm^3/y, because the incoming groundwater flow reduced by the same amount. The groundwater levels around the extracting ends of this super khettara would be substantial, also affecting the most upstream khettaras of Jorf (see figure 91).

Table 28: Modelled Groundwater balance of the Margat area after introducing super khettara of Fezna.

Flows	Period 2000-2010	Individual khettaras Jorf & Hannabou + Super khettara Fezna
	Mm^3/y	Mm^3/y
IN		
Groundwater inflow along outcrop Gara Gfifate	8.1	6.1
Infiltration in the plain	3.5	3.5
Lateral groundwater inflow from Anti-Atlas	0.1	0.2
River inflow	2.0	2.0
Irrigation infiltration	7.0	7.0
Total	*20.7*	*18.8*
OUT		
Groundwater outflow near Krayr	4.6	4.6
Pumping	7.8	7.8
Khettaras	8.3	7.0
Jorf	*5.3*	4.3
Hannabou	3.0	2.7
Total	*20.7*	*19.4*

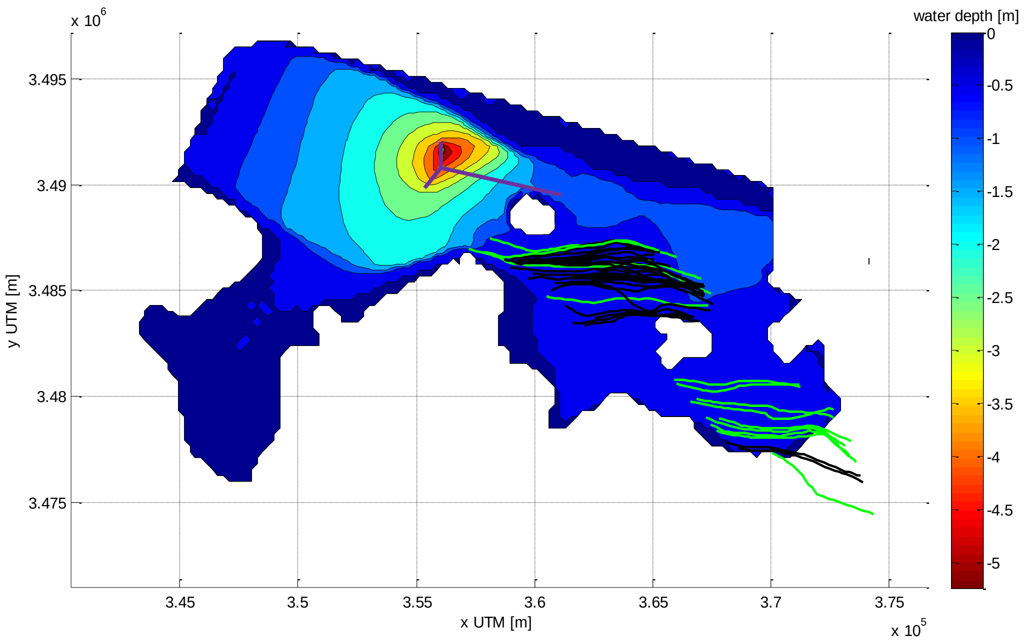


Figure 91: Calculated groundwater level difference after the implementation of the super khettara of Fezna (purple). The functioning individual khettaras are presented in green and the not functioning in black.

To conclude, implementation of a super khettara near Fezna does not seem possible without affecting the yield of the current khettaras of Jorf and Hannabou. The discharges are largely complementary; one khettara gains what the other loses. This impact on existing active khettaras can be mitigated in several ways:

- Part of the water extracted by the super khettara is guided to the agricultural areas with reducted khettara supply.

- Drip irrigation would be applied as it saves roughly 50 % of water and increases the crop yield (more about drip irrigation in sections 6.3.2 and 6.3.3).
- Well pumping in the study area can be reduced. In sections 6.1.3 and 6.2.1 it is shown that the khettaras yield less water when pumping goes up, the opposite is true as well.
- When the recharge is increased near the intake section of the super khettaras. This can be achieved by placing basins which capture flood water.

6.3.2 Drip irrigation

Local farmers in the study area stated that the use of drip irrigation is stimulated by the government through the subsidies of drip irrigation related equipment (see figure 92). However, farmers do not make much use of this arrangement because at the same time it obliges them to register the use of water (anecdotic information from CEDTOD, see section 3.4.1). Nevertheless, the use of drip irrigation has many advantages, such as an increase of crop yield by 15-85 % per unit area (Irrigation Australia, 2013), better weed control and saving water. Compared to surface irrigation, which is the most practiced irrigation technique in the Tafilalet (see figure 93), water conservations of 50-60 % per unit area are achieved (Irrigation Australia, 2013).

Figure 92: Test setup of drip irrigation in the agricultural area of Jorf.

Figure 93: The application of surface irrigation in the area of Jorf, which is the traditional method for irrigation.

Obviously, the combination of khettaras and drip irrigation requires some adaptations to the irrigation system. Basins could be constructed near khettara outlets to store water and generate sufficient pressure for drip irrigation. Vidal-Mbarga (2005) states that the use of small reservoirs is preferable above the use of a central basin for reasons of flexibility. Drip irrigation systems usually require pressures of about 1.25 - 2 bar, (EVMWD, no date) that equals about 12.7 – 20.4 m water column. Small basins are unable to provide this pressure. In addition to such small basins where water can be stored, pressure pumps (or water towers) are required to enable the distribution. Pumps are needed to transport the water to the basins and to water towers. Figure 94 shows a schematization of drip irrigation systems.

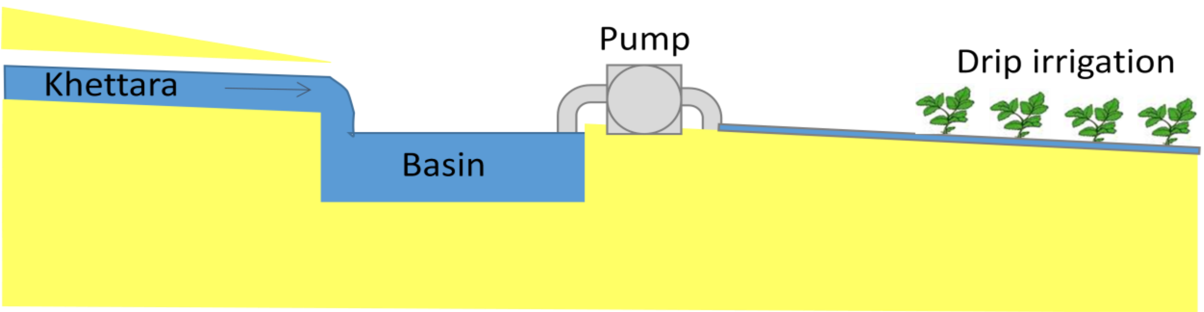


Figure 94: Schematic cross section of the combined use of khettaras and drip irrigation. The pressure is provided by a pump.

In this scenario, drip irrigation is used with water supplied by khettaras and by pumps. It is assumed that no infiltration occurs as a result of drip irrigation, due to the efficiency. Only irrigation water from floods in the oued Rheris infiltrates.

Table 29 shows that the calculated khettara discharge would decrease compared to the current situation. The same is true for the groundwater outflow. Both are caused by the decline in groundwater level (see figure 92), which, in turn, is the consequence of the reduction in total irrigation infiltration.

Table 29: Modelled Groundwater balance of the scenario 'Drip irrigation'.

Flows	**Period 2000-2010**	**Drip irrigation**
IN	Mm^3/y	Mm^3/y
Groundwater inflow along outcrop Gara Gfifate	8.1	7.7
Infiltration in the plain	3.5	3.5
Lateral groundwater inflow from Anti-Atlas	0.1	0.2
River inflow	2.0	2.0
Irrigation infiltration	7.0	3.6
Total	*20.7*	*17.0*
OUT		
Groundwater outflow near Krayr	4.6	2.6
Pumping	7.8	7.8
Khettaras	8.3	6.7
Total	*20.7*	*17.1*

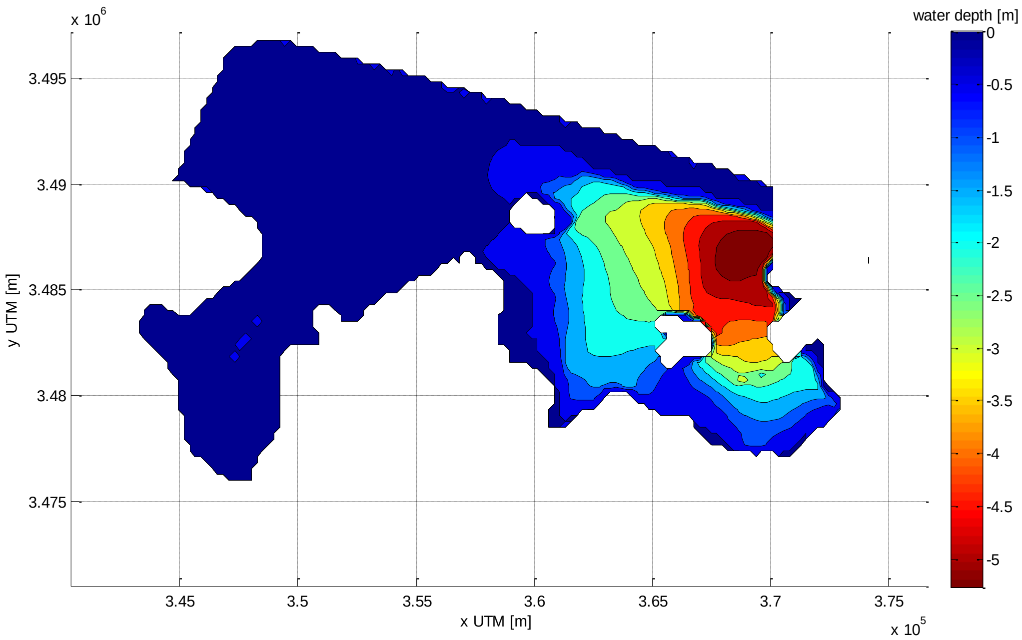


Figure 95: Calculated difference groundwater levels between the use of drip irrigation and the current situation.

Drip irrigation leads to a reduction of the khettara discharges by 25 % as compared to current practice. However, drip irrigation may also be used to expend the irrigated area supplied by khettaras by a factor 0.75×2.0 = 1.5 due to the water saving it provides. And on top of that, a yield increase of on average 50 % leads to a crop production rise by a factor 1.5×1.5 = 2.25 as compared to the current situation. Hence, despite a decrease of khettara discharge, the production would increase when a move to drip irrigation were made. The farmers that make use of pumps achieve an even larger rise in crop production by a factor 2.0×1.5 = 3. The crop production for the entire area increases by a factor 2.6.

6.3.3 No pumping & drip irrigation

Dvoran (2012) states that the combined use of drip irrigation and khettaras may be the most sustainable way of irrigation. The groundwater extraction by the khettaras is currently about the same as the total withdrawal by pumping. By implementing drip irrigation and, hence, saving 50 % of the water, the yield of khettaras would be sufficient to sustain the present agricultural activities, so that pumping in the area could be entirely abandoned.

Another beneficial effect could be the increase of groundwater flow to the downstream Tafilalet plain. As a result, more groundwater would become available and irrigation fields, currently in poor conditions, could be rehabilitated.

The model calculated a significant increase of the total khettara discharge from about 9 to 12 Mm^3 per year (see table 30). The groundwater outflow, however, hardly augments under this scenario and remains about 5 Mm^3/y. Hence, the residual groundwater, which is not extracted by pumping, is eventually still being withdrawn by the khettaras.

Figure 97 shows that the groundwater levels would rise, especially in the northeastern part of the model, at the location where pumping occurred before. As a result, several khettaras, that were dry before, started draining in this scenario (see figure 96).

Table 30: Modelled Groundwater balance of the scenario with the use of drip irrigation and the abandoning of pumping.

Flows	Period 2000-2010	Drip irrigation & no pumping
IN	Mm^3/y	Mm^3/y
Groundwater inflow along outcrop Gara Gfifate	8.1	8.9
Infiltration in the plain	3.5	3.5
Lateral groundwater inflow from Anti-Atlas	0.1	0.2
River inflow	2.0	2.0
Irrigation infiltration	7.0	3.6
Total	*20.7*	*18.2*
OUT		
Groundwater outflow near Krayr	4.6	5.1
Pumping	7.8	-
Khettaras	8.3	12.9
Total	*20.7*	*18.0*

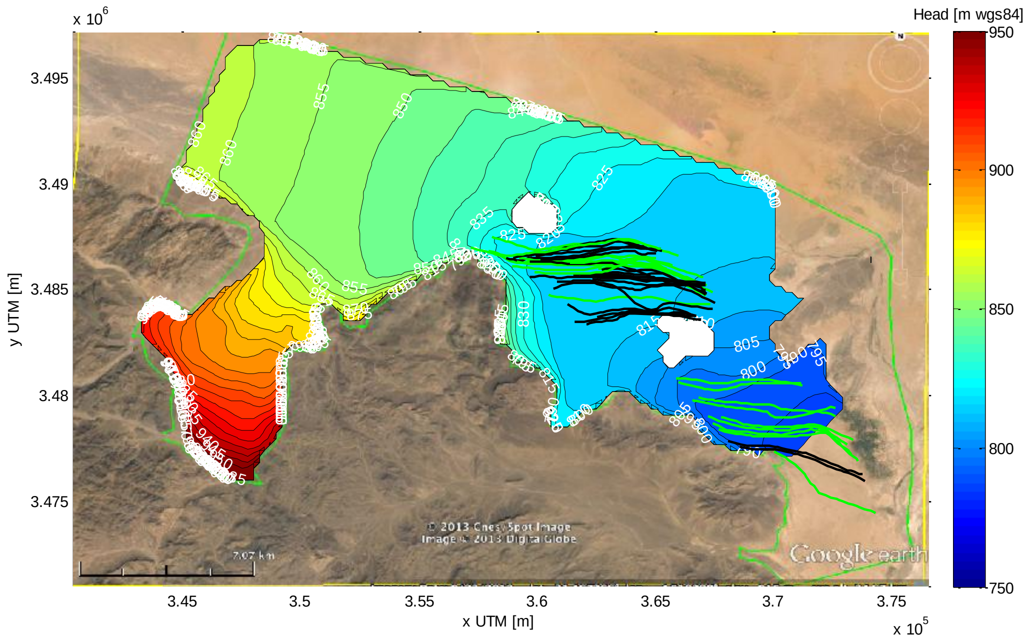


Figure 96: Calculated groundwater levels after the introduction of drip irrigation and abandoning of pumping. The khettaras that function are presented in green and the ones that do not function in black.

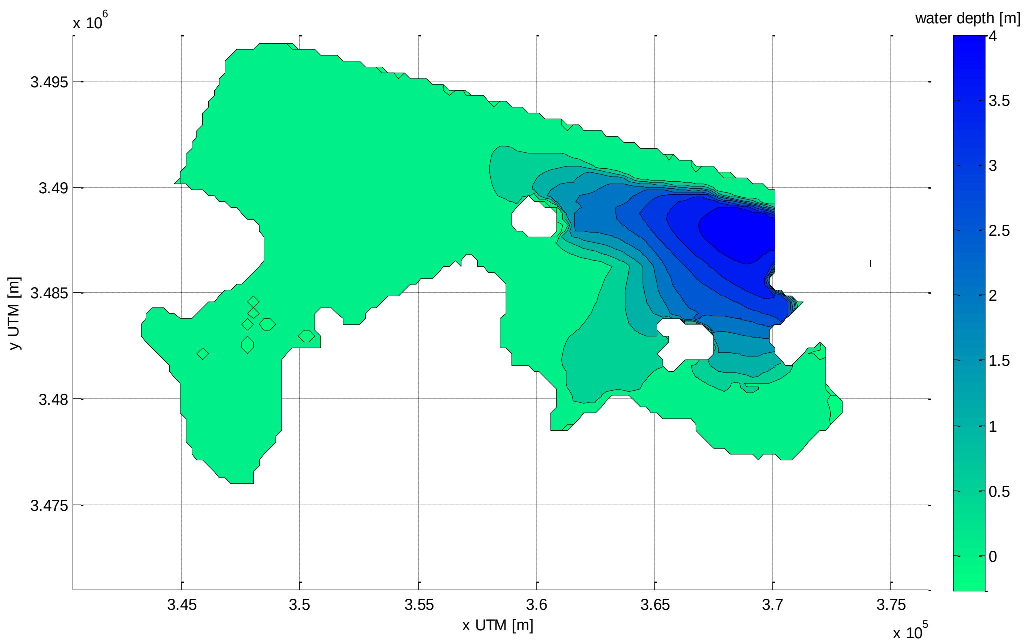


Figure 97: Modelled groundwater level changes after the use of drip irrigation and the banning of pumping.

In conclusion, the introduction of drip irrigation and the abandoning of pumping leads to a significantly higher yield of the currently active khettaras. This enables farmers to extend the agricultural area of Fezna, Jorf and Hannabou by 30 %. By taking into account an average crop yield rise of 50 % and a water saving of 50% per unit area (Irrigation Australia, 2013), the total crop production in this scenario would increase by a factor (12.9/(7.8+8.9))×1.5×2.0 = 2.3 as compared to the current situation.

The irrigation areas in the Tafilalet plain downstream of Hannabou would not benefit because the groundwater flow downstream does not increase in this scenario. Nevertheless, this increase can be realized by shortening of the khettaras (at the upstream side) or the implementation of control valves, which both will lower the khettara discharges. This will be more feasible for the super khettaras which are easier to control.

7 Discussion and Conclusions

7.1 Behaviour of the groundwater system of Fezna-Jorf-Hannabou

To gain a better understanding of the groundwater system of Fezna-Jorf-Hannabou, a numerical groundwater model was set up. Most of the khettaras present in the area were included in the model. Margat (Ruhard, 1977) estimated hydraulic conductivities (see table 31) and flows (see table 32) in his study area (see figure 19). When using Margat's upper limit of 43 m/d for the conglomerate, applied to the period 1959-1969 when Margat did most of his surveys, the model computes groundwater levels upstream Fezna that are above ground surface (see figure 41), groundwater flows across the line south-north through outcrop of Gara Gfifate 45 % lower than estimated by Margat, and a groundwater flow across the line between the Anti-Atlas and the village of Krayr that is only 15 % of Margat's value (see table 12). Four hypotheses were investigated to solve these discrepancies related to: 1) hydraulic conductivity of the conglomerate, 2) river infiltration, 3) wadi flow instead of groundwater flow along the outcrop of Gara Gfifate, 4) irrigation return flow in the agricultural areas.

The first hypothesis is related to the geology of the groundwater system. The aquifer transmissivity is essentially determined by the conglomerates (and where available by gravels). However, the hydraulic conductivity of these conglomerates depends mainly on the degree of cementation, which varies significantly in the area (Ruhard, 1977). Given the sizes of the pebbles, which reach up to 10 cm, the conductivity of conglomerate may easily reach hundreds of m/d, i.e. an order higher than the maximum value of the range given by Margat of 1-43 m/d. If we take into consideration the material found on the hills surrounding the shafts of the khettaras, especially near their water-bearing end (mother wells), we generally observe pebbles without any cementation (see figure 62 and figure 63). From this, we conclude that in many cases the so-called conglomerate is often uncemented. Of course, an unconsolidated pebble layer should not be called conglomerate, however we keep this name to prevent confusion. It is hypothesized that the cementation of the conglomerate may be more dominant towards the northern part of the study region, where more calcium carbonate is present in the water, which in the north generally originates from the High Atlas. In that case, the khettaras, which are located more to the south towards the Anti-Atlas, would extract their water from conglomerate with less cementation. The northern part of the study area was much better investigated by Margat, including the execution of many pumping tests, than the southern part. Therefore, there is room to raise the conglomerate conductivity beyond the maximum value of 43 m/d given by Margat. The calibration of the model indicated an average conglomerate conductivity in the study area of 86 up to 192 m/d, respectively two to four times the maximum value given by Margat (see table 31). Investigation of the cementation of the conglomerate is a strong recommendation for further work.

Table 31: Margat's and own estimations of the hydraulic conductivities of the formations present in the groundwater system of Fezna-Jorf-Hannabou.

Soil type	Hydraulic conductivities	
	Margat's range*	Own estimated range
	m/d	m/d
Silt	0.1 - 1	0.1 - 1
Sand & gravel	90 - 260	90 - 260
Limestone	1 - 43	1 - 43
Conglomerate	1 - 43	86 - 192
Bedrock (schist & sandstone)	Impermeable	

*Ruhard (1977)

Model simulations with and without river infiltration showed that a too large amount of river infiltration may well be a main reason for the groundwater levels above groundwater levels upstream of Fezna computed by the model (see figure 41). This was verified on the one hand by a computation with MODFLOW's River package, that simulates the effects of flow between surface water features and groundwater systems, and on the other hand, by an analytical calculation of the amount of infiltration of river water consistent with the transmissivity and the length and number of the floods occurring per year, with an estimated flood stage of 1 m (see section 5.2.2.2). The resulting river infiltration from the oued Rheris between the entrance of Fezna and the dam of Hmida, where the Rheris leaves the model (see figure 20), equals 133 m^3/m/y or 2.0 Mm^3/y, which is 40 % of the value given by Margat (see table 32). The model gives reasonable results with 133 m^3/m/y infiltration for the entire length of the Rheris (see figure 51).

Wadi patterns in the alluvial fan near Oukhit suggest that during floods large amounts of water run down from the upper catchments in the Anti-Atlas, with a total catchment area of 200 km^2. The model clearly shows that the underground in the passage between the Anti-Atlas and the outcrop of Gara Gfifate is unable to transport large volumes of groundwater (see table 12 and figure 41). The wadi patterns indicate, however, that substantial amounts of flood water go through this passage overland as surface water that infiltrates in the plain between the Anti-Atlas and the villages of Fezna and Jorf. Margat estimated the recharge in this plain to be 2 Mm^3/y. However, the model indicated that this amount is insufficient to feed the khettaras in the plain between the Anti-Atlas and the villages of Fezna and Jorf, or otherwise they cannot yield the measured flows. The model was adapted so that the recharge in the plain was increased by 1.8 Mm^3/y at the cost of 1.5 Mm^3/y less recharge in the plain southwest of the outcrop of Gara Gfifate (see table 15). The resulting recharge in the plain between the Anti-Atlas and the villages of Fezna and Jorf was consequently set to about 3 Mm^3/y, which made the computed total khettaras discharge match the estimated value of Margat (see table 32).

Margat (Ruhard, 1977) estimated that in the 1950s and 1960s on average 12 Mm^3/y flood water was diverted from the oued Rheris for irrigation in the agricultural areas of Fezna and Jorf. With an average infiltration percentage of 30 to 50 %, as derived by Margat from observed groundwater rise of the aquifer in Jorf, the infiltration from irrigation was estimated at 5 Mm^3/y. However, for unknown reasons Margat mentions nowhere irrigation infiltration from khettaras and pumped tube wells. The latter water balance terms are missing in his text as well as in his water balance table (Ruhard, 1977, p393). However, khettaras and wells together supply a substantial volume of 10 Mm^3/y (see table 7). The infiltration from khettaras and pumps is expected to be substantially lower than the 30 to 50 % estimated for the infiltration from floods diversions, because the recharge of the groundwater as return flow from fields irrigated from khettaras and pumps is much more continuous. Irrigation return flow from the khettaras and pumps was therefore fixed in the model at 10 % of their supply, resulting in a total recharge of 6 Mm^3/y. The model, which includes this volume of the irrigation return flow, computed a total khettara discharge matching their measured values (see table 32).

With the model containing the described adaptations, a new water balance was setup for the area studied by Margat (see table 32). Obviously, the values contain an uncertainty band around them which could not exactly be defined in this research. The same is true for the values derived by Margat. However, the model generates a balance that is at least consistent.

Table 32: Computed groundwater balance of the groundwater system of Fezna-Jorf-Hannabou for the period 1959-1969, compared to the estimates done by Margat based on his surveys in the nineteen fifties and sixties.

Flows	Margat (Ruhard, 1977)	Modelled 1959-1969
IN	Mm^3/y	Mm^3/y
Groundwater inflow along outcrop Gara Gfifate	16	**7.4**
Infiltration in the plain	2	**2.8**
Lateral groundwater inflow from the Anti-Atlas		**0.1**
River inflow Fezna-Jorf	5	**2.0**
Irrigation infiltration Fezna-Jorf	5	**6.0**
Total	*28*	***18.3***
OUT		
Groundwater outflow near Krayr	11	**4.6**
Pumping	2	**2.0**
Khettaras	12	**11.7**
Drainage in the Rheris and evaporation	3	**-**
Total	*28*	***18.3***

Simultaneously to the period 1959-1969, the model was also calibrated on more recent data of the period 2000-2010. Table 33 shows the water balance of the period 2000-2010. The precipitation in both periods hardly differ with 101 mm for the period 1959-1969 and 111 mm for the period 2000-2010, but they differ substantially in the amounts extracted by pumps and khettaras.

Table 33: Computed groundwater balance of the groundwater system of Fezna-Jorf-Hannabou for the period 2000-2010, compared to the estimates done by Ourahou (1998).

Flows	Ourahou (1998)	Modelled 2000-2010
IN	Mm^3/y	Mm^3/y
Groundwater inflow along outcrop Gara Gfifate	12.2	**8.1**
Infiltration in the plain	-	**3.5**
Lateral groundwater inflow from Anti-Atlas	-	**0.1**
River inflow Fezna-Jorf	2.2	**2.0**
Irrigation infiltration Fezna-Jorf	11	**7.0**
Total	*25.4*	***20.7***
OUT		
Groundwater outflow near Krayr	11	**4.6**
Pumping	8	**7.8**
Khettaras	3.7	**8.3**
Drainage in the Rheris and evaporation	2.7	**-**
Total	*25.4*	***20.7***

7.2 Scenarios

Various past and future scenarios were evaluated using the model for the period 2000-2010. Although the uncertainties, discussed in section 7.1, do not allow conclusions that are too firm, the results are nevertheless expected to give a fair and physically correct indication of the impact on the groundwater system of the changes, covered by the scenarios.

In the natural situation, before any human intervention, the groundwater levels in the Tafilalet were shallow and probably supported an extended natural oasis (Lightfoot, 1996). The model supports this idea as it computes shallow groundwater levels in this natural scenario (see figure 70). However, the model required permanent drainage to keep the water table at or below ground surface over an extended area (see “Drainage Rheris” in table 23). Whether the Rheris actually drained continuously is not certain; the subsurface water may also have evaporated and evaportranspired. Nevertheless, abundance of surface water seems unlikely, because khettaras were apparently needed for permanent irrigation. Anyway, the people started construction of khettaras in the Tafilalet in the 14th century (Lightfood, 1996). Groundwater withdrawal by khettaras, however sustainable, does lower the water table, and will have had negative effect on the natural vegetation, in the benefit of crop production. The model makes this effect visible (see figure 73). From the 14th century or at least from the period that the number of khettaras reached its current value, the groundwater situation was more or less stable. Khettaras cannot deplete an aquifer, as they only extract what actually available and renewed. This situation was completely disrupted when motor-driven pumps were introduced, first by the French in the 1930s and later by farmers using private pumps from the 1960s, when pumping became extensive (Ruhard, 1977; Lightfoot, 1996). Currently, the agricultural areas of Fezna and Jorf houses about 224 pumps, (ORMVA, 2006). The model shows that the groundwater levels were lowered by more than 6 m compared to the situation without pumping (see Figure 75). This pumping caused the discharges of various khettara to decline and a substantial number of them to dry up, which inter alia happened to all the khettaras of Fezna in the 1950s (Ruhard, 1977).

Current groundwater pumps are predominantly powered by diesel or electricity. More and more farmers, however, switch to solar panels to drive their pumps. Already 40 of the 224 wells are equipped with solar panels, often having about 8 to 20 panels of 1.5 m^2 (CEDTOD, see section 3.4.1).

This trend is expected to continue due to subsidies for solar panels. As electricity is free once the panels are installed, these farmers have the tendency to let their wells pump continuously whenever the sun shines. Consequently, the overall amount of groundwater pumped increases, and will continue to do so. The model shows that in case the pumping in the area doubles from 8 to 16 Mm^3/y, groundwater tables will decline further will cause the remaining khettaras to yield about 35 % less compared to in the period 2000-2010 (see figure 79 and table 26).

Pumping in contrast with gravity-drained khettaras easily deplete available groundwater. This includes the volumes accumulated slowly over long periods. Natural restoration of aquifers once emptied may take hundreds to thousands of years in arid areas. Next to this, pumping by means of tube wells occurs in the agricultural areas that surround the villages, in contrast to khettaras, which always have their intake upstream. The concentrated extraction by pumping causes inward groundwater flow from all sides, as this extraction tends to form a depression cone in the water table. Part of the irrigated water returns to the aquifer as irrigation return flow and is subsequently pumped and used again. The attracted groundwater contains salt, for which there is no escape, so that the salt in the agricultural areas accumulates with each pumping cycle, until it can no longer be used for crop production. In case of the irrigation areas of Fezna and Jorf, the model shows that salinization by pumping is to some extent mitigated by the natural gradient, which allows some groundwater to escape from the crop areas (see Figure 78 in section 6.2.1). At the same time, fresh flood water diverted from the oued Rheris may flush the groundwater, including the salt that it contains. Nevertheless, the model indicates that depressions may occur with highly concentrated pump extraction equal to 2 Mm^3/y (see figure 80 and figure 81) with rising salt concentrations as its consequence.

Sustaining the khettaras is also becoming more difficult for lack of available labour, as a consequence of socio-economic changes with people, especially the young ones, migrating to urban areas (De Haas, 2006; Spoerry, 2007). Moreover, work inside khettaras is increasingly considered to be complex, dangerous, labour and time intensive, especially in relation to jobs in cities (Spoerry, 2007). Therefore, the combination of sustainable use of groundwater and modern technologies was investigated. So-called super khettaras were proposed in this study. It is not intended to replace the existing the khettaras by them, but to explore their possibilities. Such a super khettara could potentially combine the capacity of multiple traditional khettaras and, therefore, save hundreds of kilometres of khettara galleries and their maintenance. In this scenario the khettaras of Jorf were replaced by one super khettaras, and the same was done to those of Hannabou (see section 6.3.1). It turned out that each of these super khettaras is indeed capable of providing the combined flow of the existing active khettaras (see table 27). Also, a super khettara near the location of the old khettaras of Fezna, which became dry in the 1950s, was examined. This super khettara also enables large amounts of groundwater extraction. However, this would go at the expense of the yield of the current khettaras of Jorf and Hannabou (see table 28). Nevertheless, this side effect could be undone when pumping is reduced, thus making more groundwater available for the khettaras.

Drip irrigation is likely to be used more and more as it can raise crop production by 15-85 % using 50-60 % less water per unit area (Irrigation Australia, 2013). Moreover, drip irrigation is promoted by subsidies. Therefore, it seemed useful to explore the possible consequences of extended drip irrigation on the groundwater system. The model showed that drip irrigation will cause water tables to decline due to the reduction of irrigation return flow. This results in a decrease of the discharges of the khettaras. Nevertheless, using the figures above (Irrigation Australia, 2013), crop production may still rise in the agricultural areas of Fezna and Jorf by a factor 2.6 compared to the current situation.

Dvoran (2012) states that drip irrigation combined with the khettaras might be the most preferable irrigation method. Drip irrigation may allow to stop pumping while keeping sufficient irrigation water from the khettaras alone. The model shows that even with a complete stop of pumping and a complete transition to drip irrigation, the khettaras would yield 50 % more water than in the period 2000-2010 (see table 30). When considering the figures related to drip irrigation (Irrigation Australia, 2013), it was calculated that when using only khettaras, it should be possible to increase the crop production in the area of Fezna and Jorf by a factor 2.3 compared to the current situation.

8 Recommendations

In order to improve the concept of the groundwater system of Fezna-Jorf-Hannabou, this chapter contains recommendations related to the following aspects:

1. Reports of Margat
2. Geological structure and water table
3. Cementation of the conglomerate
4. Groundwater fluctuations
5. Pumping
6. Khettaras
7. Floods in the plain and oued Rheris
8. Flood water diversion for irrigation

Regarding sustainable water resource management, recommendations are given related to:

9. Combination of khettaras and drip irrigation
10. Solar energy driven pumps
11. Modern khettaras
12. Recharge dam (seuil)

1.

The original data of Margat from measurements, like pumping tests, were not available during this study. Instead, the extended summaries in Ruhard (1977) were used. Margat's original reports, however, are expected to be of great value for any research with respect to the water resources in the study area. According to Margat (oral communication, Marrakech October 2013), he let one copy of his work at the ministry, one in the Agence Hydraulique du Bassin GZR (see section 3.4.1), while he also keeps one copy at his home. It is strongly recommended to collect a copy of all of his original reports, scan it and keep it available, preferably on a public website like that of a university. It is also recommended to ask Margat's permission to scan his original reports at his home, to make sure the set of information and data will be complete.

2.

The elevation of the bedrock, depth of the conglomerate and gravel layer as wells as the depth of the water table requires extended mapping, because they are unknown throughout the plains between the Anti-Atlas and the villages, except for the locations investigated by Margat. The latter are located within and around the villages of Fezna, Jorf and Hannabou. It is recommended to map these quantities geophysically, for which the following methods are considered most suitable MRS (Magnetic Resonance Sounding), GPR (Ground-Penetrating Radar), TDEM (Time-Domain Electromagnetics) and Seismic Refraction.

It is recommended to focus on (see figure 98):

- The plain upstream of Fezna between the village of Touroug and the outcrop of Gara Gfifate, along the oued Rheris.
- The plain between the Anti-Atlas and the villages of Fezna, Jorf and Bouia.
- The passage between the Anti-Atlas and the outcrop Gara Gfifate.
- The passage between the Anti-Atlas and the outcrop Monkara.
- The line used as model boundary upstream (see figure 24).

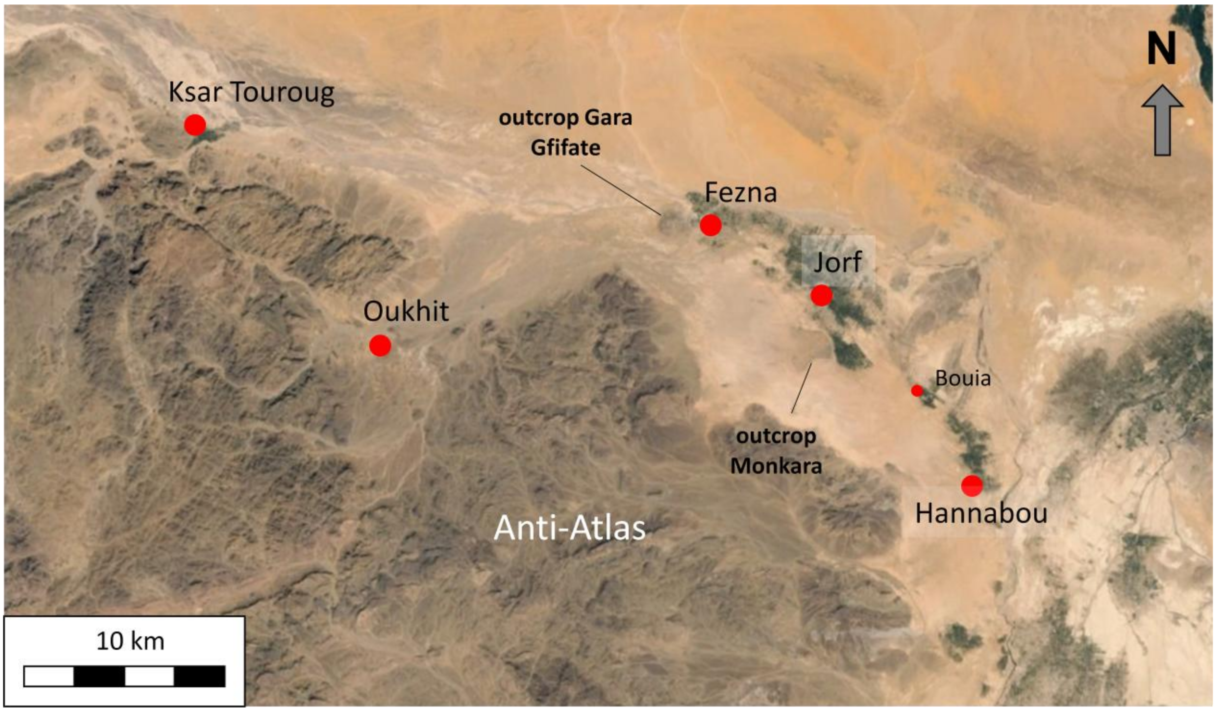


Figure 98: Map of the study area.

3.

It is recommended to investigate the degree of cementation of the conglomerate throughout the area. This degree of cementation is highly uncertain, yet very important, because the cementation largely determines the hydraulic conductivity of the conglomerate, which may reach up to hundreds of m/d. Hence, it plays a crucial role in the amounts of groundwater transported through the aquifer. The degree of cementation of the conglomerate may be investigated through MRS geophysics as mentioned above. The second method could be through inspection of the conglomerate that is dug up and dropped around the shaft hills of the khettaras. Additionally, one may inspect the material of the interior of the upstream section of the khettara tunnel by taking pictures.

4.

It is recommended to record the fluctuation of the water table apart from its absolute level. These data give much information on the groundwater dynamics, including recharge. Therefore, it is recommended to install groundwater loggers at several locations, both in the agricultural areas and in the plains, so as to record the groundwater pattern especially after floods. It is recommended to focus on the following locations (see figure 98):

- The irrigation areas around the villages of Fezna, Jorf and Hannabou (including Bouia and Krayr). Existing piezometers are 1028/57, 3628/57, 3630/57, 1029/57, 1031/57.
- Along the route of the oued Rheris at both sides. Upstream of Fezna two open wells may be used, which are located just south of the road R702 (lat: 31.52886, lon: -4.482327; lat: 31.521917, lon: -4.541167).
- The alluvial fan near the village of Oukhit.

- The plain between the Anti-Atlas and Fezna, Jorf and Hannabou. To measure the water table here, it may be possible to hand drill shallow holes at the bottom of the khettara tunnels in order to easily reach the groundwater level below these tunnels (see figure 99).

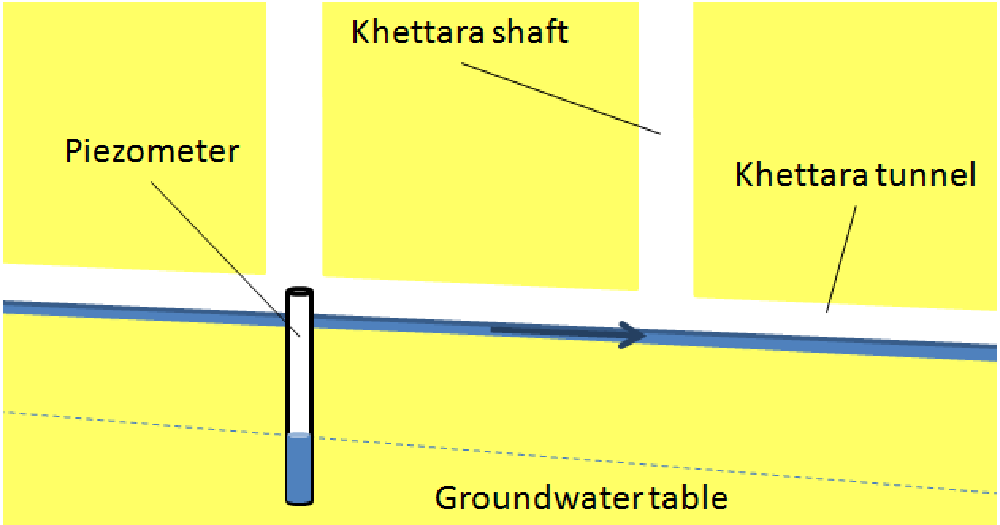


Figure 99: Schematization of a setting of a piezometer within a khettara tunnel.

5.
It is recommended to map the distribution of pumped wells, their capacities and their pumping regime in the agricultural areas around Fezna, Jorf and Hannabou. Representatives of local communities may be best to collect this information. Attention should also be given to upcoming crop areas such as near the village of Oukhit (see figure 98), which is a potential threat for the groundwater resources of the traditional irrigation areas.

6.
It is recommended to better investigate the khettara network and the tunnel elevations. This information is still relatively uncertain as not all khettaras could be fully traced on Google Earth or Google Maps, especially the khettaras of Jorf. It is recommended to more regularly measure the discharge of individual khettaras to obtain their behaviour as function of winter and summer, dry and wet periods and long-term trend as a result of climate change, droughts and by pumping within or outside the study area.

7.
It is recommended to record the occurrence, the duration and the stage of floods both in the oued Rheris and in the plain between the Anti-Atlas and the villages of Fezna and Jorf (oued Batha). These flood characteristics may enable a fair estimate of flood infiltration.

8.
It is recommended to record the water quantities diverted from the oued Rheris during floods to the irrigation fields via the small dams of Kfifet, Sidi Majbar, El Gara and H'mida. One may install vertical meter rulers in the irrigation canals from which water heights can be read. Also farmers may be interviewed with respect to the amount of water they receive from the irrigation network.

9.
It is recommended to further investigate the consequences, positive and negative, of the combined use of khettaras and drip irrigation.

10.
It is recommended to create awareness on also the consequences of groundwater pumping driven by solar energy. It may be an idea to connect the solar panels to the electricity network in order to make money, which could reduce the incentive to extensively use groundwater pumps.

11.
It is recommended to research the exact construction of the modern khettara near Marrakech, which was constructed by the French in the 1920s and is currently owned by ONEE. Relevant information might be: its discharge, the geological and hydrological setting, the construction and used materials as well as the required maintenance. It is recommended to investigate the possibilities to increase the recharge by capturing and infiltrating Rheris flood water upstream Fezna (see Olsthoorn et al., 2013), possibly in combination with the design and possible future construction of a super khettara west of Fezna.

12.
It is recommended to register the groundwater level variations both upstream, downstream and away from the small dam (sieul) constructed in 2013 by the Agence Hydraulique du Bassin GZR in the plain near the Anti-Atlas (lat: 31.427827, lon: -4.394470). Groundwater fluctuation will help to obtain a more reliable picture of the recharge of the aquifer.

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Appendices

Appendix A: Geological time scales and figures on geological evolution

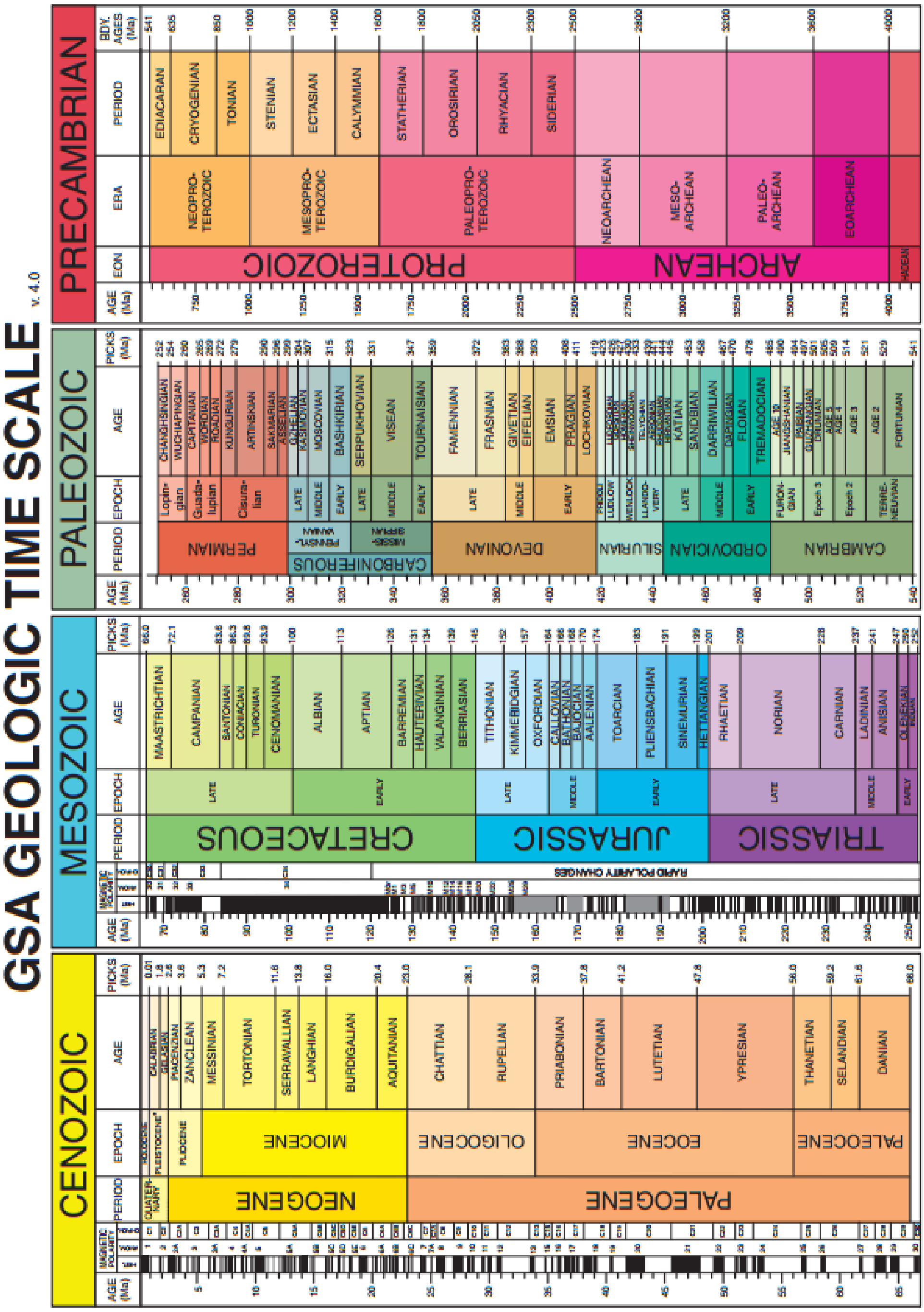


Figure 100: Geological time scale (the geological society of America: http://www.geosociety.org/science/timescale/timescl.pdf).

LES VERTÉBRÉS FOSSILES DU MAROC ATLANTIQUE, CENTRAL ET ORIENTAL DU QUATERNAIRE

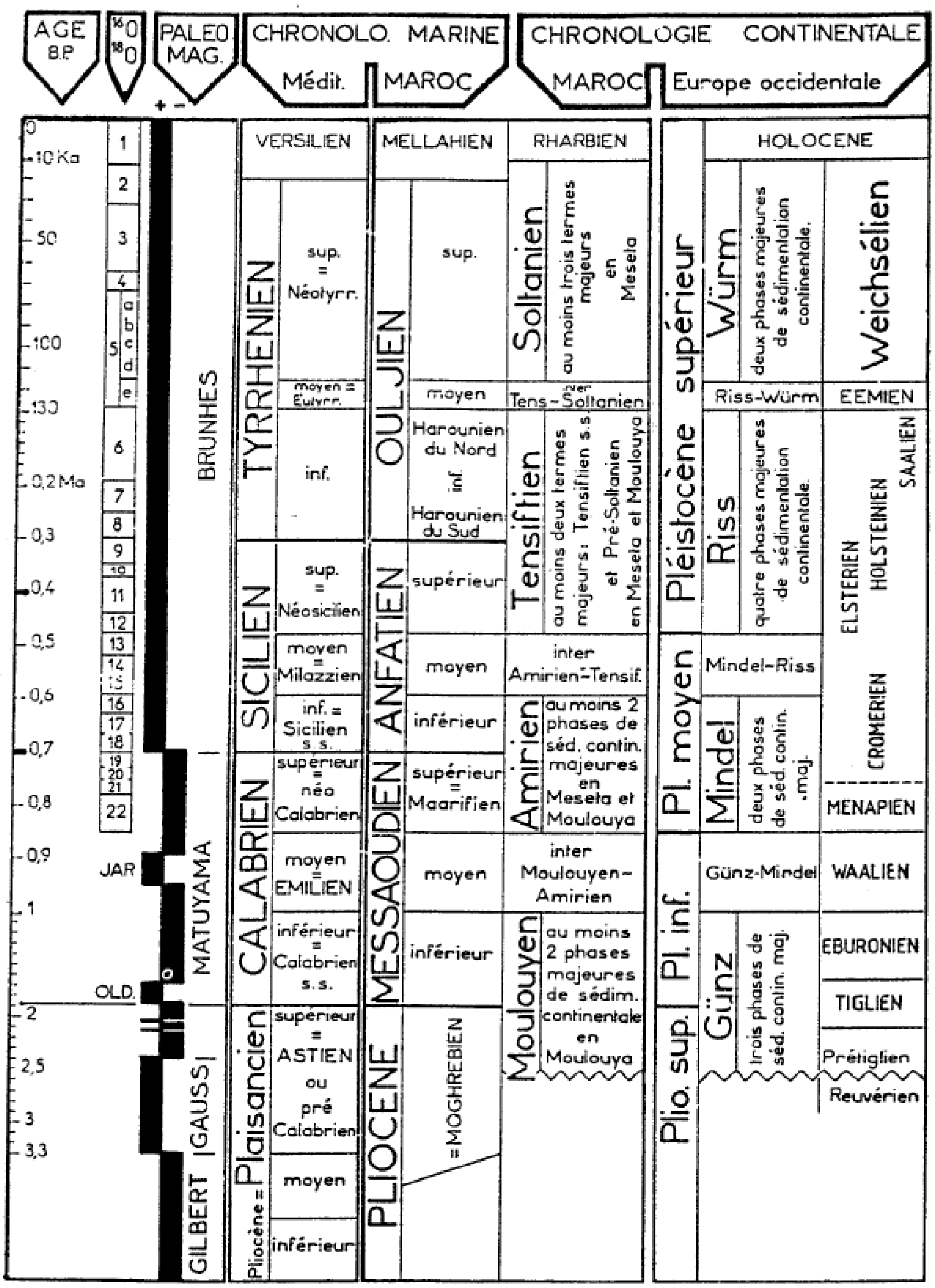


Figure 101: Geological time scales including Moroccan standards (Michel, 1992). The Moulouyen period corresponds with the end of the Pliocene and the Lower Pleistocene, the Amirien period with the Middle Pleistocene and the Tensifitien and Soltanien period with the Upper Pleistocene.

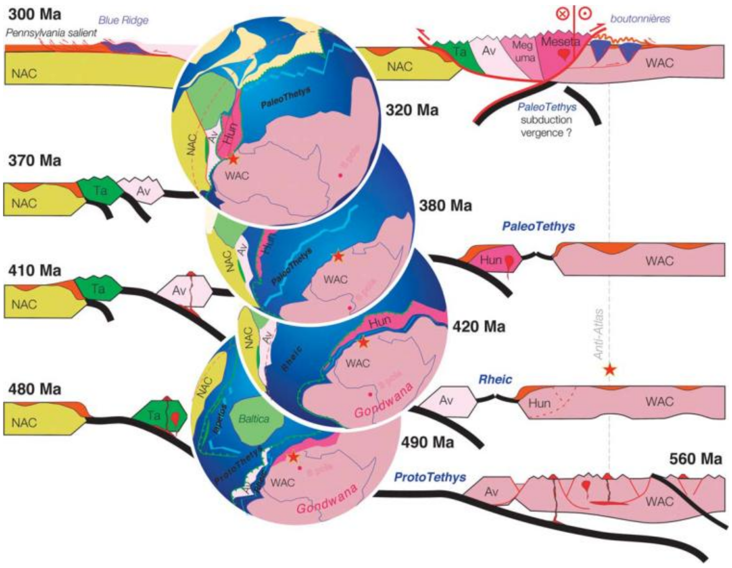


Figure 102: Schematic visualisation of evolution of the Anti-Atlas (right) and Appalachian chain (left) (Burkhard et al., 2006).

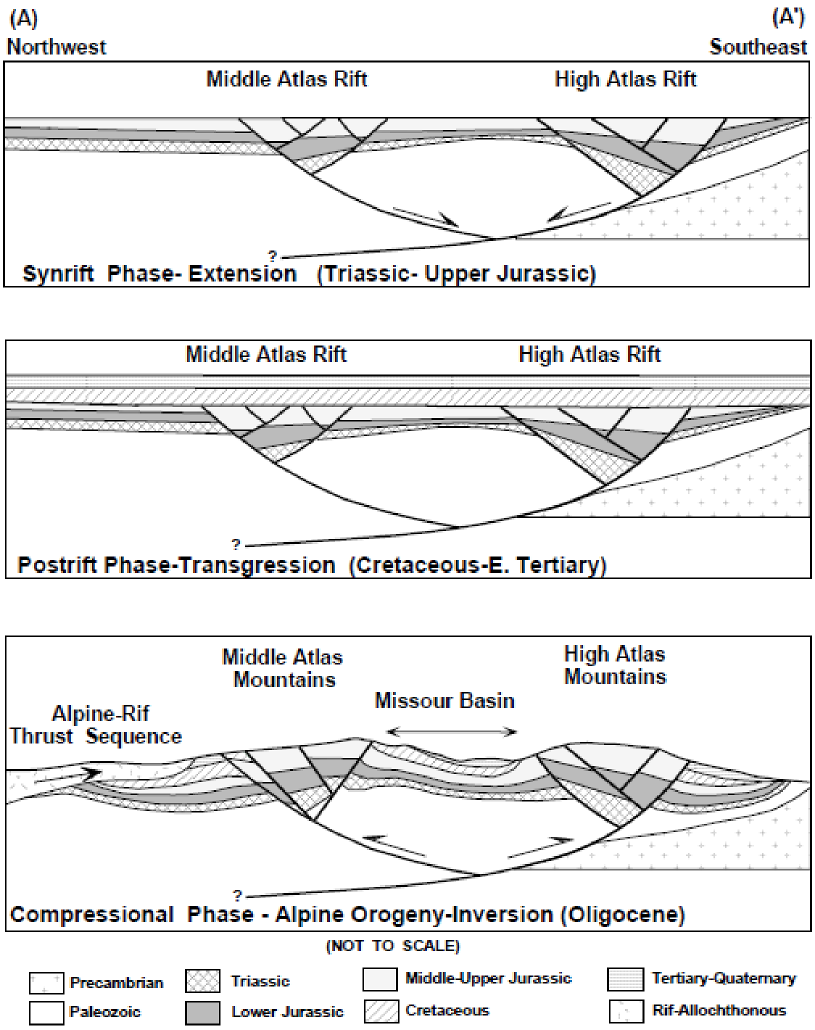


Figure 103: Conceptual model of the evolution of the Middle and High Atlas Mountains (Beauchamp et al., 1996).

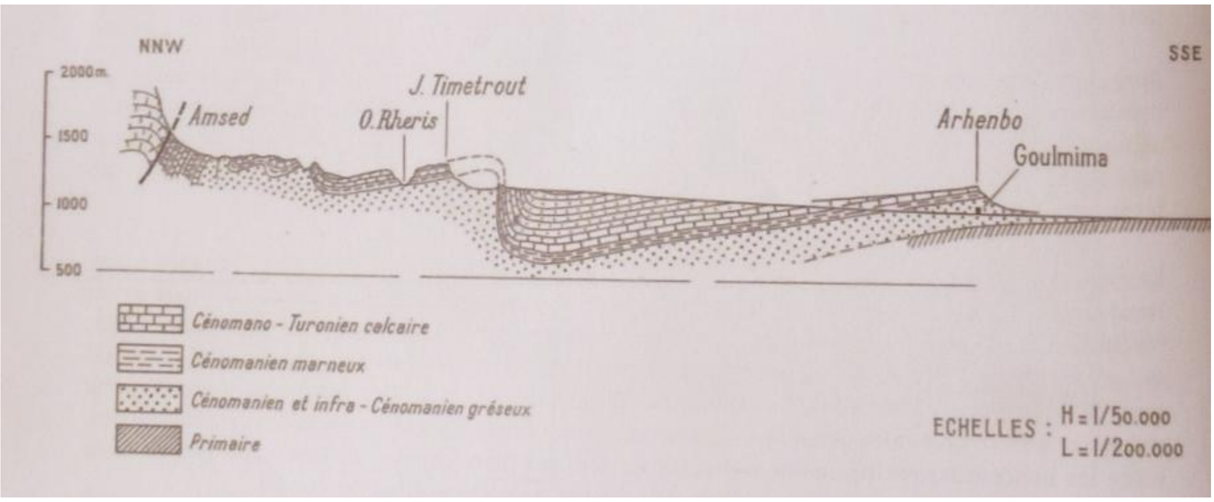


Figure 104: Geological transverse cross section of the Hamada system (Cretaceous basin), from the High Atlas (left) in the direction of the Anti-Atlas (right) (Margat, 2012). The layers in the legend are (from top to bottom): Cenomanien – Turonien limestone, Cenomanien marl, Cenomanien and Lower Cenomanien sandstone, and primary Paleozoic bedrock. More information on the geological periods can be found in figure 100 and figure 101 in this appendix).

Appendix B: Precipitation data

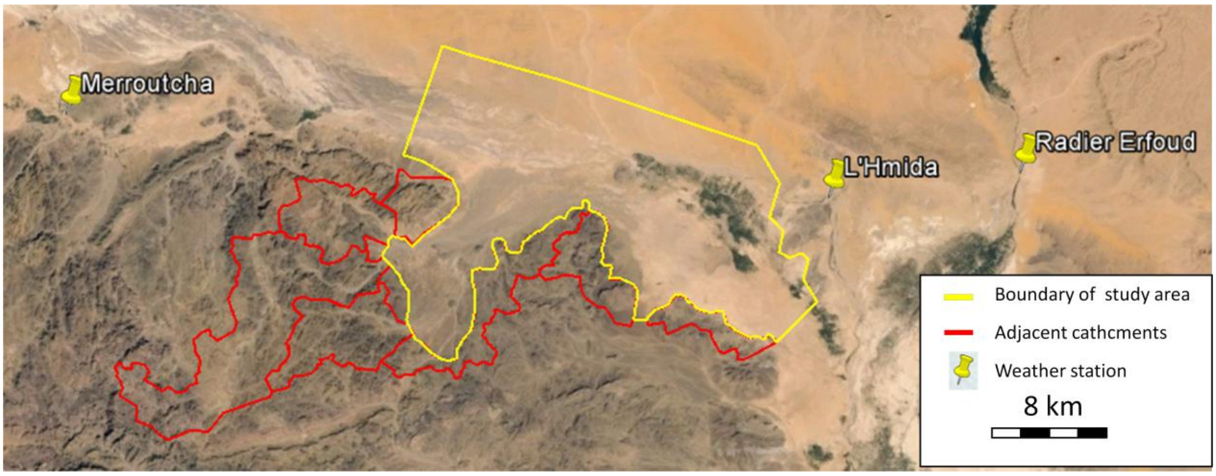


Figure 105: Locations of the observation stations in the vicinity of the model area.

Table 34: Monthly precipitation data measured in Radier Erfoud (Source : L'Agence du bassin Hydraulique du Guir-Ziz-Rheris). *precipitation not available.

Year	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
1957/1958	2.8	10.6	10.1	21.2	6.5	8.6	*	0	0.4	3.4	*	*
1958/1959	*	*	1.6	6.5	*	5.1	39	*	9	*	*	0.4
1959/1960	1.3	38	*	*	7	0	19.2	17	1.5	28	8	0
1960/1961	0	0	0	8.5	0	2	0	7	1.5	1.5	0	0
1961/1962	0	2.5	14	1.5	0	5.5	27	0	2	9.5	0	0
1962/1963	16	0	16.5	13.5	12	0.5	2.5	8.5	13.5	5.5	2	0
1963/1964	3.5	0	0	4	2.5	0	0	2	1.5	*	*	*
1964/1965	6	0	2.5	10.5	29.3	56	4.5	17.8	0	0	0	0
1965/1966	7.5	33.8	*	*	*	*	*	*	*	*	*	*
1967/1968	9.5	24.3	53.8	*	*	20.2	*	13.7	4.7	2.6	0.3	0.3
1968/1969	*	*	3	10.4	8.4	22.8	3.2	3.2	6.1	4.8	0.8	15.8
1969/1970	6.3	*	5	1.8	9.9	0	12.7	0.3	*	0	0	2
1970/1971	2.1	6.1	*	15.6	0.2	4.8	1.7	52.8	0	0	0	0
1971/1972	12.3	1.4	10.3	8.5	0.3	9.1	2.7	26.8	3.1	0	0	0
1972/1973	6.5	10	60.3	17.3	0	0	1.2	12.8	0	9.6	0	4.1
1973/1974	0	0	27.2	5.2	0	0	15.5	5.8	2.3	0	0	1.2
1974/1975	25.8	0	20.3	2.5	0	0	0	67.3	25.2	0	1.5	0
1975/1976	6.9	0	0.8	5.2	4	7.5	7.7	2.5	21.8	3.8	0	0
1976/1977	8.1	0.3	0	34.3	17.1	*	0	5.1	1.4	0	0	0
1977/1978	1.6	4.5	5.4	3.5	24.6	0.9	0	0.2	0	0	0	4.1
1978/1979	3.5	0	0	1.3	107.8	0	0.4	0	0	2.7	0	0
1979/1980	7.7	71.7	0.6	0	7.1	4.5	19.3	21.4	1.4	0	0	0
1980/1981	0.6	0	3.5	28.5	0.5	6.7	0	1.7	0	0.8	0	0.1
1981/1982	0.4	0	2.8	0	28.6	5.6	0	43.4	3.6	0	0	0
1982/1983	0.5	0.2	10	0.5	0	2.9	0.5	0	15.7	0	0	6.4
1983/1984	5	0.5	0	0	2.9	0	0	0	1.1	1.2	0	0
1984/1985	2	0.3	27.4	0	17.1	25.1	*	0.9	13.9	0	0	0
1985/1986	51.5	1.2	3	31.4	12.6	5.8	0.2	0	1.2	*	0	2
1986/1987	11.2	11.9	*	0	1.2	0	7.1	0	15.6	4.3	0	0

1987/1988	3.6	0	13.6	3.2	8.5	27	3	0	2.9	1	0	0
1988/1989	0.5	3.8	24.7	0	6.8	4.5	3.1	5.2	0	6.6	0	14.2
1989/1990	9.9	30.3	18.3	32.5	0.9	0	1.3	7.6	6.6	*	5.7	*
1990/1991	9.2	1	0	7.6	0	12.9	3.5	8	*	9.5	0	2.2
1991/1992	0.6	3.8	0	3.1	0	3.8	*	*	2.5	0	*	0
1992/1993	0	0	4.8	11.9	5.5	7.6	1.9	*	*	0	0	*
1993/1994	3.5	4.1	8.3	0.3	27.8	0.6	0.7	*	0	*	0	*
1994/1995	0.5	36.9	1.5	0	0	0	12.9	11.9	0	*	*	*
1995/1996	0.3	14.9	0.2	7.6	3.6	17	13.3	1.7	0.6	14.2	14	0
1996/1997	0	0.6	0	3.5	8.3	0	6.9	14.6	0.3	0	*	2.1
1997/1998	4.1	0	0	0	2.1	18.6	*	0.6	0	0	*	1
1998/1999	2.6	0	0	2	4.8	2.9	*	0	0.8	*	*	1.4
1999/2000	0.7	3.6	0.3	0.6	0	0	0	1.7	22.3	*	0	*
2000/2001	*	4	0.5	3.9	0	0	0	1	2.1	0	0	0.2
2001/2002	*	10.5	*	1.4	0	*	13.1	7.2	4.8	0	0	1.2
2002/2003	6.3	*	7	*	0	7.1	1.2	2	*	0.4	0.5	1.7
2003/2004	4.4	13.1	3.6	0	0	6.8	0	1.8	6.6	*	*	1.2
2004/2005	3.2	1.2	2.3	7	0	6.3	1.1	0	*	2.7	2.1	0
2005/2006	0.3	3.1	4	0.7	24.8	6.2	0	0.3	11.4	0	1.4	0
2006/2007	19.7	5.9	16.9	4.1	6.3	7.4	0	20.5	0	0	7.4	7.9
2007/2008	*	19.2	1 3,8	0	0	35.2	*	0.3	4	2	0	*
2008/2009	8.8	77.8	17.2	15.2	13.9	4	45.1	0.7	0.3	2.2	*	*
2009/2010	26.4	0.0	0.0	1.4	21.8	15.3	3.7	1.5	*	0	16.7	6.4
2010/2011	4.9	6.4	0.0	0.0	*	*	*	*	*	*	*	*

Table 35: Monthly precipitation data measured in L'Hmida (Source : L'Agence du bassin Hydraulique du Guir-Ziz-Rheris). *precipitation not available.

Year	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**
1977/1978	10.2	1.7	1.2	2.5	36.8	0	0	0	0	0	0	0
1978/1979	0	0	0	2.5	91.9	0	0	0	0	2.9	0	0
1979/1980	3.6	89.1	0	0	11.7	4.9	12.7	20.6	2.4	0	0	0.6
1980/1981	2.7	0.2	8.6	29.6	0.5	9.9	0	5	0.3	3.7	0.2	0.3
1981/1982	2	0	3.4	0	24.7	5.3	0	55	18.6	0	0	0
1982/1983	0	0	16.6	2.2	0	1	0	0	18	0	1.5	5
1983/1984	8	1.4	0	0	1.3	0	0	0	5	0	0	0
1984/1985	0.5	2.2	21	0	20	19.4	*	3.5	12.4	0	0	0
1985/1986	25.3	3.6	2.3	17.8	14	6.1	1.9	0	*	5.5	0	0
1986/1987	13.6	13.4	0	0	0.3	0	12.8	0	15.4	3.5	0	0
1987/1988	9.2	2.7	13.2	5	9.2	26	0	0	3.1	0	0	0
1988/1989	0.4	6.4	8.2	0	0	10	0	3.9	0	13.5	0	18
1989/1990	17.9	37.9	37.7	23.5	0.4	0	1.2	40	25.7	0	0	0
1990/1991	6	0	0	11.1	0	9.5	5.2	12.9	2	4.5	0	3
1991/1992	3.5	0	0	4.9	0	8	0	0	5.1	0	0	0
1992/1993	0	0	0	24.9	8.4	12.7	*	0	0	0	0	0
1993/1994	0	4.2	28	0	56.2	2.6	0	0	0	0	0	0
1994/1995	*	8.8	5.7	0	0	0	25.8	*	0	0	*	0
1995/1996	0	32.8	0	8.8	15.8	30.6	4.3	*	*	*	*	*
1996/1997	*	*	*	*	*	*	*	*	*	*	*	*
1997/1998	*	*	*	*	*	*	*	*	*	*	*	*
1998/1999	*	*	*	*	*	*	*	*	*	*	*	*
1999/2000	*	*	*	*	*	*	*	*	*	*	*	*
2000/2001	*	*	*	*	*	*	*	*	*	*	*	*

2001/2002	*	*	*	*	*	*	*	*	*	*	*	*
2002/2003	*	*	*	*	*	*	*	*	*	*	*	*
2003/2004	*	*	*	*	*	16.1	0	3.5	12	0	0	*
2004/2005	5	0	2.6	5.6	0	13.4	0	0	1	2.1	0	*
2005/2006	7	0	12	0	50.8	20.8	0	2.5	43.3	3.2	20.8	*
2006/2007	46	15	35.5	7.4	13.4	7.4	0	31.1	0	0	0	*
2007/2008	0	20.3	17.8	0	0	35.7	11.5	*	1.5	7.1	2.1	*
2008/2009	22.6	88.6	22.7	10.2	6.1	5.2	48.7	1.5	*	14.3	0	0
2009/2010	33.4	0	0	0	17.9	16	0	0	2.1	0	*	14.8

Table 36: Monthly precipitation data measured in Meroutcha (Source : L'Agence du bassin Hydraulique du Guir-Ziz-Rheris). *precipitation not available.

Year	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
1977/1978	*	*	*	8.3	3.4	*	0	3.2	2	0	0	23.6
1978/1979	0.3	7	0	0.5	62.4	*	2.4	*	0.1	4.7	0	*
1979/1980	25.3	78.9	2.9	0	17.7	28.5	33	21.5	0.8	0	0	1.7
1980/1981	15.3	3.2	14.7	22.9	0	9.7	0	*	2.3	14.4	0.3	1.7
1981/1982	2.2	*	*	0	28.9	1.9	*	58	42.5	0.8	*	*
1982/1983	0.9	0.7	5.3	0	1.9	*	*	4	23.1	*	*	0.3
1983/1984	*	1.9	*	0	*	0	1.8	*	11.5	1.5	0	0
1984/1985	3.3	0	12.6	0	15.8	15.7	0.9	12	9.7	0	0	2
1985/1986	14.1	15.5	8.9	45.8	4.3	3.7	1.3	0	3.3	0.4	0	0
1986/1987	3.7	52.2	*	0	0.3	*	21.7	0	10.4	10.9	0	0
1987/1988	18.7	7.7	13.1	10.1	4	34.1	8.3	1.1	2.5	*	0	*
1988/1989	0.3	15.3	45.4	0	0	21.2	3.2	4.5	0	6.8	2.8	29
1989/1990	13.6	70.5	41.7	52.3	1.6	0	8.5	10.8	24	0	0.4	0.3
1990/1991	4.8	0	*	29.8	0	12	11.2	16	3	10.7	0.2	8.4
1991/1992	8.3	4	0	9.5	0	17.4	3.9	7.5	10.9	1.4	*	0.1
1992/1993	*	1	5.8	24.7	5.9	11.5	5.2	0	*	0	0	2.8
1993/1994	*	8.2	49	3.1	69	0	0	10	0	0	*	2.2
1994/1995	*	48.2	0	0	0	0	29.7	28.5	0	12.2	*	8.3
1995/1996	4	49.8	0	3.2	16.6	45.3	12.2	*	1.4	43.9	17.9	0
1996/1997	4.3	13.3	0	8.8	8.2	0	12	29.7	0	0	*	*
1997/1998	21.2	0	0	0	10.6	43.3	6.7	0	*	*	0	0
1998/1999	2.2	0	0	7.4	18.4	2.4	9.7	0	1.8	*	0	7.4
1999/2000	7.5	50.2	0	0	0	0	0	0	43.5	1.4	4.9	2.2
2000/2001	0	9	2.5	*	0	0	0.2	0.3	5.5	0	0	0
2001/2002	2.7	10.5	*	0.8	0	12.3	18.1	28	24.8	0	0	0.8
2002/2003	13.7	0	0	0	0	2.5	14	0	1.2	1.1	1.8	4.2
2003/2004	5.7	32.8	9.7	0	0	19	4.6	23.7	38.2	3.2	*	4
2004/2005	0.4	*	10.2	*	0	19.8	4.7	0	0	15.7	0	6.2
2005/2006	11.2	19.7	1.2	3.8	49.7	4.1	0	3.6	46.4	23.8	6.3	*
2006/2007	33.3	18.2	45.7	36.9	30.4	9.2	0	*	*	0	3.3	4.3
2007/2008	0	28.4	16.4	6.3	*	46.3	11.7	*	7.8	0.3	*	26.5
2008/2009	17	85.9	18.8	8.9	15.2	1.7	32.9	*	*	5.8	1.9	0

Table 37: Maximum rainfall event data measured in l'Himda (Source : L'Agence du bassin Hydraulique du Guir-Ziz-Rheris). *precipitation not available.

Year	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
1982/1983	*	*	*	0.5	0.0	2.9	0.5	0.0	15.7	0.0	0.0	6.4
1983/1984	5.0	0.5	0.0	0.0	2.9	0.0	0.0	0.0	0.4	1.1	0.0	0.0

1984/1985	1.5	0.3	18.8	0.0	6.0	18.6	0.0	0.9	13.5	0.0	0.0	0.0
1985/1986	26.0	0.7	2.3	17.3	12.6	5.8	0.2	0.0	1.2	0.0	0.0	2.0
1986/1987	7.0	5.7	0.0	0.0	1.2	0.0	6.3	0.0	8.8	4.7	0.0	0.0
1987/1988	1.6	0.0	7.0	3.2	7.5	11.1	2.5	0.0	2.2	1.0	0.0	0.0
1988/1989	0.4	3.4	13.1	0.0	6.8	4.5	3.1	5.2	0.0	6.6	0.0	11.8
1989/1990	9.0	25.5	13.5	24.5	0.5	0.0	0.9	4.9	4.2	0.0	4.1	0.0
1990/1991	9.2	1.0	0.0	4.0	0.0	9.5	2.5	5.8	0.0	4.0	0.0	1.4
1991/1992	0.6	2.0	0.0	2.0	0.0	2.5	0.0	0.0	1.2	0.0	0.0	0.0
1992/1993	0.0	0.0	4.8	5.6	3.8	3.5	1.9	0.0	0.0	0.0	0.0	0.0
1993/1994	3.5	4.1	2.3	0.3	15.7	0.6	0.7	0.0	0.0	0.0	0.0	0.0
1994/1995	0.5	16.5	0.8	0.0	0.0	0.0	6.2	11.1	0.0	0.0	0.0	0.0
1995/1996	0.3	7.9	0.2	5.2	2.1	7.8	7.3	1.7	0.6	10.6	7.8	0.0
1996/1997	0.0	0.6	0.0	1.8	7.0	0.0	5.1	5.9	0.3	0.0	0.0	1.1
1997/1998	1.9	0.0	0.0	0.0	2.1	9.5	0.0	0.6	0.0	0.0	0.0	1.0
1998/1999	2.6	0.0	0.0	2.0	1.8	2.6	0.0	0.0	0.8	0.0	0.0	1.0
1999/2000	0.5	2.1	0.3	0.6	0.0	0.0	0.0	1.7	16.9	0.0	0.0	0.0
2000/2001	0.0	3.6	0.5	2.1	0.0	0.0	0.0	0.7	2.1	0.0	0.0	0.2
2001/2002	0.0	8.3	0.0	1.1	0.0	0.0	6.7	7.2	4.8	0.0	0.0	1.2
2002/2003	5.4	0.0	6.5	0.0	0.0	4.1	0.8	2.0	0.0	0.4	0.5	0.8
2003/2004	4.2	8.0	3.6	0.0	0.0	5.8	0.0	1.5	2.5	0.0	0.0	0.8
2004/2005	1.2	0.7	2.1	3.7	0.0	3.8	1.1	0.0	0.0	2.5	2.1	0.0
2005/2006	0.3	2.3	3.2	0.4	9.5	3.7	0.0	0.3	7.3	0.0	0.8	0.0
2006/2007	19.7	4.7	8.9	2.8	5.3	6.9	0.0	13.3	0.0	0.0	4.0	4.3
2007/2008	0.0	10.8	13.6	0.0	0.0	23.7	T	0.3	2.3	1.2	*	5.1
2008/2009	6.9	21.1	9.4	15.2	11.2	3.8	32.9	0.7	0.3	1		

Aggregated precipitation data

In the vicinity of the model area three observation stations are located. The closest is the station of L'Hmida, located just east of the model area (see figure 106). More east, at approximately 20 km, the Radier Erfoud station is located. The observation station of Merroutcha is situated 25 km west of the model area.

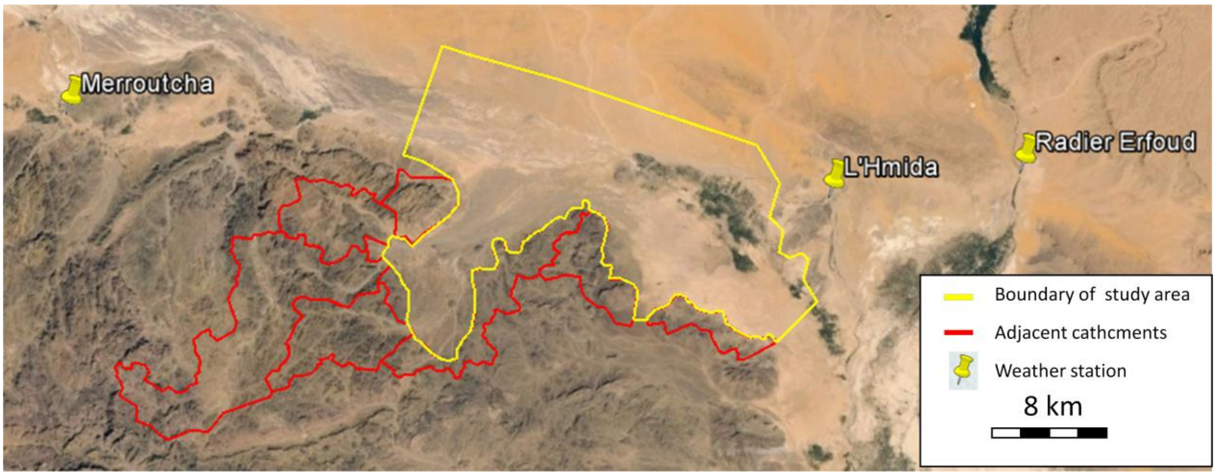


Figure 106: Locations of the observation stations in the vicinity of the model area.

Period 1959-1969

The centre of the study area, including the Anti-Atlas catchments which are also relevant for the model, is approximately in between Merroutcha and L'Hmida (see figure 106). The same is true for the elevation. Consequently, it is reasonable to think that the precipitation is in between as well.

Regression analyses are done among the precipitation data of Radier Erfoud on the one side and the stations of H'mida and Merroutcha on the other side. For the latter two stations precipitation data is available starting from year 1977. Analyses were done for the period of 1977-2009 and the period 1977-1987. The results show that the correlations found for the first period were significantly lower than for the second period. Therefore, only the correlations of the period 1977-1987 are considered. The results show that the correlation between the data of Radier Erfoud and H'mida is surprisingly high. The coefficient of determination is 0.90, close to unity (see figure 107). Also the monthly mean precipitation of both stations is about the same: 6.1 mm at Radier Erfoud and 6.3 mm at H'mida. The strong correspondence can be explained by the relative short distance between the two stations. Moreover, they face similar conditions because both are located in the Tafilalet plain. The correlation with the data of the Merroutcha station is less significant: R^2=0.58 (see figure 108). It is determined that the average monthly precipitation at Merroutcha is a factor 1.26 higher than at Radier Erfoud.

As input for the model, average precipitation data of the two stations are used. They are obtained by multiplying the precipitation data of Radier Erfoud station during the period 1959-1969 with an in between factor of (1+1.26)/2 = 1.13. The data gaps are filled with monthly averages of the latter obtained data set. The resulting aggregated precipitation data set can be seen in table 38.

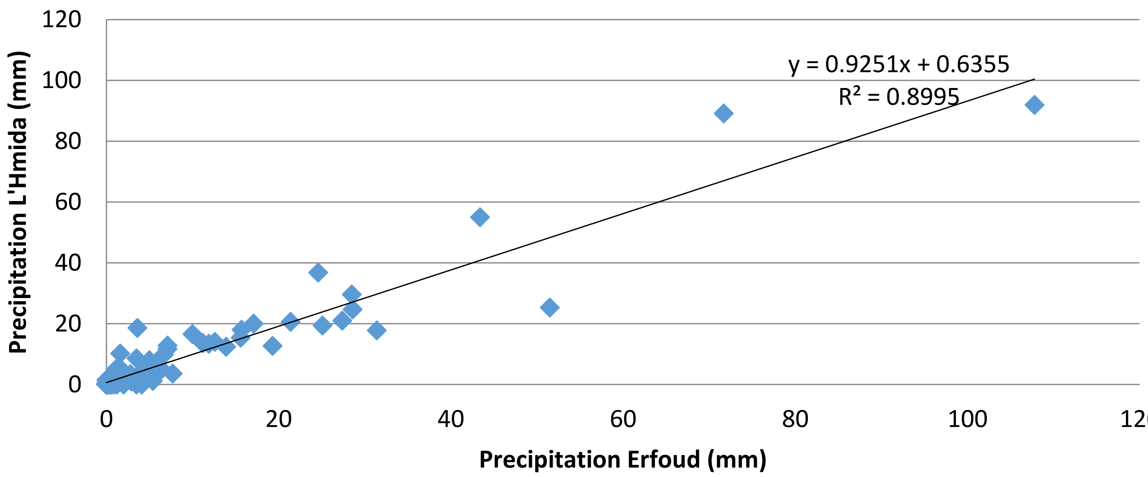


Figure 107: Regression analyses of precipitation data among the stations of Erfoud and L'Hmida for the period 1977-1987.

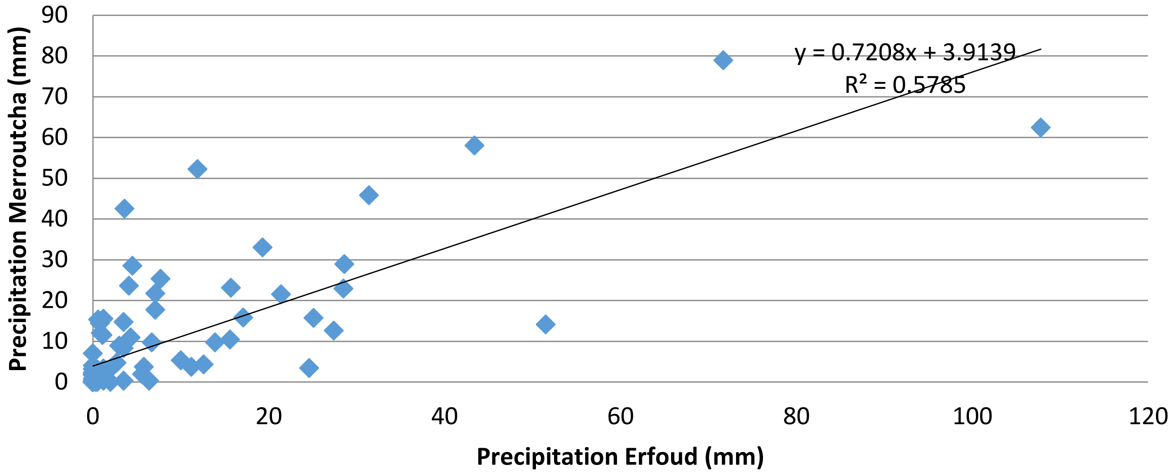


Figure 108: Regression analyses of precipitation data among the stations of Erfoud and Merroutcha for the period 1977-1987.

Table 38: The aggregated precipitation data set for the period 1959-1969, used as input for the model.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1959	9.5	5.8	44.1	7.9	10.2	6.9	1.6	0.5	1.5	43.0	12.0	9.8
1960	7.9	0.0	21.7	19.2	1.7	31.7	9.0	0.0	0.0	0.0	0.0	9.6
1961	0.0	2.3	0.0	7.9	1.7	1.7	0.0	0.0	0.0	2.8	15.8	1.7
1962	0.0	6.2	30.5	0.0	2.3	10.7	0.0	0.0	18.1	0.0	18.7	15.3
1963	13.6	0.6	2.8	9.6	15.3	6.2	2.3	0.0	4.0	0.0	0.0	4.5
1964	2.8	0.0	0.0	2.3	1.7	6.9	1.6	2.3	6.8	0.0	2.8	11.9
1965	33.1	63.3	5.1	20.1	0.0	0.0	0.0	0.0	8.5	38.2	12.0	9.8
1966	9.5	12.4	13.6	7.9	4.5	4.5	1.6	2.3	10.7	27.5	60.8	9.8
1967	9.5	22.8	13.6	15.5	5.3	2.9	0.3	0.3	6.0	13.7	3.4	11.8
1968	9.5	25.8	3.6	3.6	6.9	5.4	0.9	17.9	7.1	13.7	5.7	2.0
1969	11.2	0.0	14.4	0.3	4.5	0.0	0.0	2.3	2.4	6.9	1.1	17.6

Period 2000-2010

Just as for the period of 1959-1969, it is assumed that the average precipitation in the study area is in between the rainfall quantities of Merroutcha and L 'Hmida. Hence, precipitation data of both stations are compared.

It is determined that the yearly average rainfall at L'Hmida is 25 % less than measured at Merroutcha. Furthermore, a regression analysis among the two stations is performed for a longer period 1990-2009, because several years of data from the station of L'Hmida is missing during the period of 2000-2010. Figure 109 shows that the coefficient of determination equals 0.71. This relative low correspondence can be clarified by the large distance between both stations and their significant difference in elevation: 150 m. Furthermore, it is observed that the yearly average rainfall at L'Hmida is 25 % less than measured at Merroutcha.

As input of the model for the period of 2000-2010, the precipitation of Merroutcha is used. The reason for this is that the precipitation data from the station of Merroutcha is more complete. The data from Merroutcha is multiplied by an average factor of (1+0.75)/2 = 0.88. The data gaps are filled with monthly averages of the latter obtained data set. Table 39 shows the resulting aggregated precipitation data set.

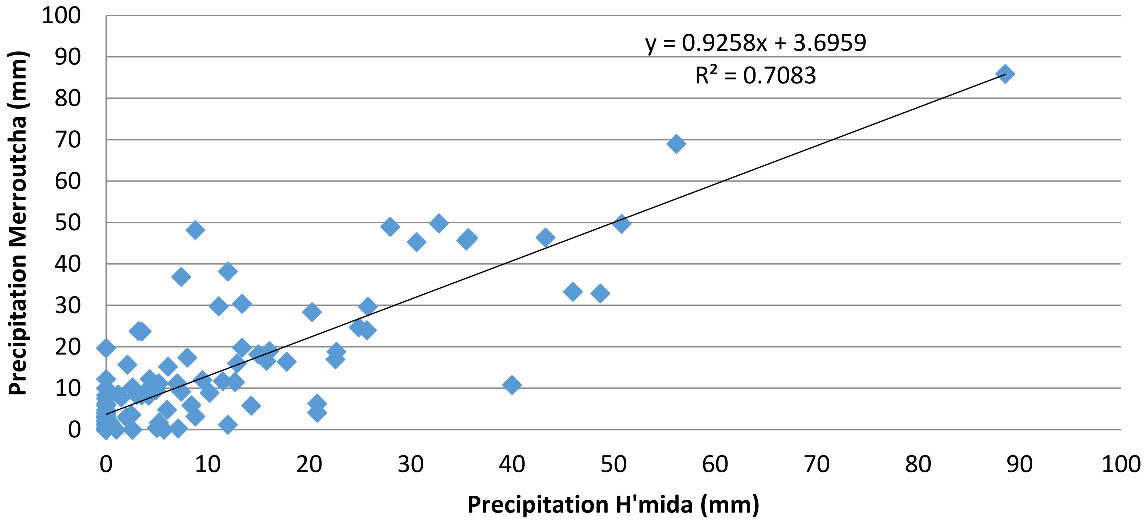


Figure 109: Regression analyses of precipitation data among the observation stations of L'Hmida and Merroutcha for the period 1990-2010.

Table 39: The aggregated precipitation data set for the period 2000-2010, used as input for the model.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	0.0	0.0	0.0	0.0	38.1	1.2	4.3	1.9	0.0	7.9	2.2	7.1
2001	0.0	0.0	0.2	0.3	4.8	0.0	0.0	0.0	2.4	9.2	11.4	0.7
2002	0.0	10.8	15.8	24.5	21.7	0.0	0.0	0.7	12.0	0.0	0.0	0.0
2003	0.0	2.2	12.3	0.0	1.1	1.0	1.6	3.7	5.0	28.7	8.5	0.0
2004	0.0	16.6	4.0	20.7	33.4	2.8	2.0	3.5	0.3	0.0	8.9	5.0
2005	0.0	17.3	4.1	0.0	0.0	13.7	0.0	5.4	9.8	17.2	1.1	3.3
2006	43.5	3.6	0.0	3.2	40.6	20.8	5.5	4.7	29.1	15.9	40.0	32.3
2007	26.6	8.1	0.0	30.0	18.3	0.0	2.9	3.8	0.0	24.9	14.4	5.5
2008	9.3	40.5	10.2	7.0	6.8	0.3	2.0	23.2	14.9	75.2	16.5	7.8
2009	13.3	1.5	28.8	7.0	18.3	5.1	1.7	0.0	39.0	0.0	0.0	0.0
2010	20.9	18.7	0.0	0.0	2.4	0.0	2.0	17.3	8.2	22.4	11.4	7.1

Appendix C: Piezometric data

Groundwater levels measured by piezometers

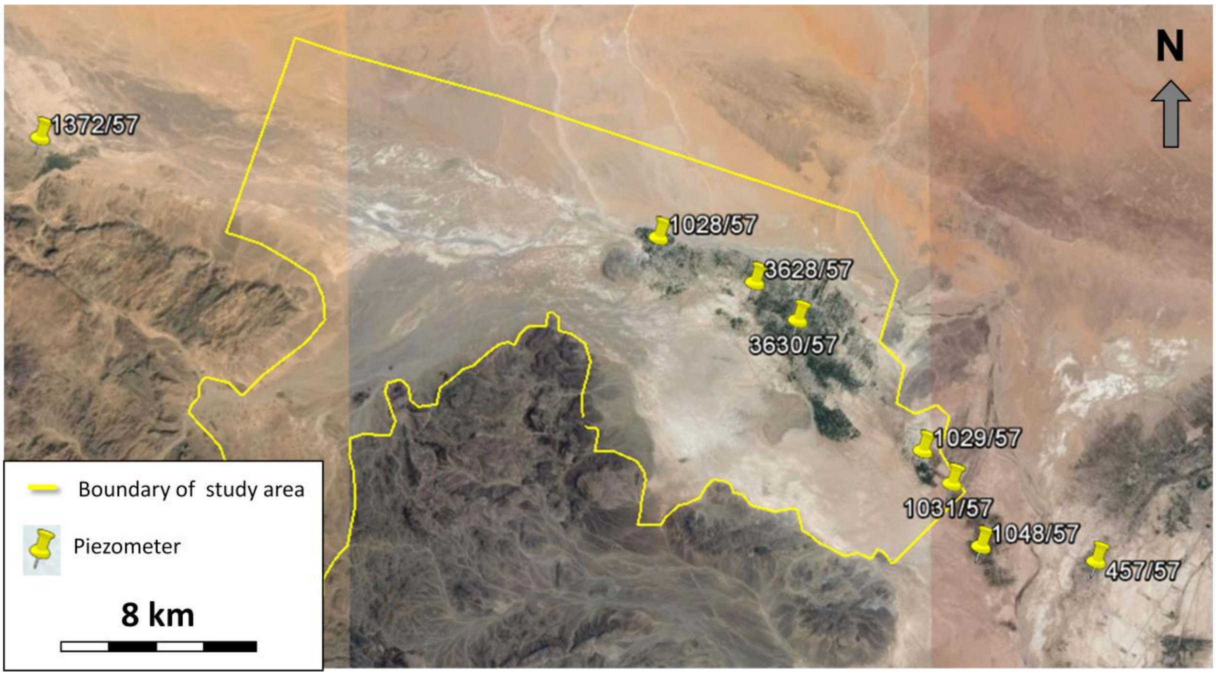


Figure 110: Locations of the piezometers in the study area.

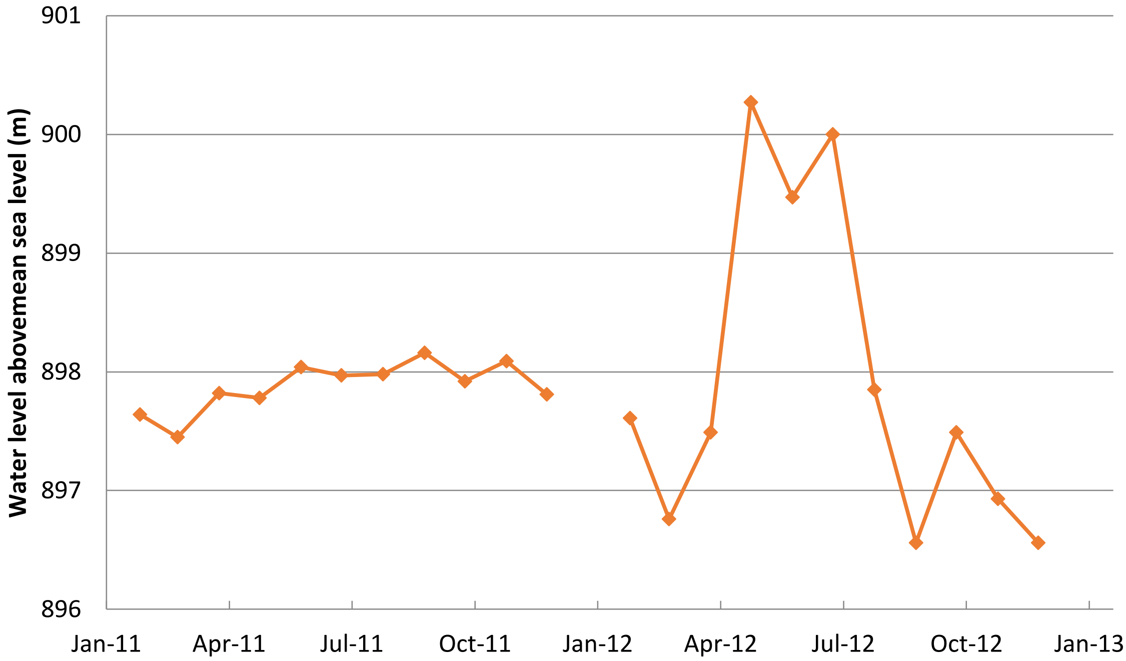


Figure 111: Water levels at piezometer 1372/57. The location of the piezometer can be seen in figure 110.

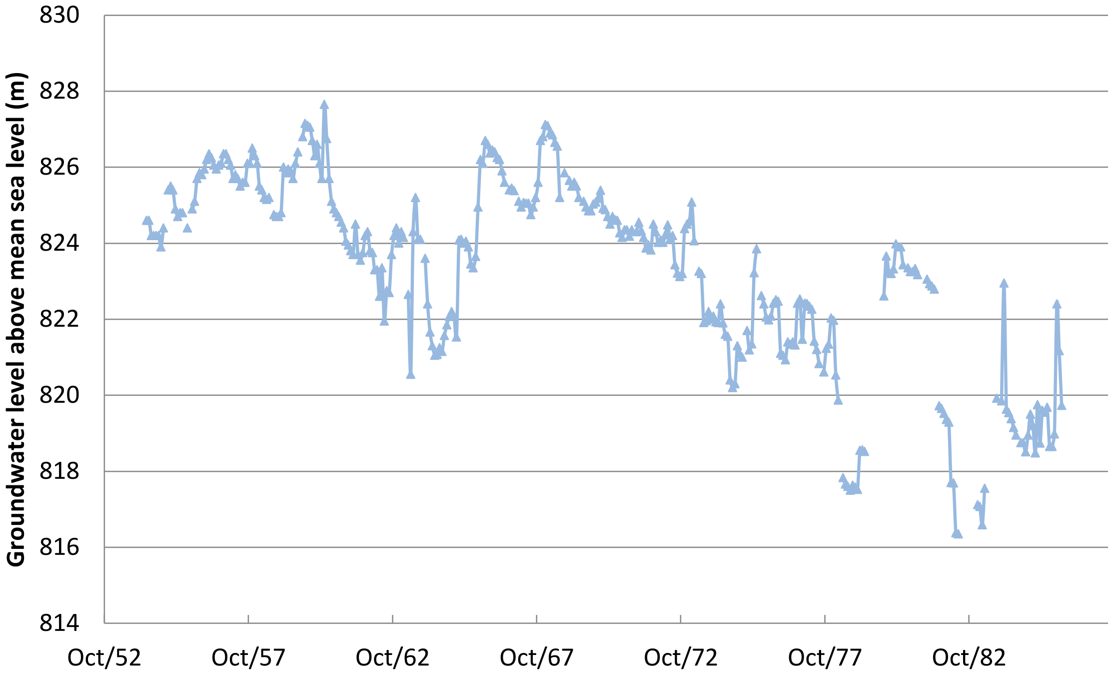


Figure 112: Water levels measured at piezometer 1028/57. The location of the piezometer can be seen in figure 110.

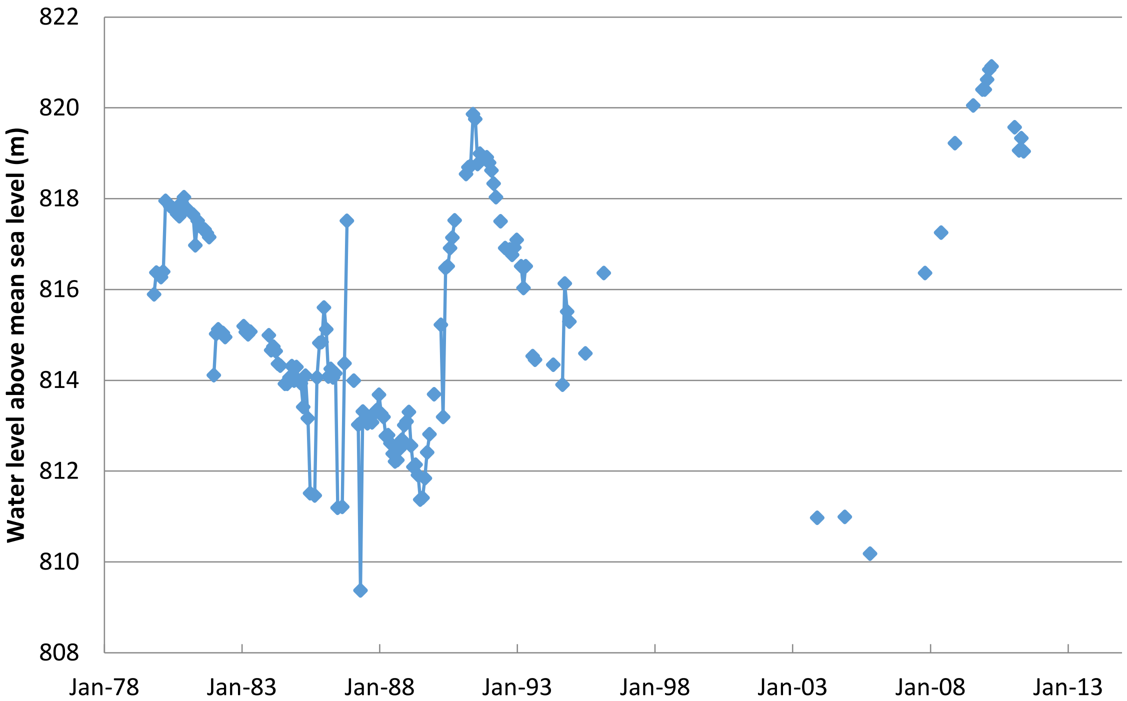


Figure 113: Water levels measured at piezometer 3628/57. The location of the piezometer can be seen in figure 110.

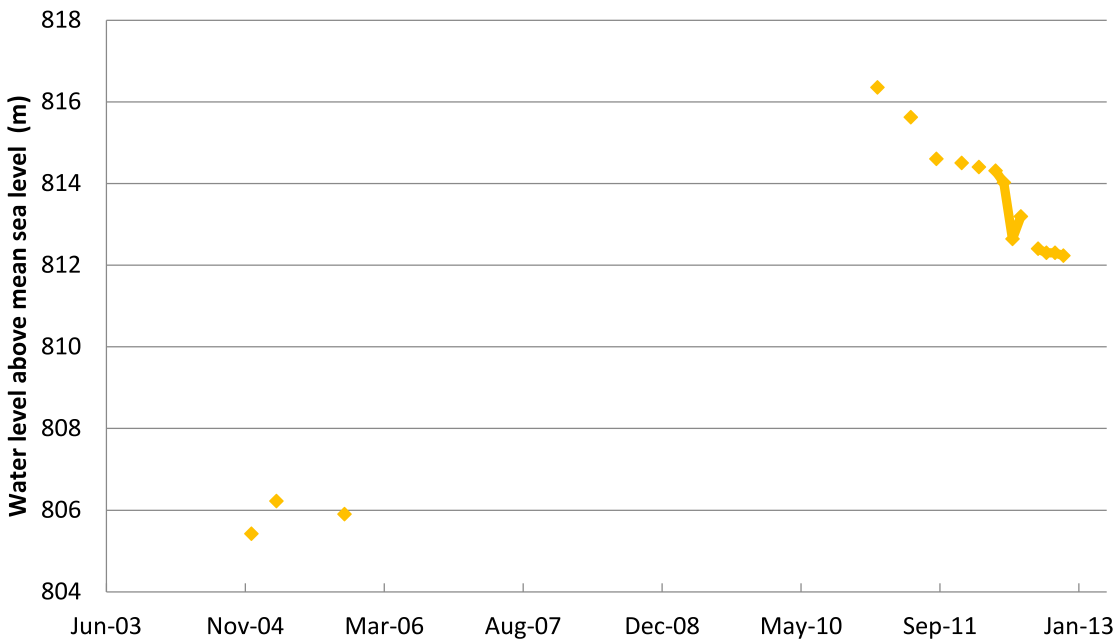


Figure 114: Water levels measured at piezometer 3630/57. The location of the piezometer can be seen in figure 110.

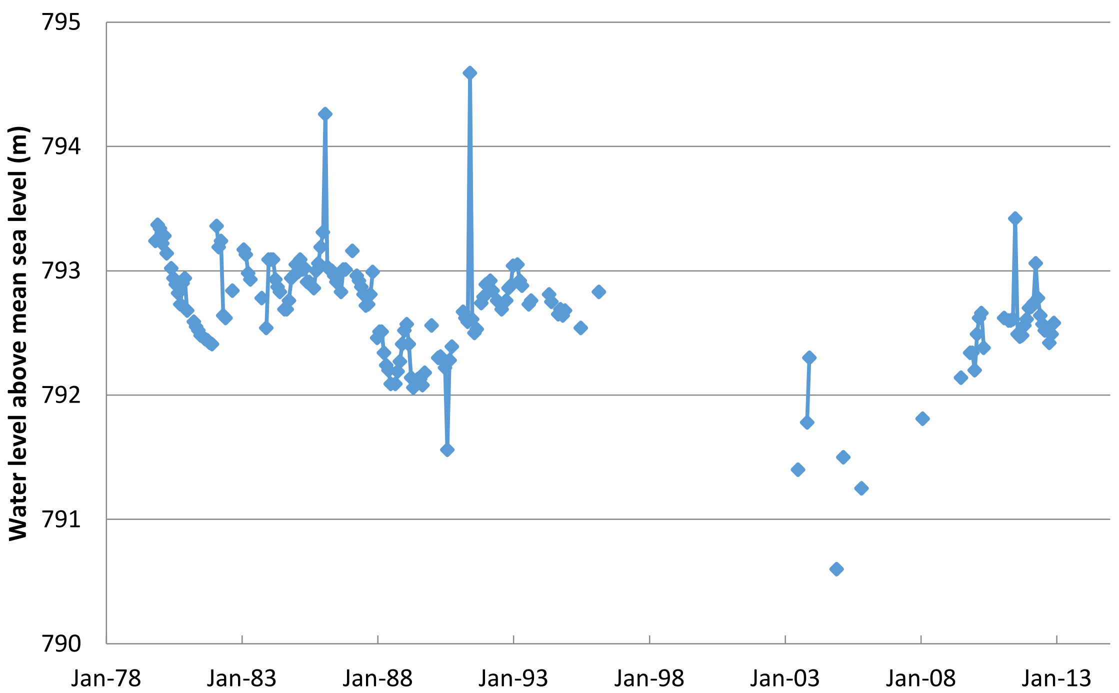


Figure 115: Water levels measured at piezometer 1029/57. The location of the piezometer can be seen in figure 110.

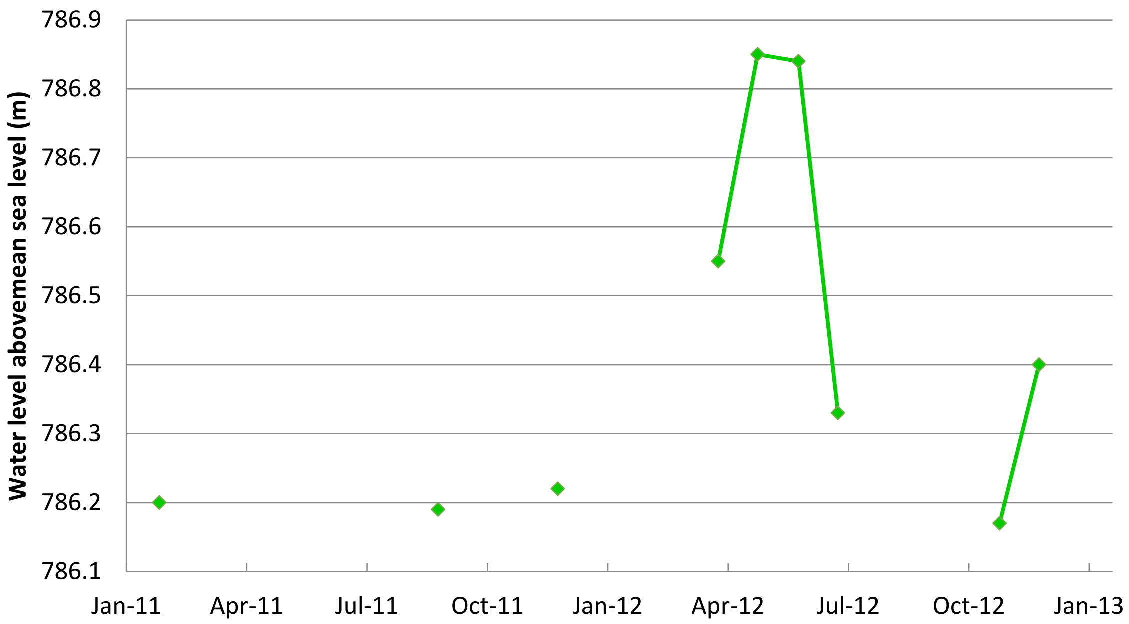


Figure 116: Water levels measured at piezometer 1031/57. The location of the piezometer can be seen in figure 110.

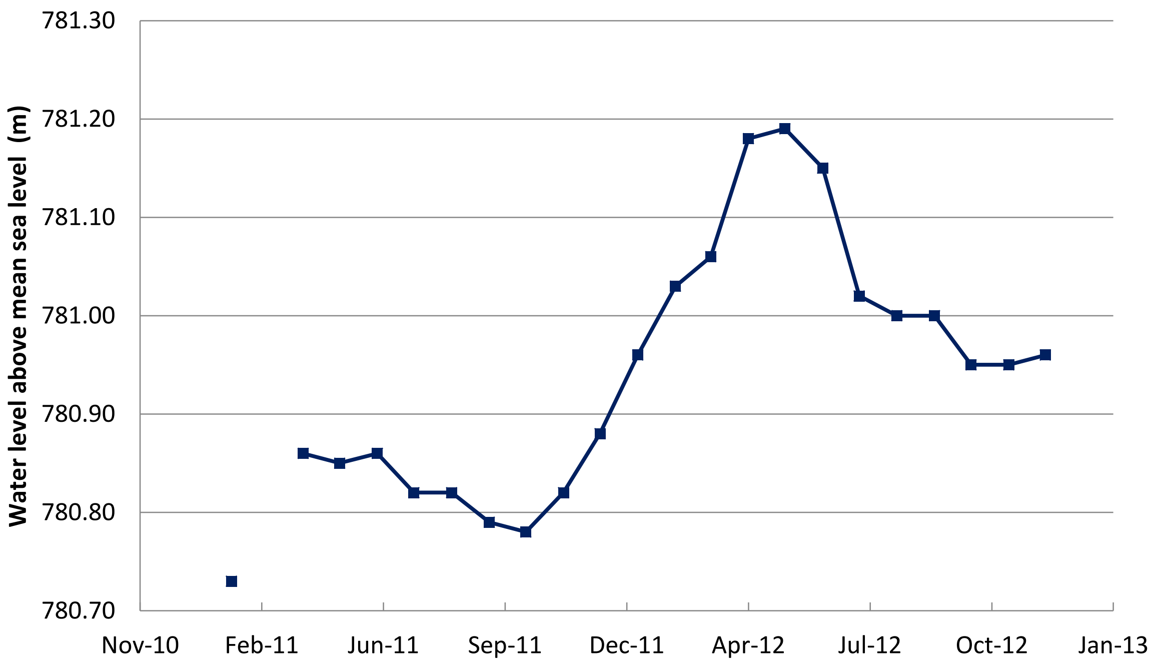


Figure 117: Water levels measured at piezometer 1048/57. The location of the piezometer can be seen in figure 110.

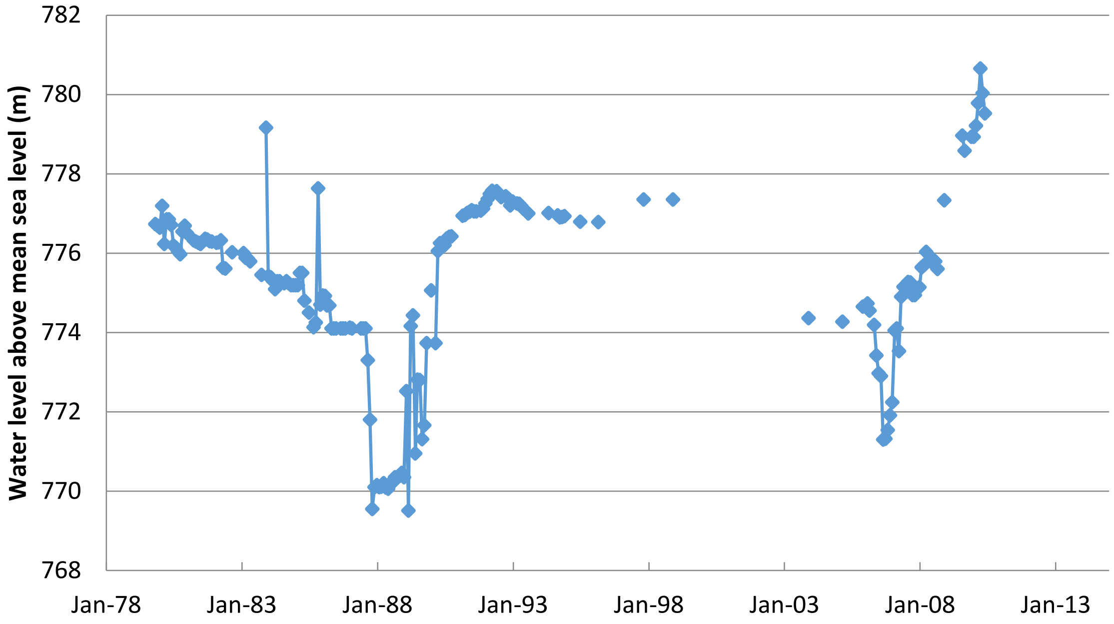


Figure 118: Water levels measured at piezometer 457/57. The location of the piezometer can be seen in figure 110.

Appendix D: Photographs of visited sites

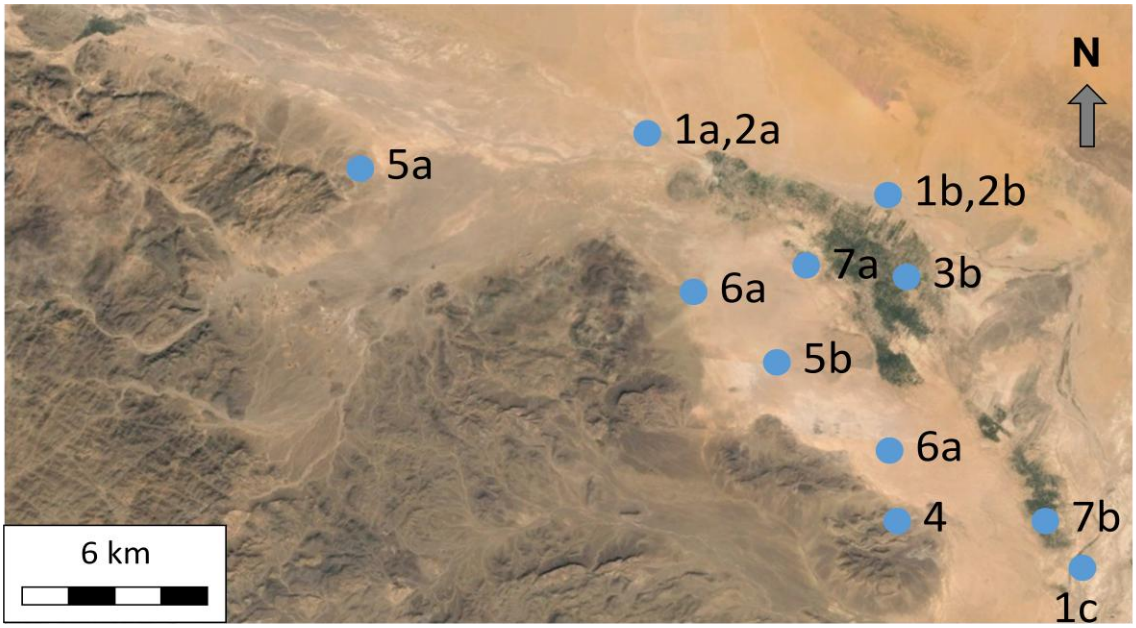


Figure 119: Visited locations during fieldwork. 1: the river bank of the river Rheris. 2: small dams used for irrigation purposes. 3: agricultural fields. 4: agricultural fields. 5: plain. 6: khettara mother wells. 7: khettara outlets.

Figure 120: Dam in the oued Rheris, which is also intented to guide the water to the irrigation canals (see location 2a in figure 119).

Figure 121: The river bed of the oued Rheris (see location 1a in figure 119).

Figure 122: The river bed of the oued Rheris (see location 1b in figure 119).

Figure 123: A dry irrigation field (see location 3a in figure 119).

Figure 124: The cultivation of grasses and dates (from the palms) in an agricultural area (see location 3b in figure 119).

Figure 125: Mountains of the Anti-Atlas with schist as top formation (see location 4 in figure 119).

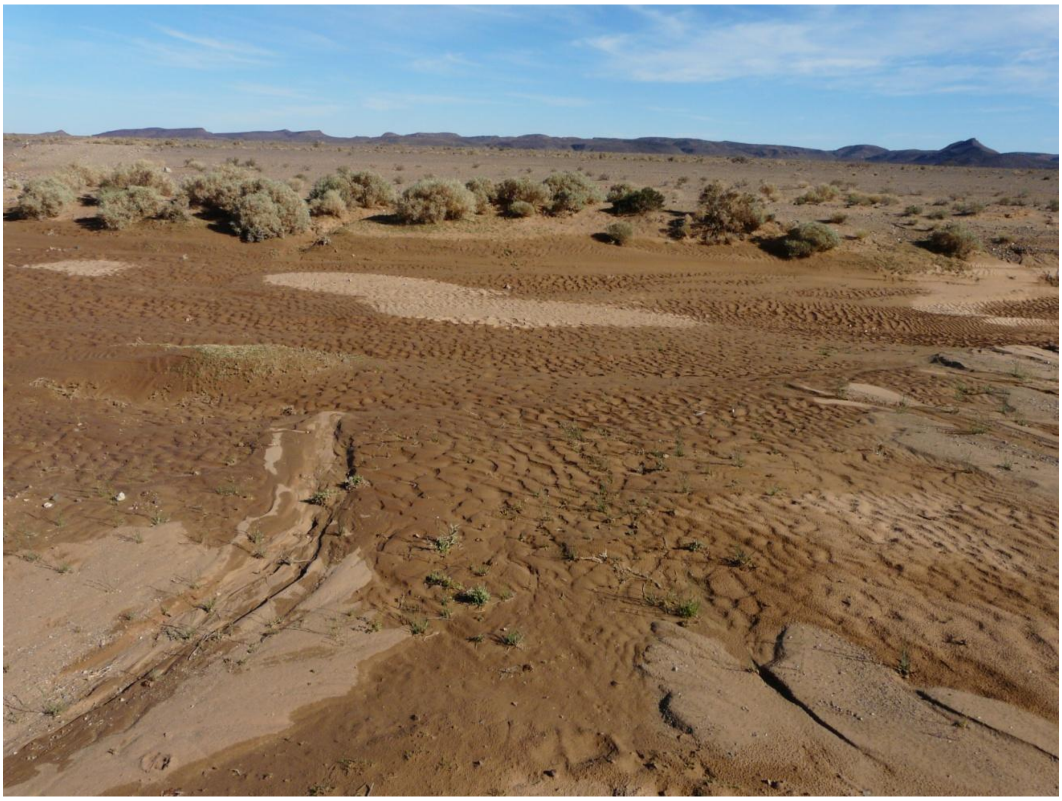


Figure 126: A small oued into the plain several days after flooding (see location 5a in figure 119).

Figure 127: The plain (see location 5b in figure 119).

Figure 128: A khettara mother well (see location 6b in figure 119).

Figure 129: A khettara outlet (see location 7b in figure 119).

Appendix E: Photographs of measurements

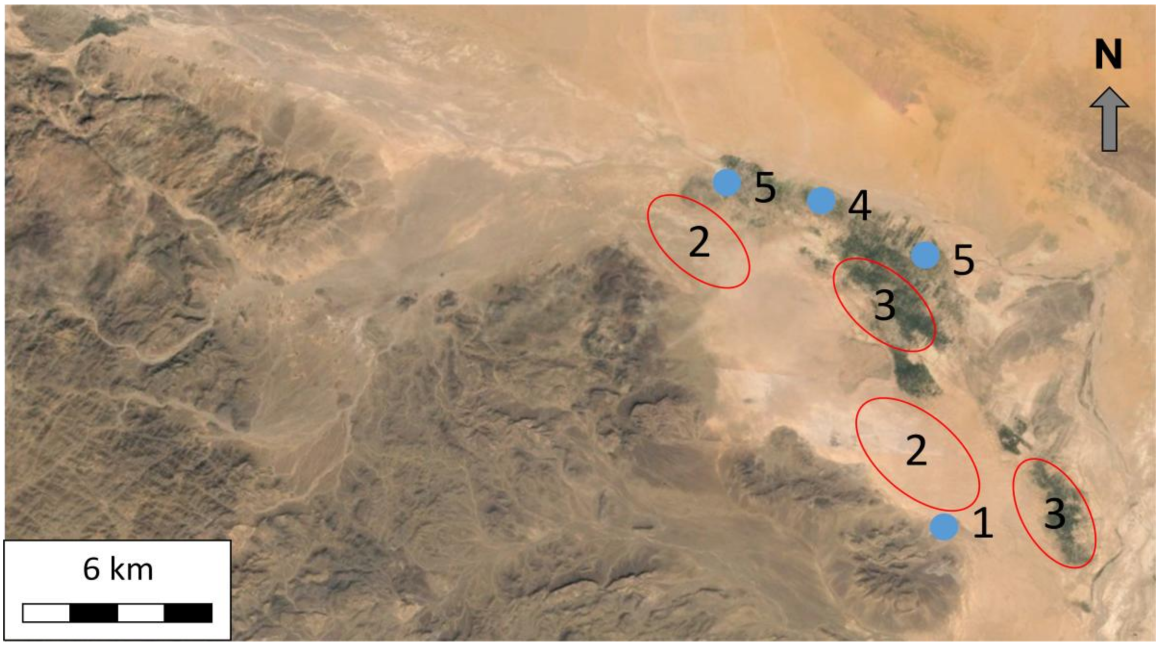


Figure 130: Measurement locations: 1: infiltration capacity. 2: khettara mother well depth. 3: khettara discharge. 4: water content. 5: groundwater table.

Figure 131: Infiltration test (see location 1 in figure 130). The drop of the water level was measured in time with a distance meter and a stopwatch. The hole was dug with an Edelman auger.

Figure 132: Measuring the mother well depth with a water level meter and a distance meter (see location 2 in figure 130).

Figure 133: Khettara discharge measurement with a floating orange, a distance meter and a stopwatch (see location 3 in figure 130).

Figure 134: A water content test using an Edelman auger, a distance meter and a TDR-probe (see location 4 in figure 130).

Figure 135: A water level measurement in an open well near Jorf with a water level meter. The loose pebbles on top of the hill, exisisting of excavation material from the well, indicate that the well goes down into poor cemented conglomerate (see location 5 in figure 130).

Appendix F: Measurement results

Measurements of the khettaras

Table 40: Locations and depths of the mother wells of Hannabou.

Name	Date of measurement	X	Y	Depth (w.r.t. surface level) (m)
Lakadima Krayr	14-03-2013	31.446033°	-4.401483°	16.40
Gadida Krayr	14-03-2013	31.444967°	-4.404033°	17.50
Mustaphia	14-03-2013	31.423033°	-4.371333°	16.50
Khtettera	14-03-2013	31.433450°	-4.383683°	14.90
Aloria	14-03-2013	31.426437°	-4.387987°	14.20
Grenia	14-03-2013	31.427650°	-4.388400°	-
Auctania	14-03-2013	31.430567°	-4.389617°	17.10
Fougania	14-03-2013	31.437517°	-4.399483°	16.50
Sayed	14-03-2013	31.438083°	-4.391033°	16.80
Guedima	14-03-2013	31.433600°	-4.393900°	-
Lakrania	14-03-2013	31.433450°	-4.393667°	17.10
Gadida Bouia	14-03-2013	31.454083°	-4.411267°	15.90
Lakdima Bouia	14-03-2013	31.452350°	-4.410800°	17.10

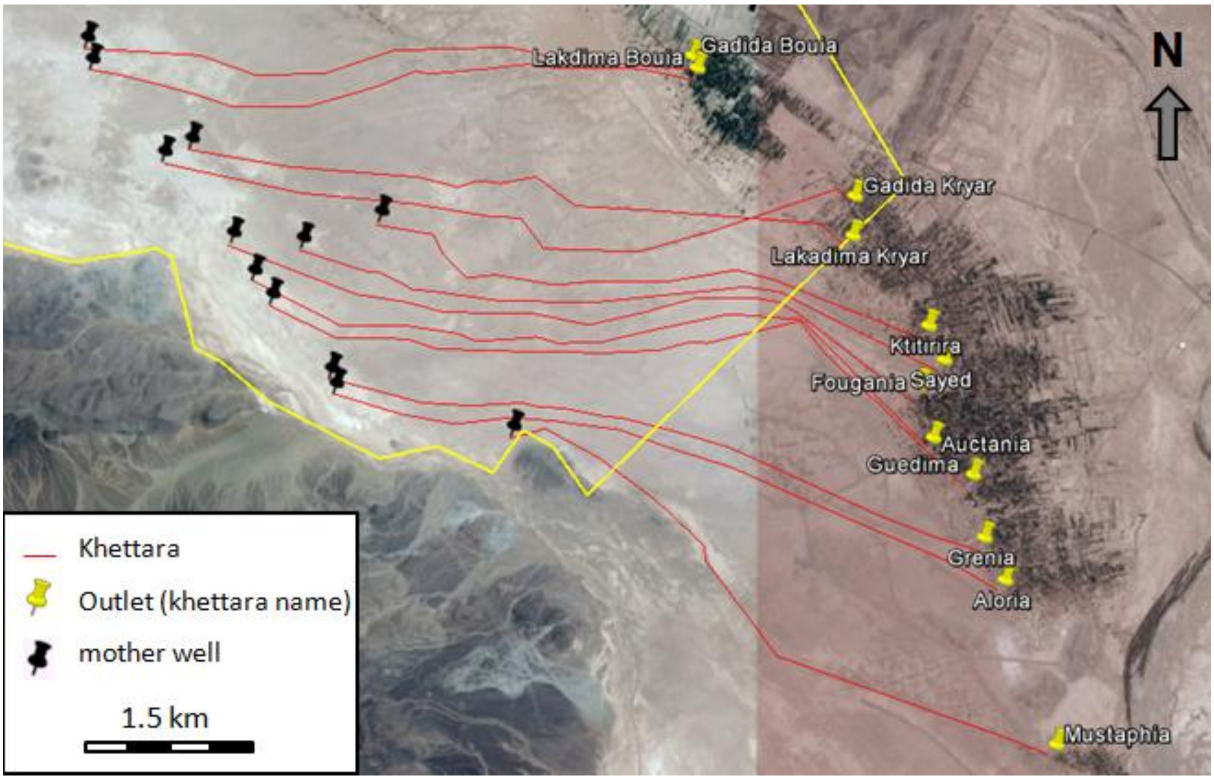


Figure 136: The locations of the khettaras of Hannabou including their mother wells and outlets.

Table 41: Measured discharges of various khettaras of Hannabou (including Kryar and Bouia) and Jorf.

Village	Name	Date of measurement	X	Y	Q (l/s)
Krayr	Lakadima	13/02/2013	-4.339583	31.438067	30
Khtettera	Khtettera	24/02/2013	-4.331883	31.433467	30.8
Krayr	Gadida	13/02/2013	-4.339383	31.441250	13.3
Hannabou	Mustaphia	24/02/2013	-4.320467	31.397300	14.6
Hannabou	Aloria	23/02/2013	-4.325283	31.410500	10.5
Hannabou	Grenia	24/02/2013	-4.327233	31.413917	5.1
Hannabou	Guedima	24/02/2013	-4.328283	31.418933	-*
Hannabou	Auctania	24/02/2013	-4.332033	31.421900	10.3
Hannabou	Fougania	24/02/2013	-4.333250	31.426167	42.7
Hannabou	Sayed	23/02/2013	-4.331000	31.428150	16.6
Hannabou	Ktitirira	24/02/2013	-4.332457	31.430883	28.9
Bouia	Gadida	24/02/2013	-4.354617	31.452467	21.9
Bouia	Lakdima	24/02/2013	-4.354183	31.451500	22.2
Jorf	Aisawia	13/02/2013	-4.394550	31.488333	16.2
Jorf	Assaouia Monkara	13/02/2013	-4.394800	31.466900	31
Jorf	Alboishabia	13/02/2013	-4.415750	31.507500	10.6
Jorf	Abrika	13/02/2013	-4.409650	31.499200	8.6
Jorf	Lahoua Monkara	13/02/2013	-4.390017	31.470750	54.2
Jorf	Lakbira	13/02/2013	-4.408317	31.502000	4.4
Jorf	Mbarkia Monkara	13/02/2013	-4.393483	31.466183	18.8
Jorf	Rozia Monkara	13/02/2013	-4.394200	31.477667	5.5
Jorf	Saidia	13/02/2013	-4.395183	31.486950	10.5
Jorf	Saihla	13/02/2013	-4.393667	31.488300	28.6
Jorf	Soihlat'de Alhaiyen/Lambarkia	13/02/2013	-4.398833	31.494017	21
Jorf	Zanoihia	13/02/2013	-4.399506	31.495400	13.9

*No discharge measurement

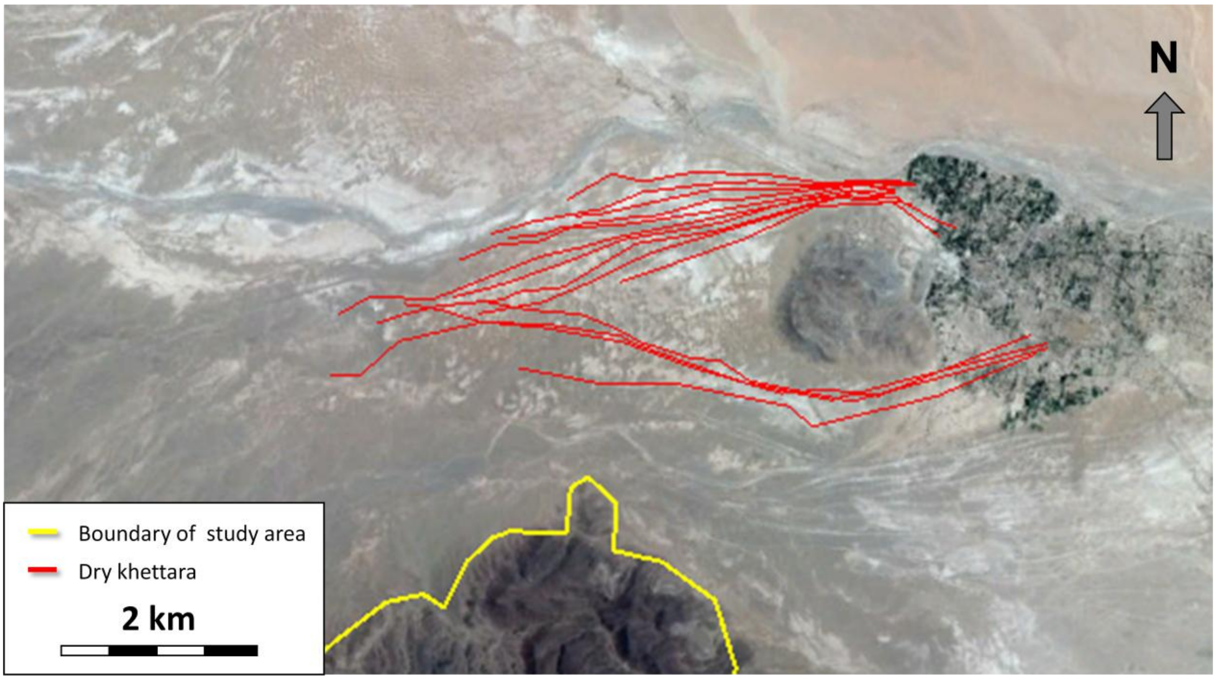


Figure 137: The location of the khettaras of Fezna. They became dry in the nineteen fifties (Ruhard, 1977).

Infiltration measurements

Infiltration test 1

Date: 15-03-2013
Name place: Dam (Seuil) 1
Coordinates: N 31°25.602' W 4°23.465'

Table 42: Results measurement 1 in silty soil.

Time	Time in between (min:sec)	Cumulated time (min:sec)	Water level from start (cm)	Cumulated water level (cm)
11.20.20- 11.27.00	6.40	6.40	12	12
11.27.00- 11.31.00	4.00	10.40	1	13
11.31.00- 11.36.00	5.00	15.40	2	15
11.36.00- 11.40.00	4.00	19.40	2.5	17.5
11.40.00- 11.47.45	7.45	27.25	3.5	21

Table 43: Results measurement 2 in silty soil.

Time	Time in between (min:sec)	Cumulated time (min:sec)	Water level from start (cm)	Cumulated water level (cm)
11.26.30-11.32.00	5.30	5.30	9	9
11.32.00- 11.36.45	4.45	10.15	3	12
11.36.45- 11.40.20	3.35	13.50	2	14
11.40.20-11.48.00	7.40	21.30	4	18

Table 44: Results measurement 3 in silty soil.

Time	Time in between (min-sec)	Cumulated time (min-sec)	Water level from start (cm)	Cumulated water level (cm)
11.34.00-11.37.00	3.00	3.00	13	13
11.37.00-11.40.40	3.40	6.40	3	16
11.40.40- 11.48.30	7.50	14.30	5	21

Infiltration test 2

Date: 15-03-2013
Name place: Dam (seuil) 2
Coordinates: N 31°26.278’ W 4°24.343’

Table 45: Infiltration measurement 1 in silty soil.

Time	Time in between (min-sec)	Cumulated time (min-sec)	Water level from start (cm)	Cumulated water level (cm)
12.26.00- 12.27.45	1.45	1.45	14	14
12.27.45- 12.29.10	1.25	3.10	4	18
12.29.10- 12.32.15	3.05	6.15	5	23
12.32.15- 12.34.15	2.00	8.15	2.5	25.5

Table 46: Infiltration measurement 2 in silty sandy soil.

Time	Time in between (min-sec)	Cumulated time (min-sec)	Water level from start (cm)	Cumulated water level (cm)
12.30.30-12.31.15	0.45	0.45	12	12
12.31.15-12.32.30	1.15	2.00	8	20

Table 47: Infiltration measurement 3 in silty soil.

Time	Time in between (min-sec)	Cumulated time (min-sec)	Water level from start (cm)	Cumulated water level (cm)
12.32.30-12.33.30	1.00	1.00	17	17
12.33.30-12.35.00	1.30	2.30	8	25

Table 48: Infiltration measurement 4 in sandy soil.

Time	Time in between (min-sec)	Time CUM (min-sec)	Water level from start (cm)	Cumulated water level (cm)
12.35.45-12.36.45	1,00	1,00	14	14
12.36.45-12.37.35	0,50	1,50	4	18
12.37.35- 12.38.35	1,00	2,50	25	25

Water content measurements

Water content measurement 1

Data: 08-03-2013
Name village: Jorf
Coordinates: N 31°30.809', W 4°23.243'

Table 49: Results water content measurement 1.

Depth (w.r.t. surface level)	Water content	Type of soil
m		
0	0.237	Clay
0.25	0.183	Clay
0.48	0.142	Clay
0.63	0.101	Clay
0.83	0.136	Clay/very fine sand
1.07	0.175	Clay/very fine sand

Open well measurements

Table 50: Results open well measurement 1.

Date	08-03-2013
Coordinates	N 31°31.725' W 4°28.941
Depth w.r.t. surface level	18.7 m
Water level w.r.t. surface level	16 m
Diameter	1.92 m

Table 51: Results open well measurement 2.

Date	08-03-2013
GPS (X,Y)	N 31°29.738' W 4°22.478'
Depth (w.r.t. surface level)	8.70 m
Water level (w.r.t. surface level)	6.00 m
Diameter	-
Additional information	Measurements done after four days of no pumping. Three days an after rain event water level was 1 m below the surface. Formation starting from top: 6m silt/clay, 2.70 m conglomerates.

Table 52: Results open well measurement 3.

Date	**08-03-2013**
GPS (X,Y)	N 31°31.318' W 4°32.465'
Depth (w.r.t. surface level)	26.20 m
Water level (w.r.t. surface level)	20.20 m

Table 53: Results open well measurement 4.

Date	**08-03-2013**
GPS (X,Y)	N 31°32.042' W 4°28.068'
Depth (w.r.t. surface level)	20.50 m
Water level (w.r.t. surface level)	18.20 m
Additional information	Last time the pump was used was 4 days ago.

Appendix G: Interview lists

Interview list - Khettara

1. Name contact person ?
2. The name of the khettara?
3. What is the number of families who make use of this khettara?
4. And the number of people?
5. What are the purposes of the water?
   - Irrigation
   - Sanitation
   - Drinking water
   - Other purposes
6. What is the proportion between them?
7. What is the surface area of the irrigation field?
8. How much is irrigated by khettaras?
9. What is a typical variation of the flow during the day?
   - During the day?
   - During the night?
10. What is the seasonal variation of the flow?
    - Flow in spring?
    - During summer?
    - During autumn?
    - During winter?
11. Does the khettara fall dry (during the seasons)? When? How long?
12. What is the trend of the flow during the last 5 years?
13. Did the flow increase/decrease in this period?
14. What is the change (in percentage)?
15. Did the Khettara fall dry during this period? When? How long?
16. Do you get enough water from the khettara? Do you need more?
17. Is the khettara well maintained?
    - Currently?
    - In the past?
    - In the near future, what do you think?
18. What is the reason for rehabilitation?
    - Floods
    - Collapse of gallery
    - Low groundwater table
19. Which parts of the khettara are recently rehabilitated?
20. Does the khettara has multiple branches/arms?
21. Has the gallery of the khettara a lining (for preventing infiltration)? Which part?
22. Are there other sources of water here (like open wells)?
23. Are there also other khettaras nearby? How many?

Interview list - Pumping

1. Name contact person?
2. The name of the place/village?
3. Do you make use of pumps?
4. What is the number of families who make use of pump?
5. And the number of people?
6. What type of pump do you use?
7. What is the capacity (flow) of the pump?
8. How many horse power does the pump has?
9. Do the other farmers (in this village) have the same type of pump?
10. How deep is the well?
11. What is the formation of the soil over depth (when you digged the well) ?
12. What is the water level before you pump?
13. What is the variation of the water level during seasons?
14. What is the variation of the water level during the last 10 years ?
15. What is the lowest water level in the last 10 years?
16. What is the water level after a day pumping? And for how long you pumped?
17. How does your irrigation scheme look like?
    - How many hours per day/week do you irrigate?
    - Which seasons do you irrigate?
    - Do you have the same scheme during these periods?
18. Does the irrigation water stay in the irrigation field only?
    - Does the irrigation water flow to another location?
    - Where does the water flow to?
    - Does it flow to another irrigation field? Or to a non-irrigation location (river)?

Appendix H: Geological information: drillings & cross sections

Locations of drillings and geological cross sections

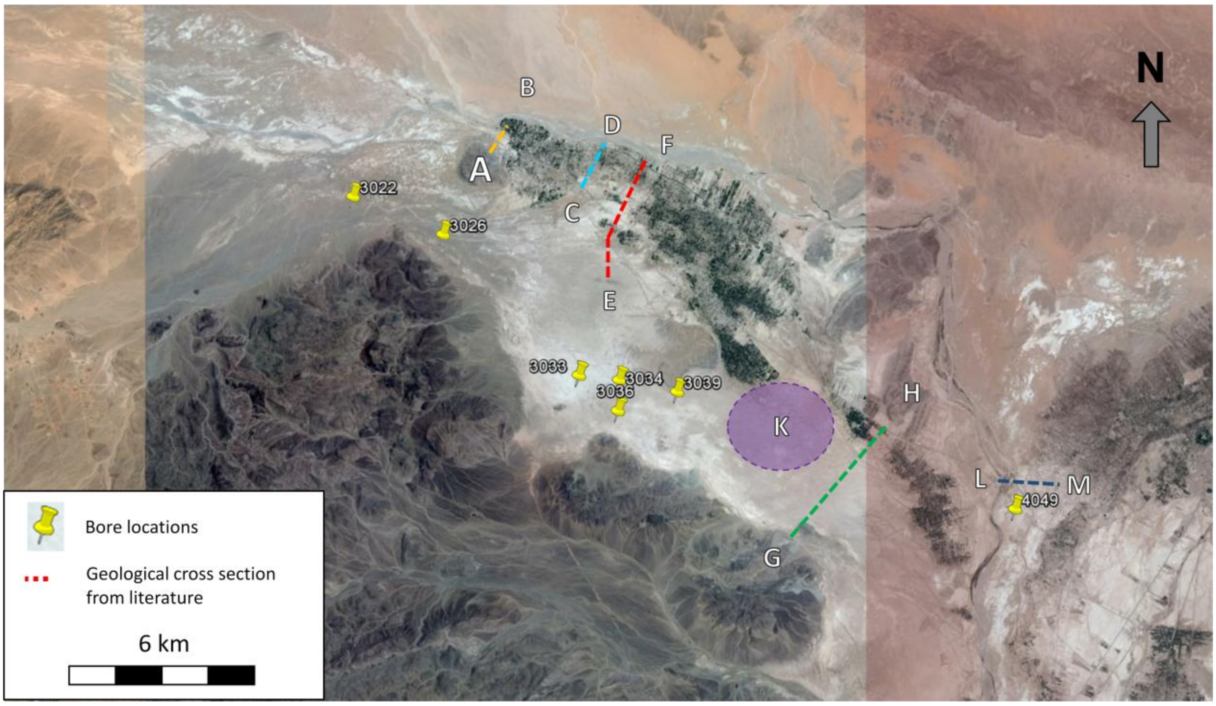
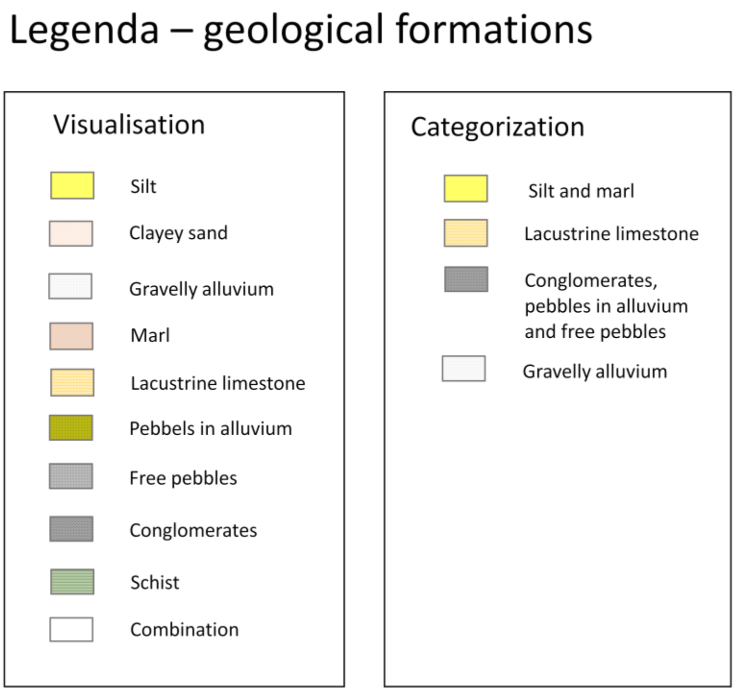


Figure 138: Locations of the drillings and the geological cross sections. The location of cross section K is not exactly known.

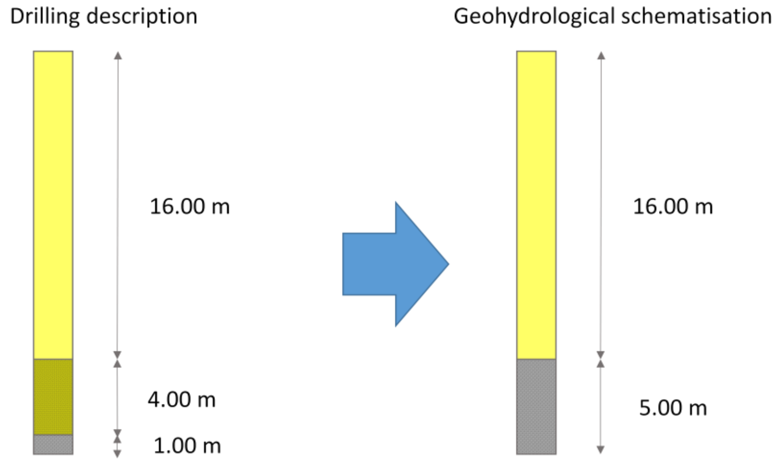
Bore logs



Bore log 3022/57

N 31° 30' 48,84"
W 4° 31' 8,23"

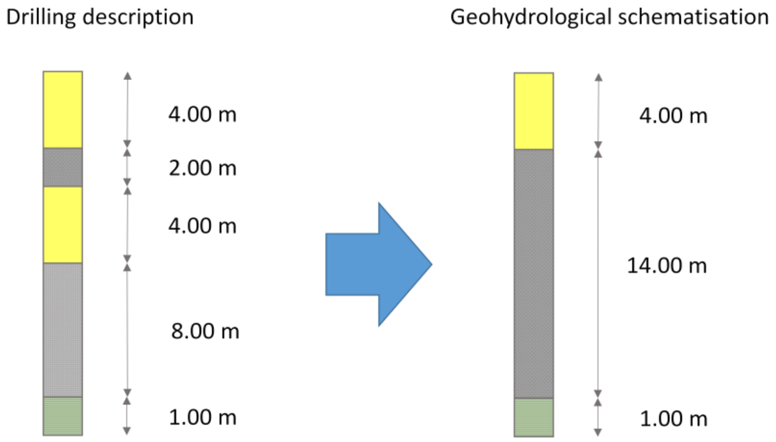
Soil type	From GS	Thickness
Ground surface	0,00	
sand and silt	1,00	1,00
Brown silt and packet boulders (large pebbles)	3,00	2,00
Compact clayey brown silt	6,00	3,00
Sandy silt	8,00	2,00
compact very clayey brown silt	16,00	8,00
Brown silt with packed boulders	18,00	2,00
Brown silt with packed boulders of rock cristaline	20,00	2,00
Very cemented and compacted conglomerates	21,00	1,00



Bore log 3026/57

N 31° 29' 59,28"
W 4° 29' 11,26"

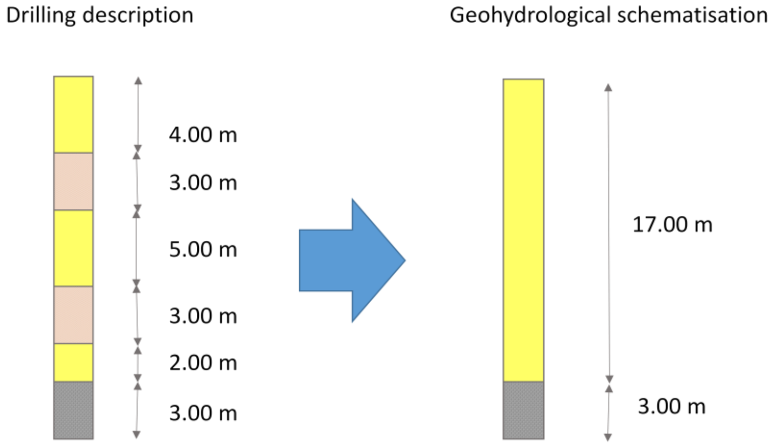
Soil type	From GS	Thickness
Ground surface	0,00	
Brown clayey silt	4,00	4,00
50/50 cemented conglomerates	6,00	2,00
brown clayey silt	10,00	4,00
Free pebbles	17,00	7,00
Sand and pebbles with schist	19,00	2,00



Bore log 3033/57

N 31° 27' 47,63"
W 4° 25' 21,57"

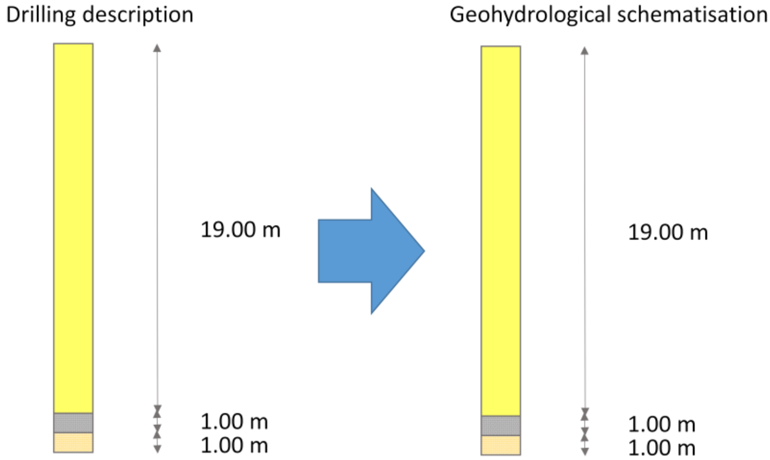
Soil type	From GS	Thickness
GS	0,00	
Brown clayey silt	4,00	4,00
Grey marl	7,00	3,00
Brown clayey silt	12,00	5,00
Grey marl	15,00	3,00
Brown clayey silt	17,00	2,00
50/50 cemented conglomerates	20,00	3,00
Schist		



Bore log 3034/57

N 31° 27' 47,63"
W 4° 25' 21,57"

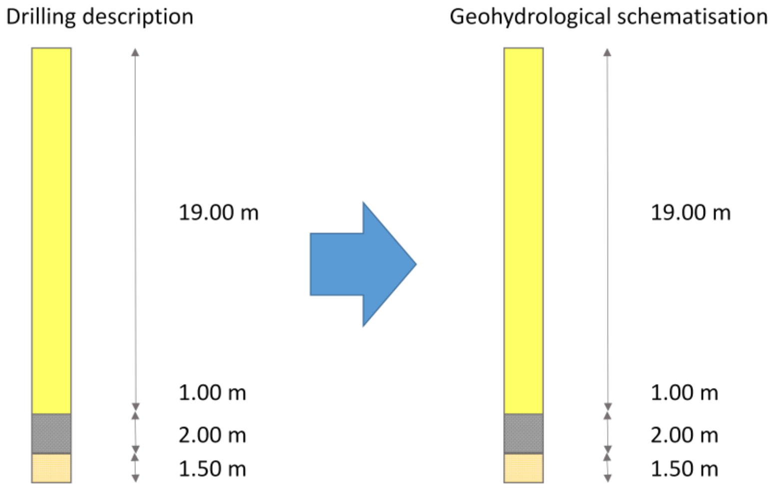
Soil type	From GS	Thickness
GS	0,00	
Brown clayey silt	19,00	19,00
Free pebbles	20,00	1,00
Lacustrine limestone	21,00	1,00



Bore log 3036/57

N 31° 27' 8,90"
W 4° 25' 50,40"

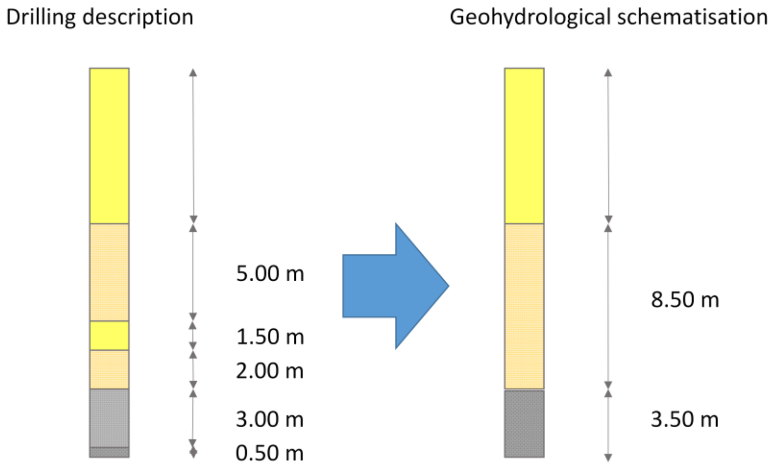
Soil type	From GS	Thickness
Ground surface	0,00	
Brown clayey silt, passages of coated pebbles (of 8 -10m)	19,00	19,00
Very cemented conglomerates	21,00	2,00
Lacustrine limestone	22,50	1,50



Bore log 3039/57

N 31° 27' 24,70"
W 4° 24' 36,38"

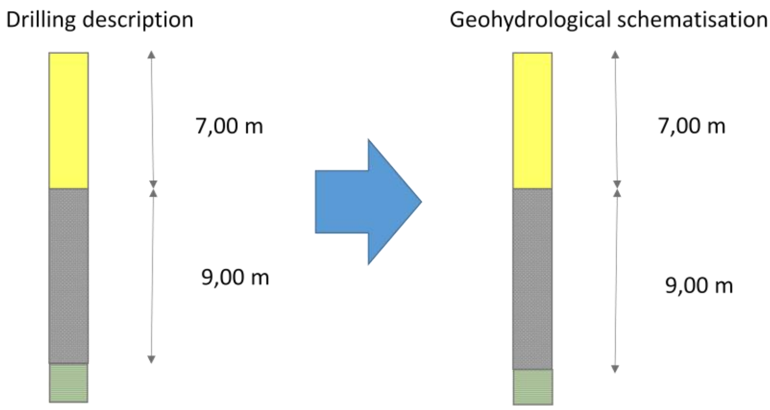
Soil type	From GS	Thickness
Ground surface	0,00	
Brown clayey silt	6,00	6,00
Lacustrine limestone	11,00	5,00
Brown clayey silt	12,50	1,50
Lacustrine limestone	14,50	2,00
Free alluvial pebbles	17,50	3,00
Conglomerates	18,00	0,50



Bore log 4049/57

N 31° 25' 24,15"
W 4° 17' 59,87"

Soil type	From GS	Thickness	Period
Ground surface	0,00		
Clayey silt	7,00	7,00	Quater-nary
Hard conglomerates	16,00	9,00	
Schist	34,00	18,00	Primair/ Devoon



Geological cross sections

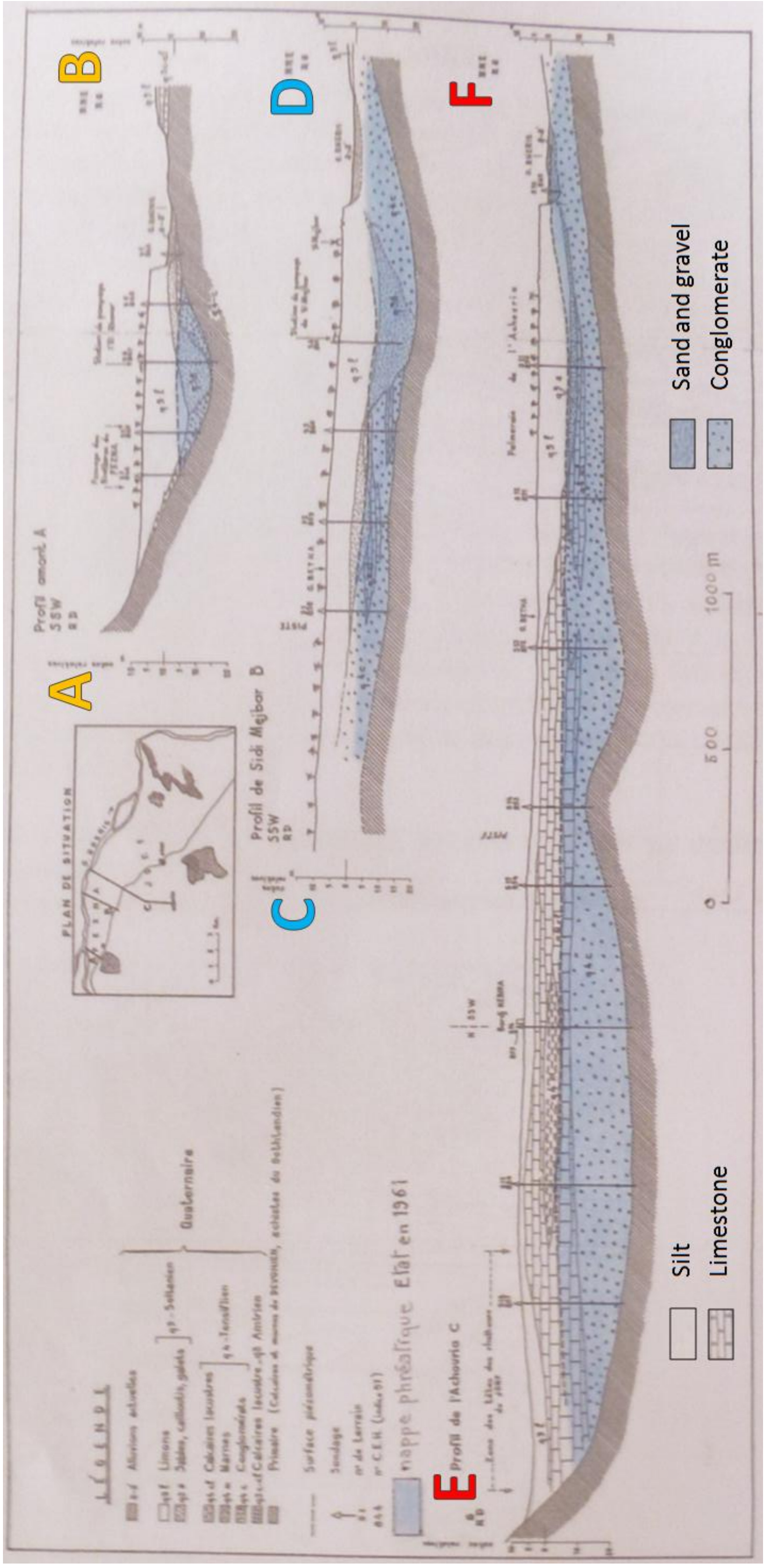


Figure 139: Geological cross sections A-B, C-D and E-F. For locations see figure 138.

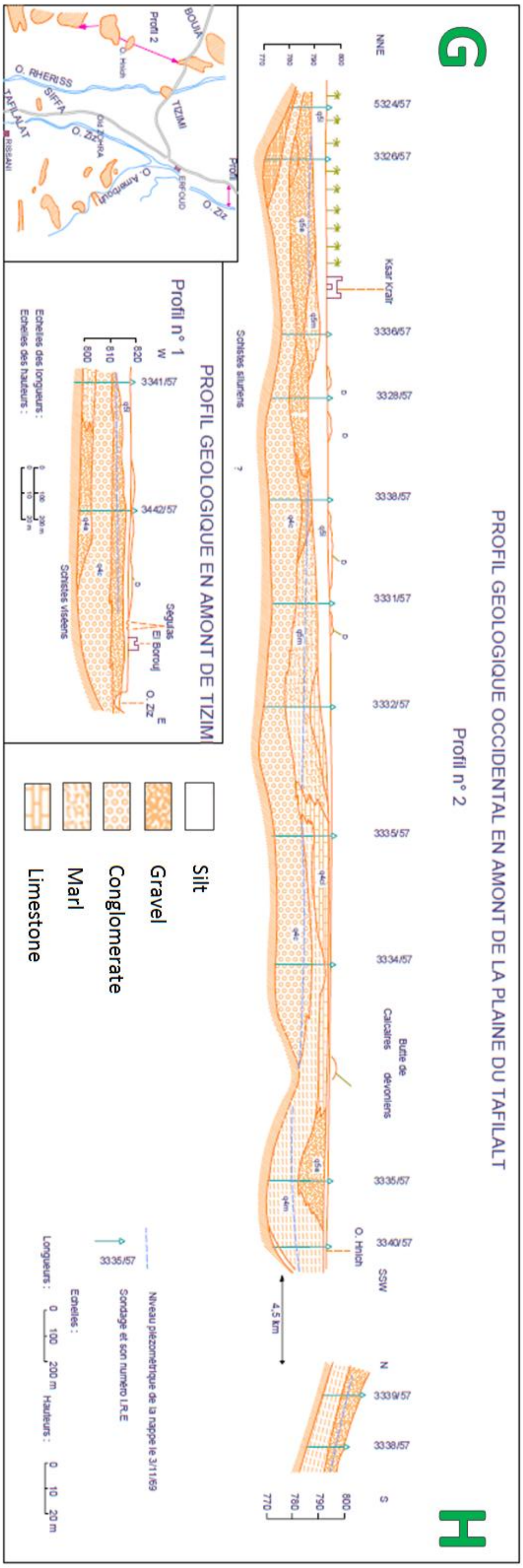


Figure 140: Geological cross section G-H. For locations see figure 138.

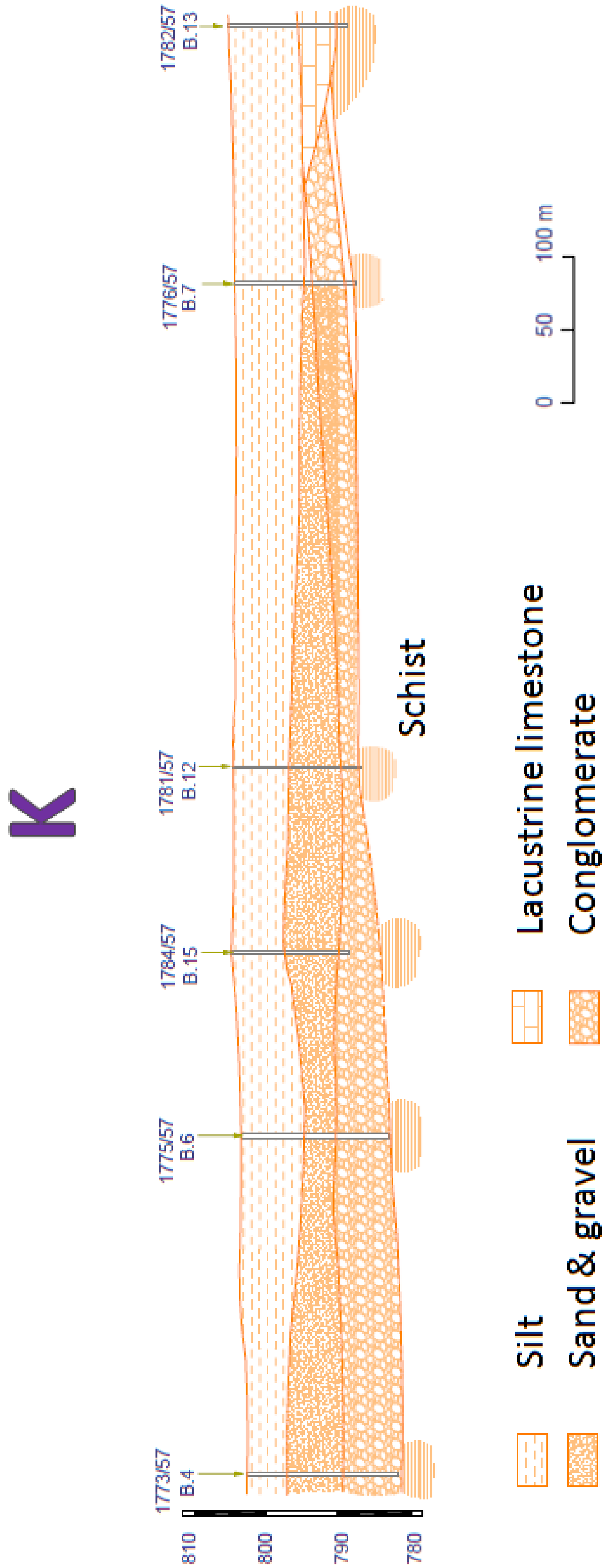


Figure 141: Geological cross section K. For locations see figure 138.

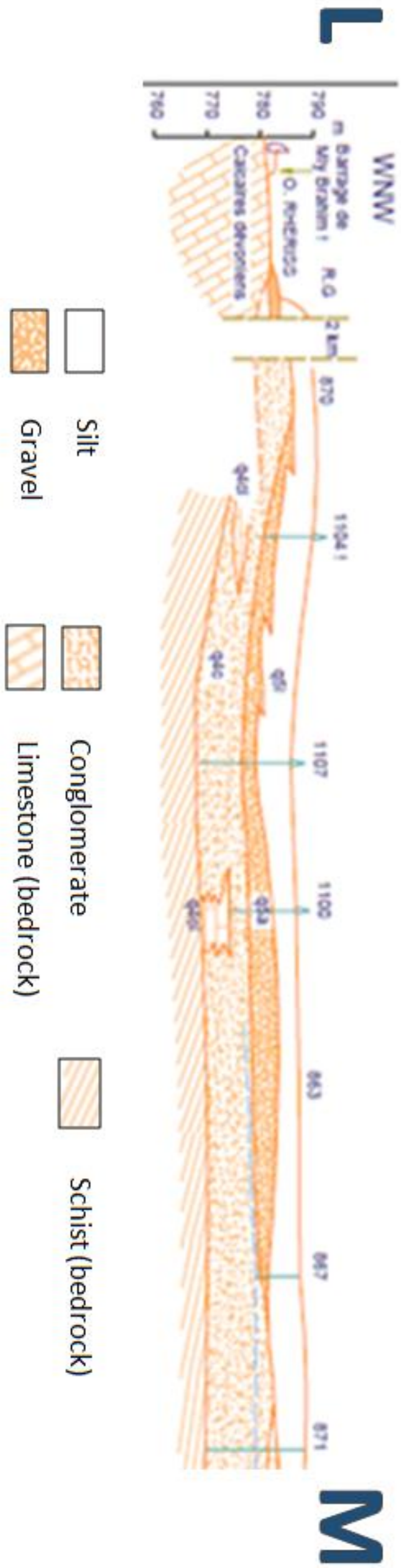


Figure 142: Geological cross section LM. For locations see figure 138.

Appendix I: Geological maps

Figure 143: The lay-out (boundaries) of the sedimentary aquifer of the Tafilalet (A.Bouaziz , 2005). The study area is encircled in red.

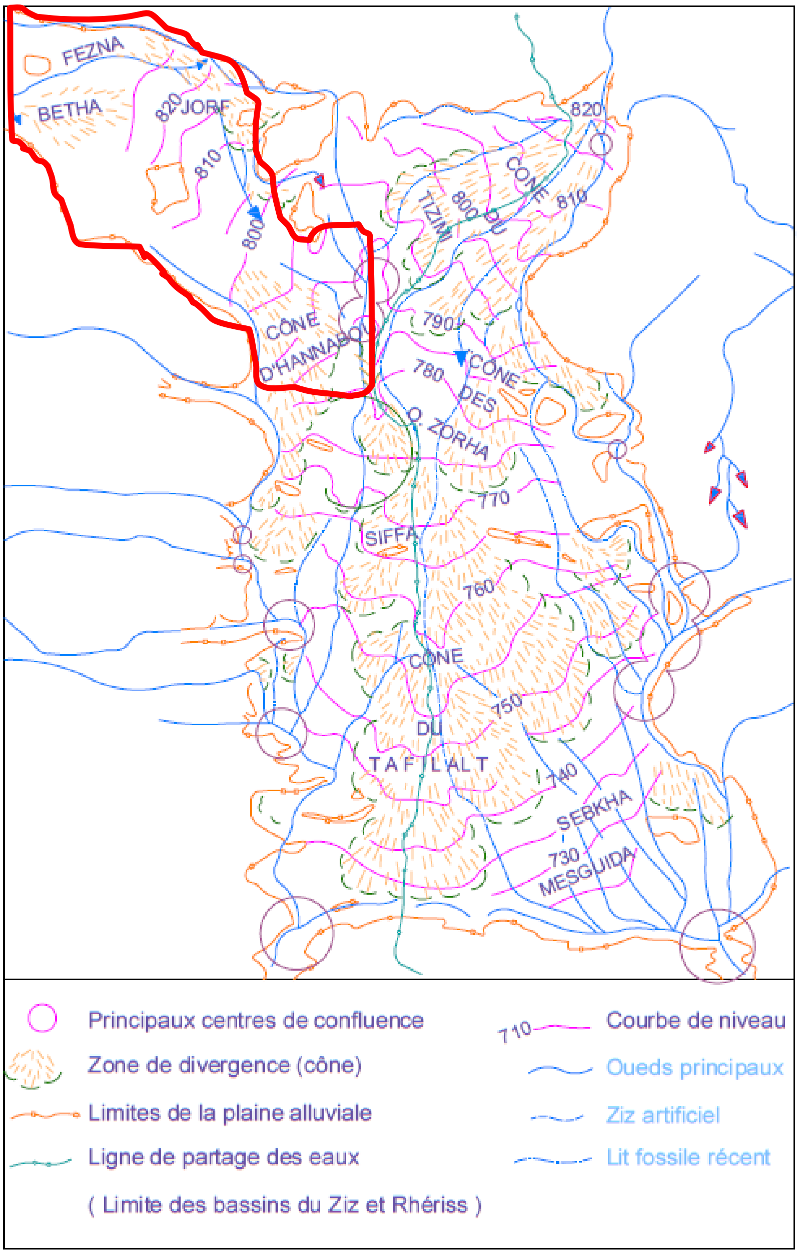


Figure 144: The lay-out (boundaries) of sedimentary aquifer system of the Tafilalet (Ruhard, 1977). The area of interested is encircled in red.

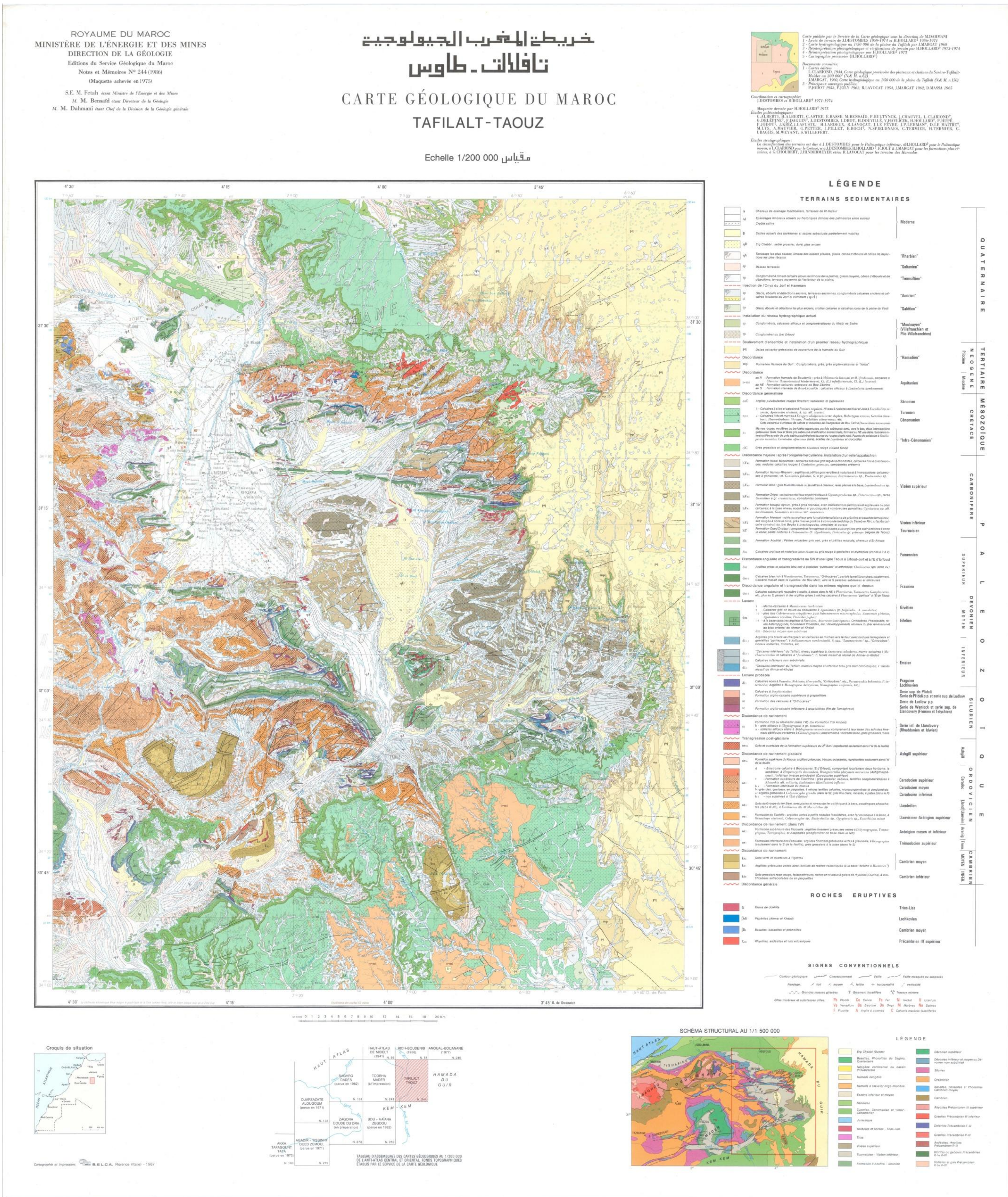


Figure 145: Geological map of the Tafilalet-Taouz.

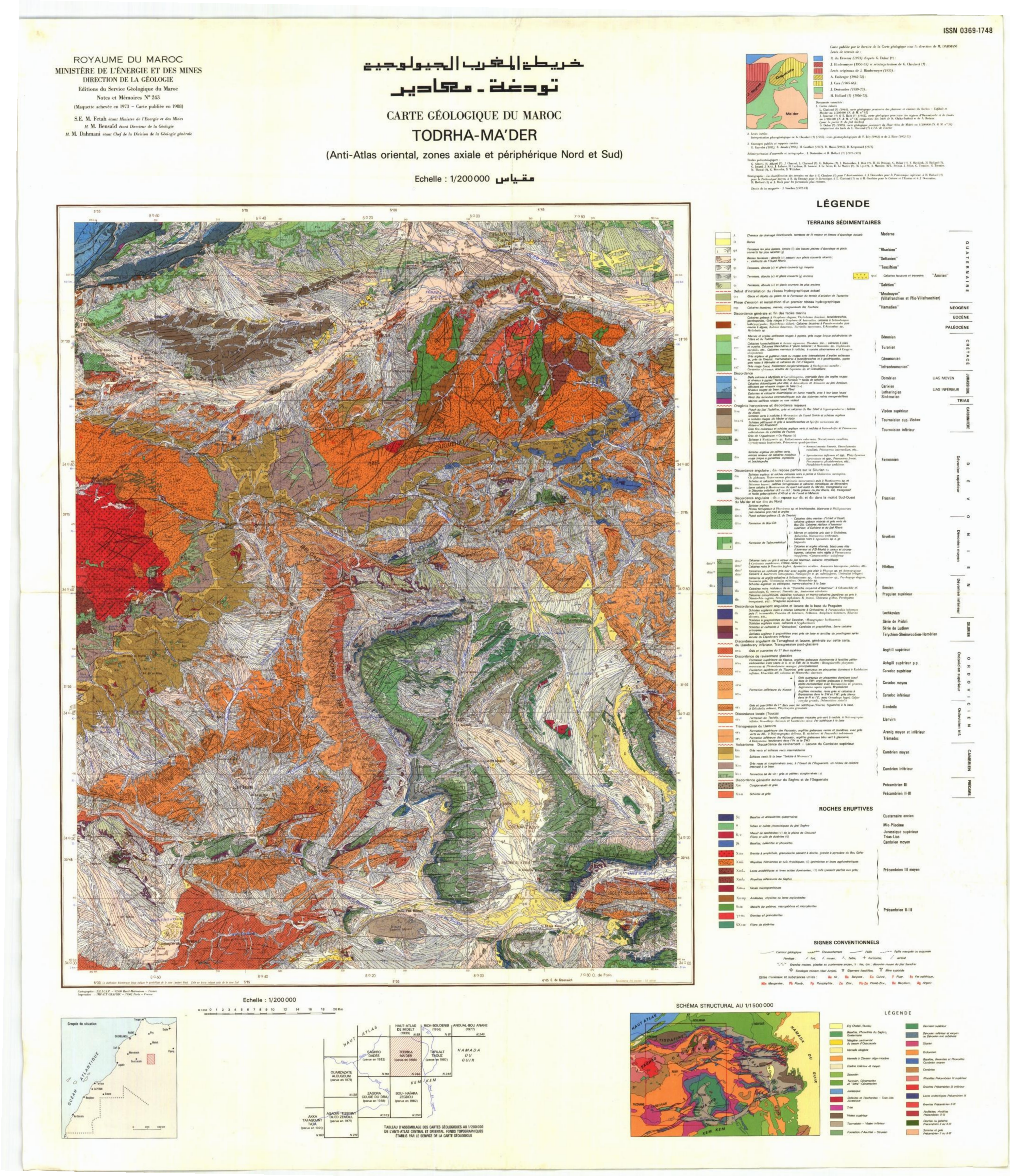


Figure 146: Geological map Todrha - Ma'der.

Appendix J: Building the model layers

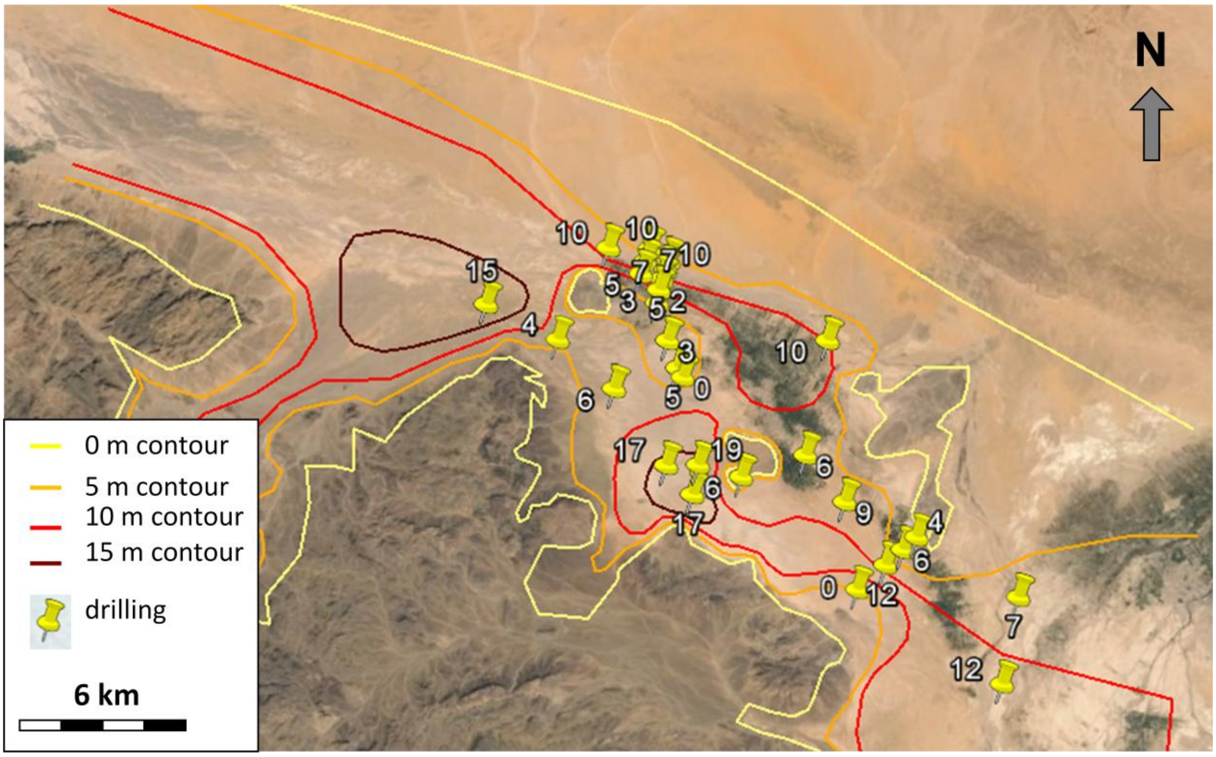


Figure 147: Drillings and contour information on the thickness of the silt formation.

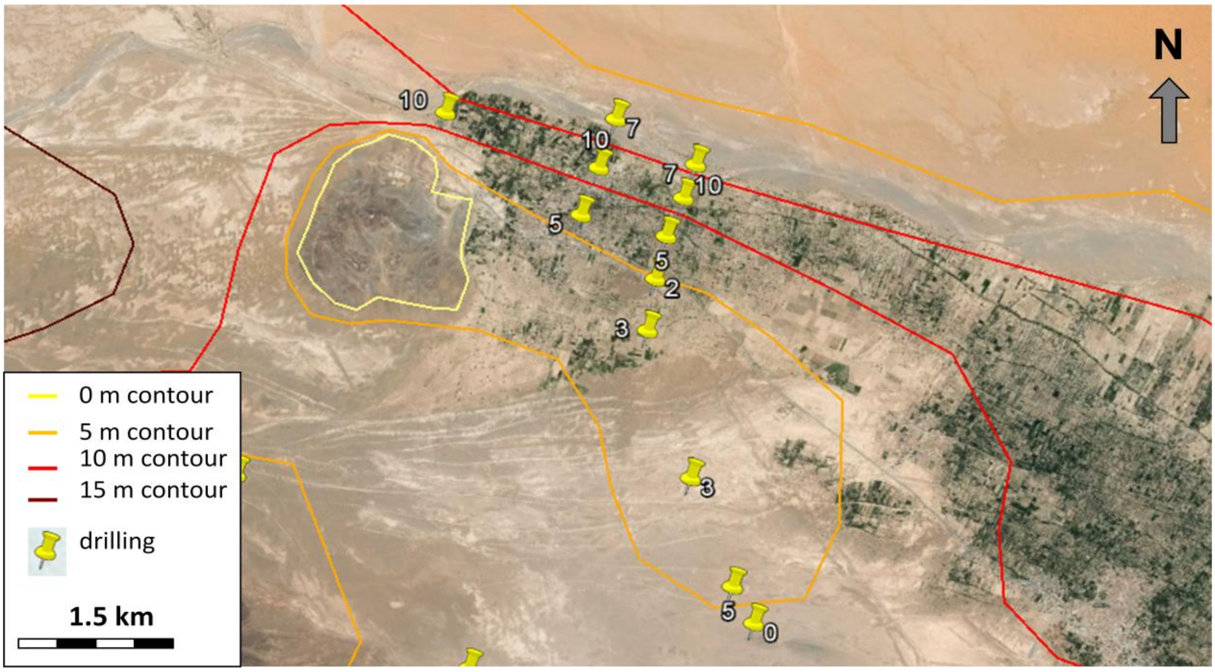


Figure 148: Drillings and contour information on the thickness of the silt formation (zoom near Fezna).

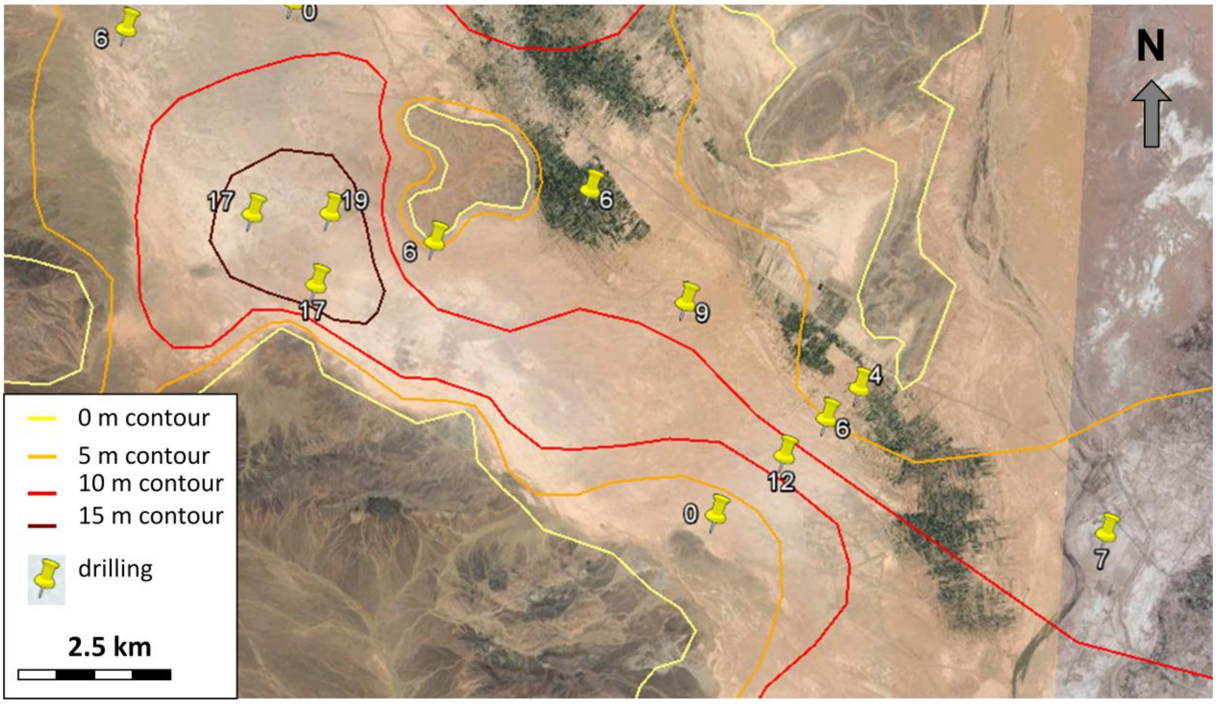


Figure 149: Drillings and contour information on the thickness of the silt formation (zoom Jorf and Hannabou).

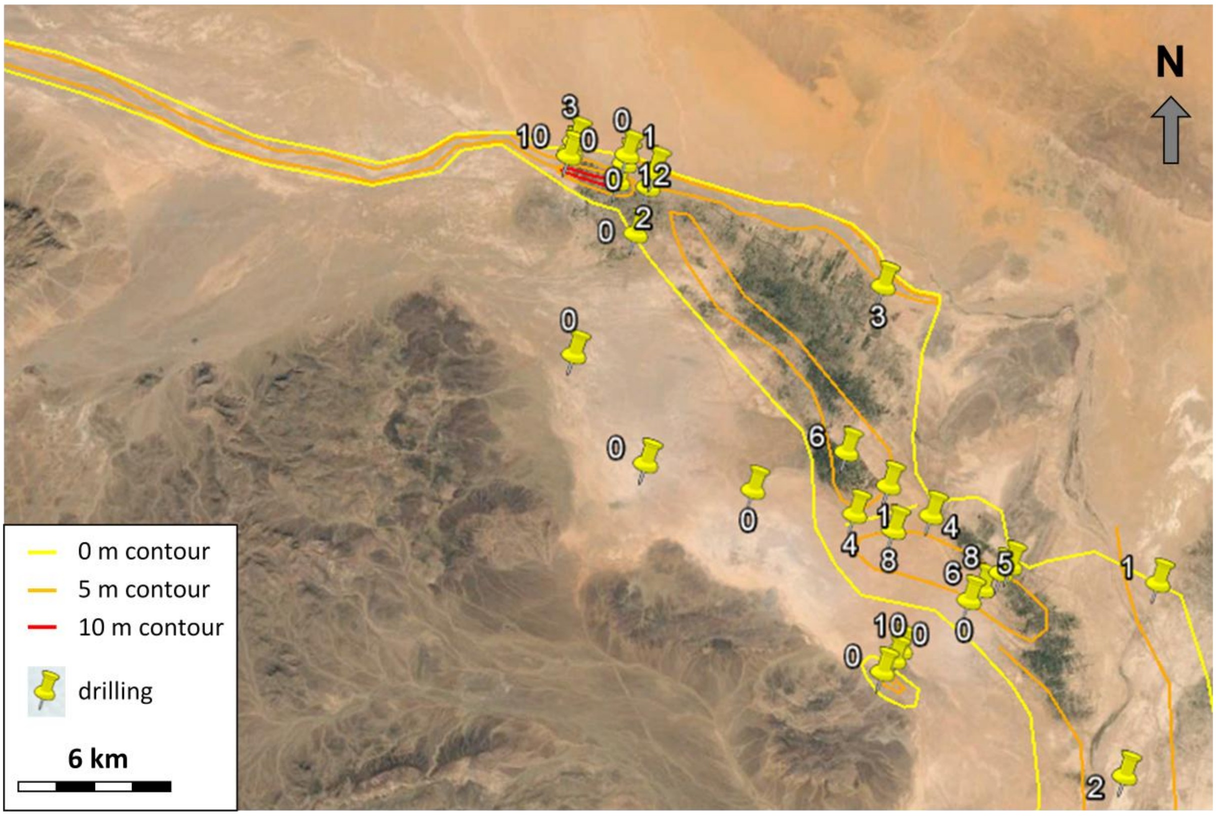


Figure 150: Drillings and contour information on the thickness of the gravel formation.

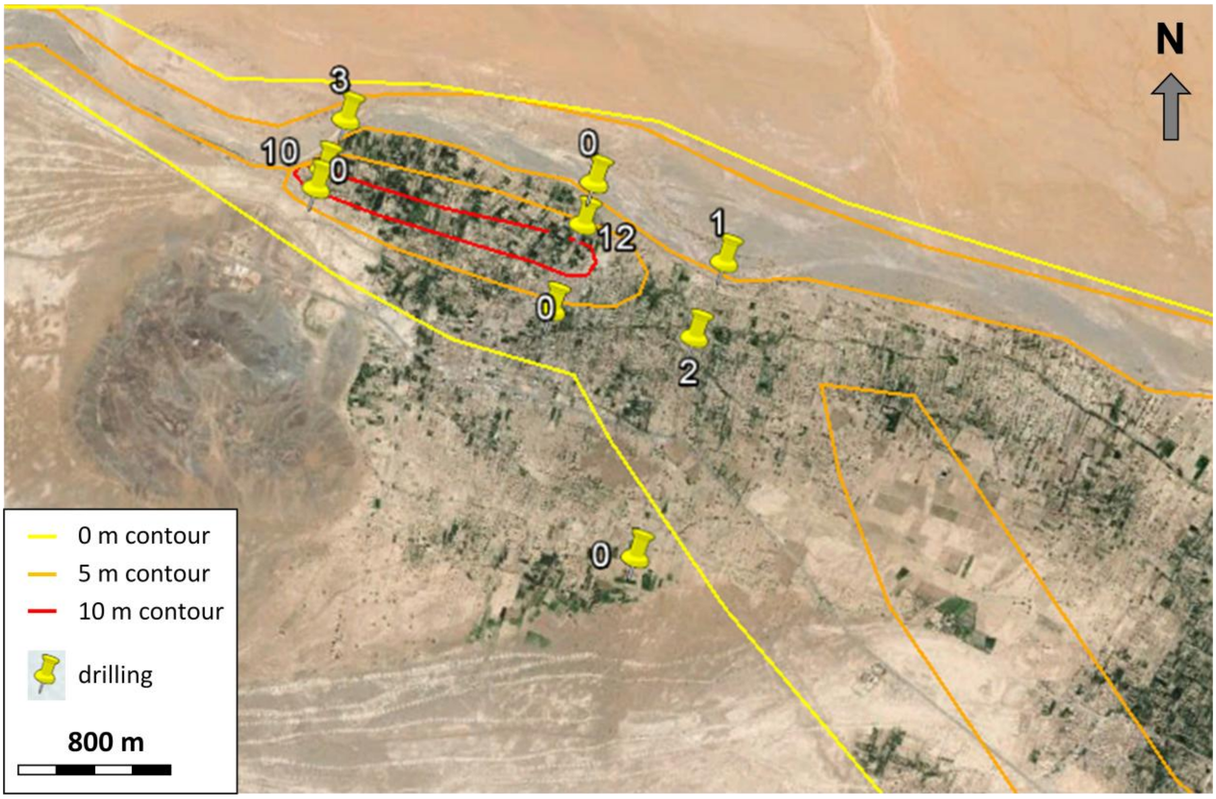


Figure 151: Drillings and contour information on the thickness of the gravel formation (zoom Fezna).

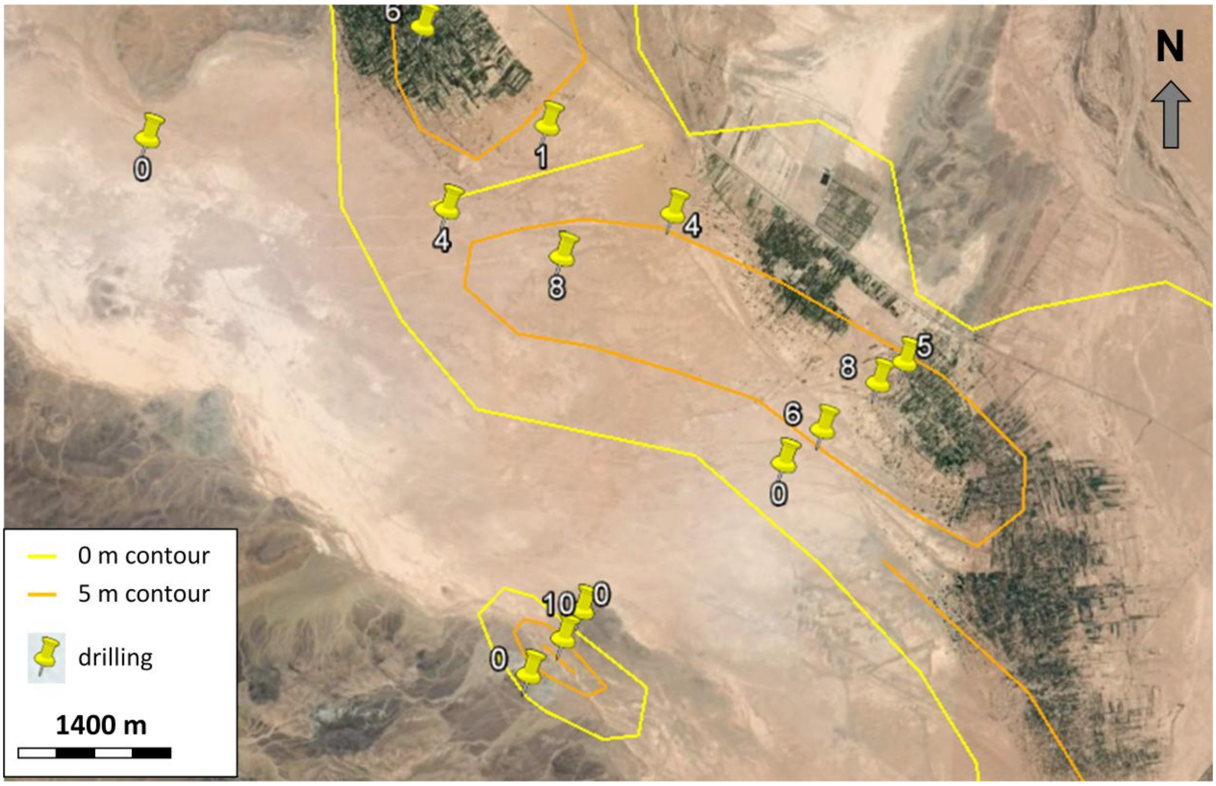


Figure 152: Drillings and contour information on the thickness of the gravel formation (zoom Hannabou).

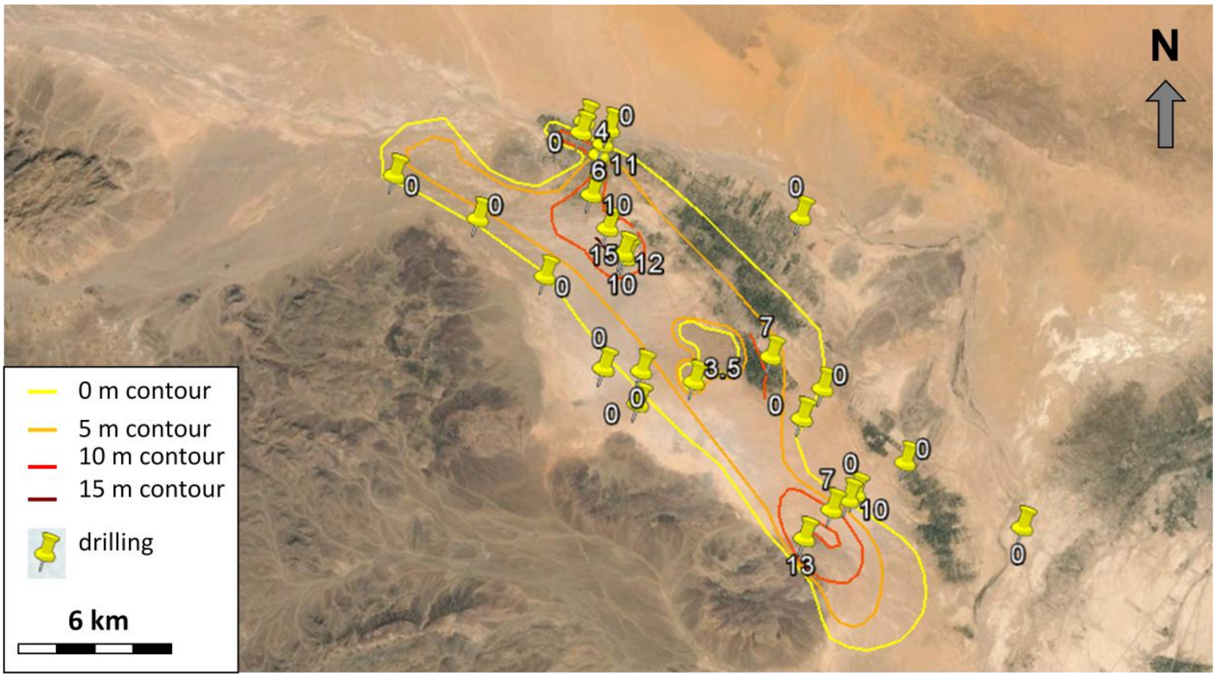


Figure 153: Drillings and contour information on the thickness of the limestone formation.

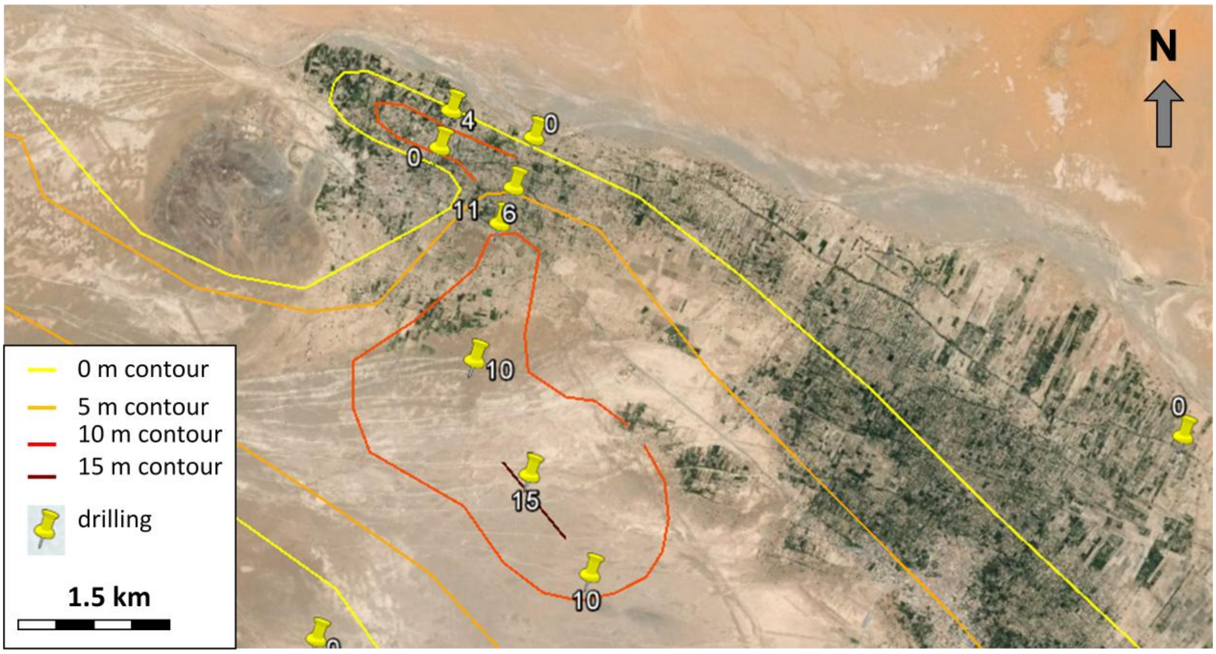


Figure 154: Drillings and contour information on the thickness of the limestone formation (zoom Fezna).

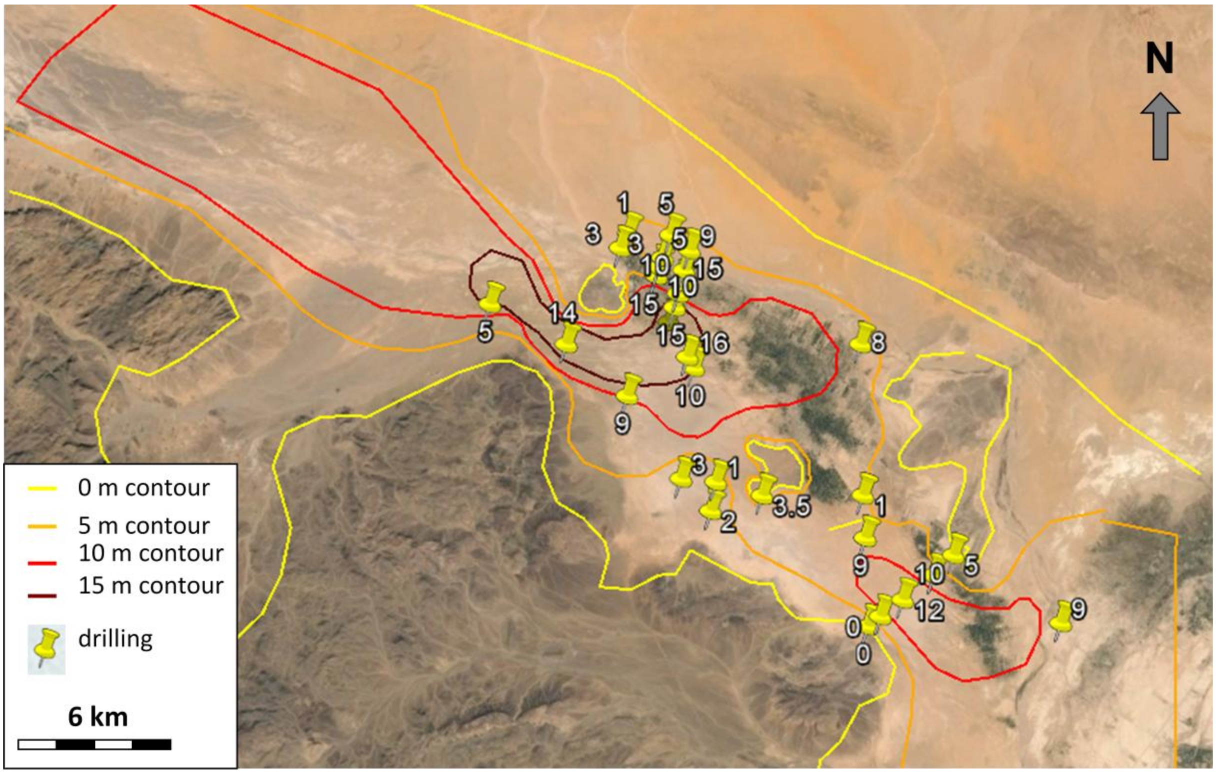


Figure 155: Drillings and contour information on the thickness of the conglomerate formation.

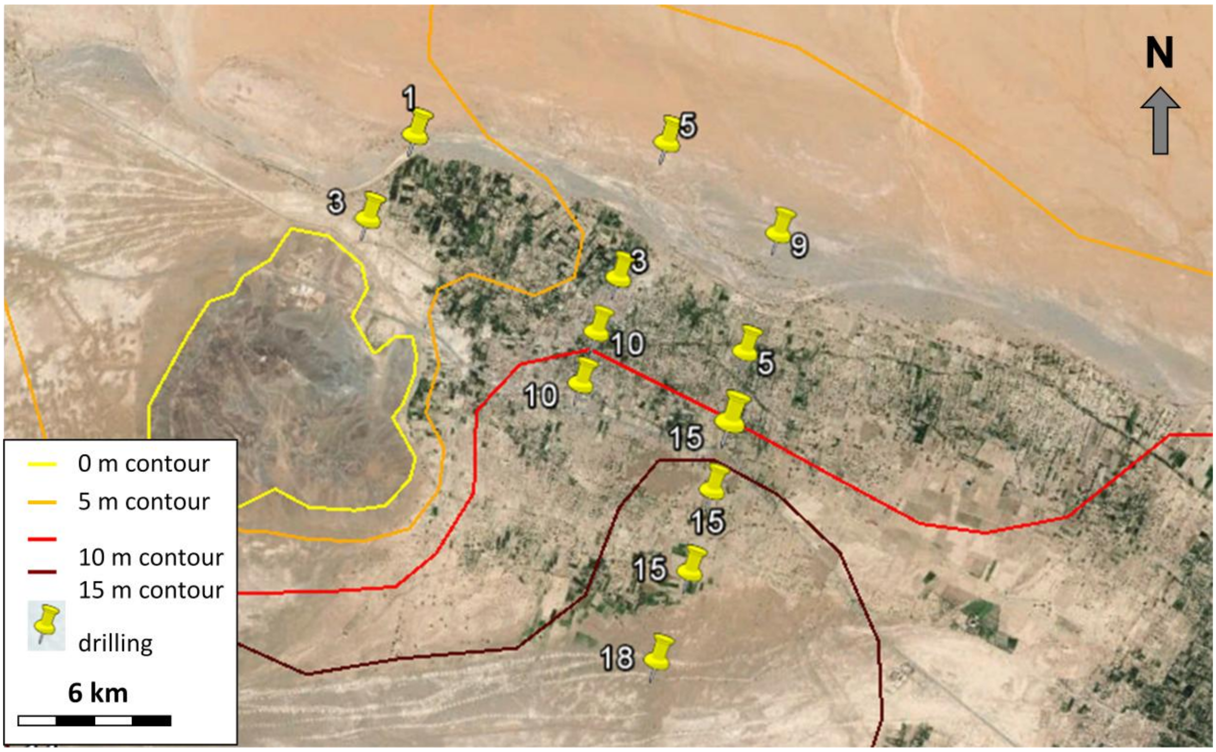


Figure 156: Drillings and contour information on the thickness of the conglomerate formation (zoom Fezna).

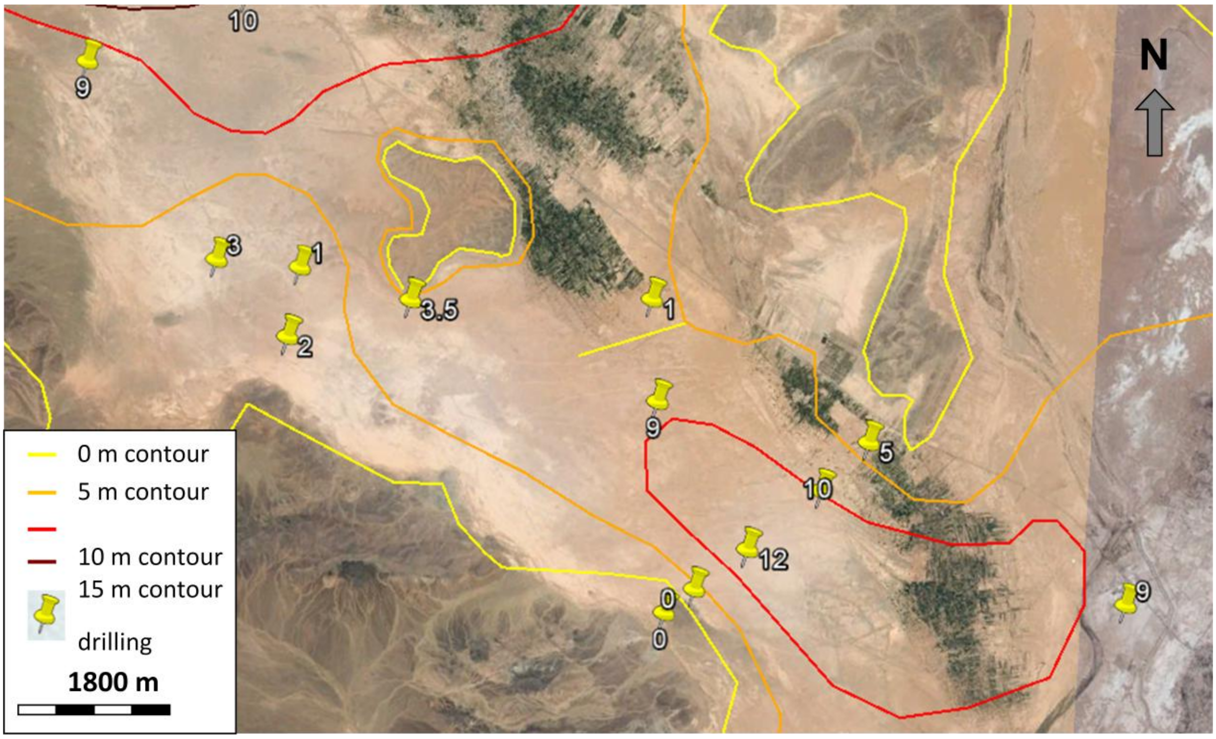


Figure 157: Drillings and contour information on the thickness of the conglomerate formation (zoom Jorf and Hannabou).

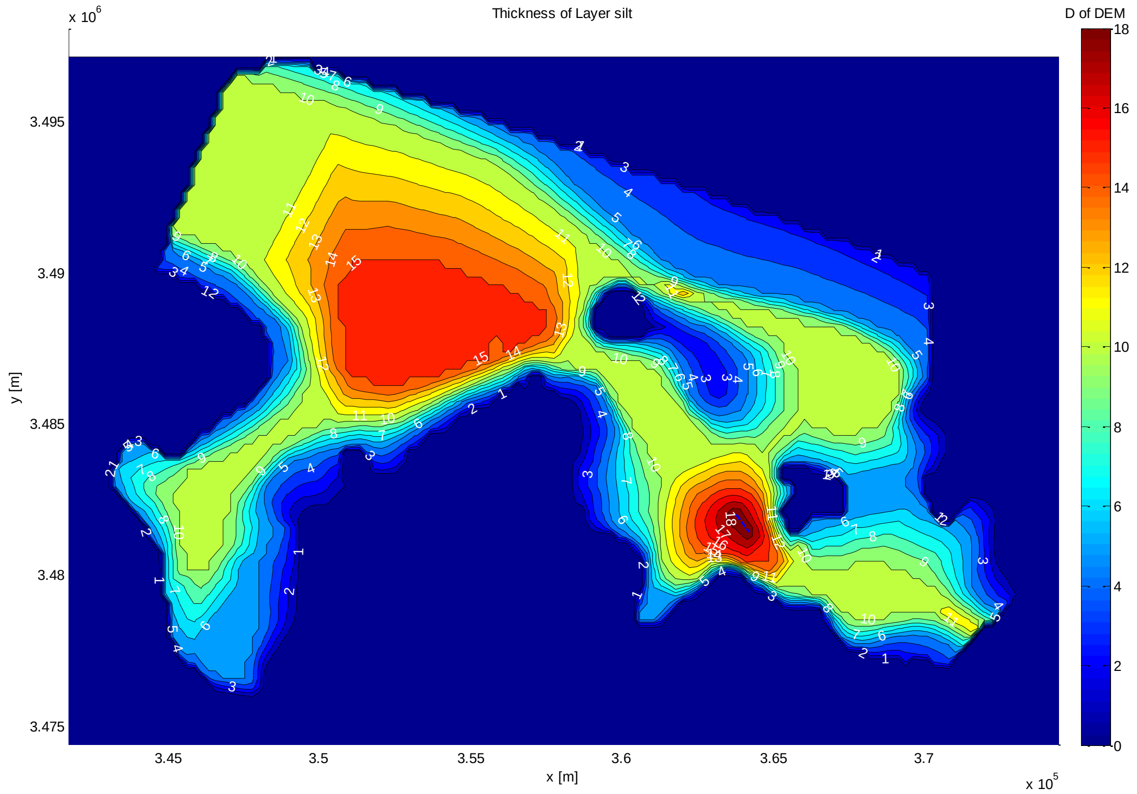


Figure 158: The thickness of the silt layer in the model.

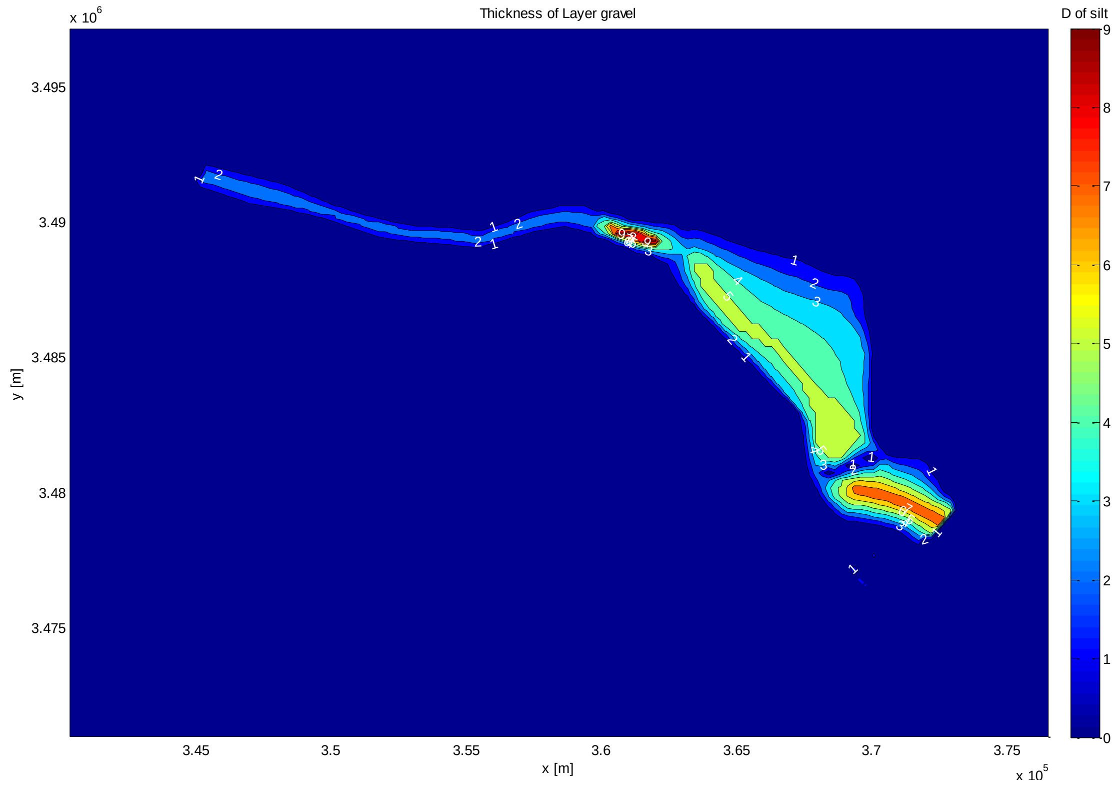


Figure 159: The thickness of the silt gravel in the model.

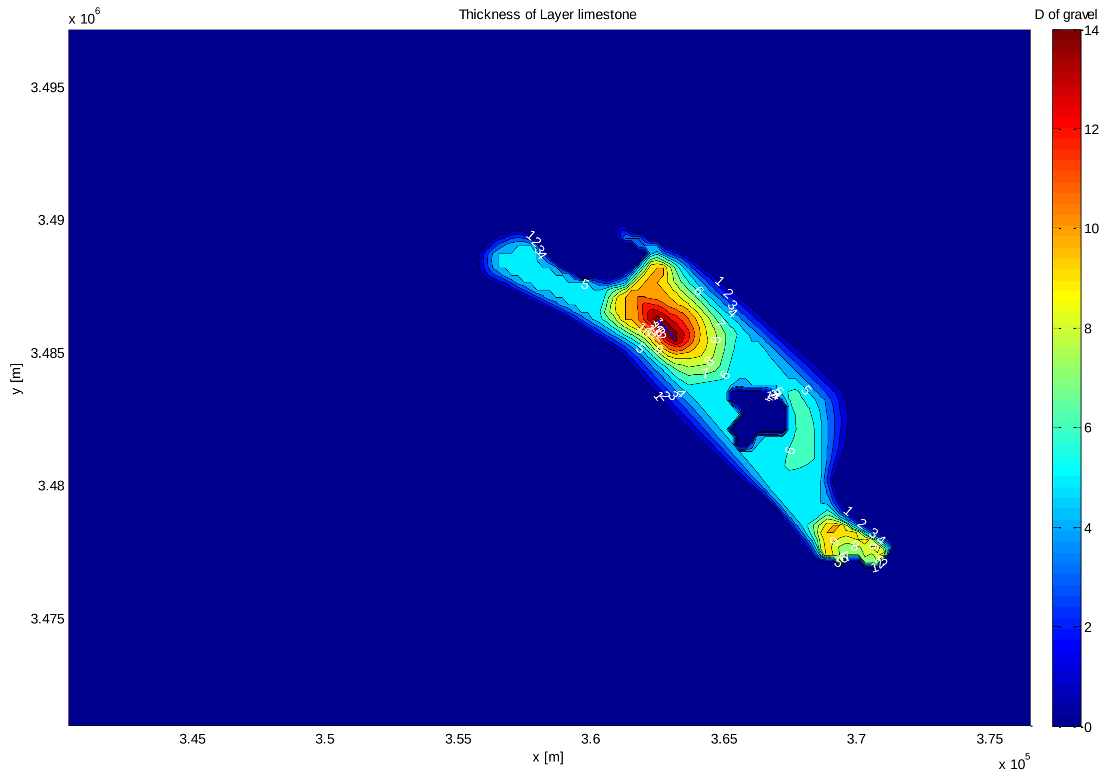


Figure 160: The thickness of the limestone layer in the model.

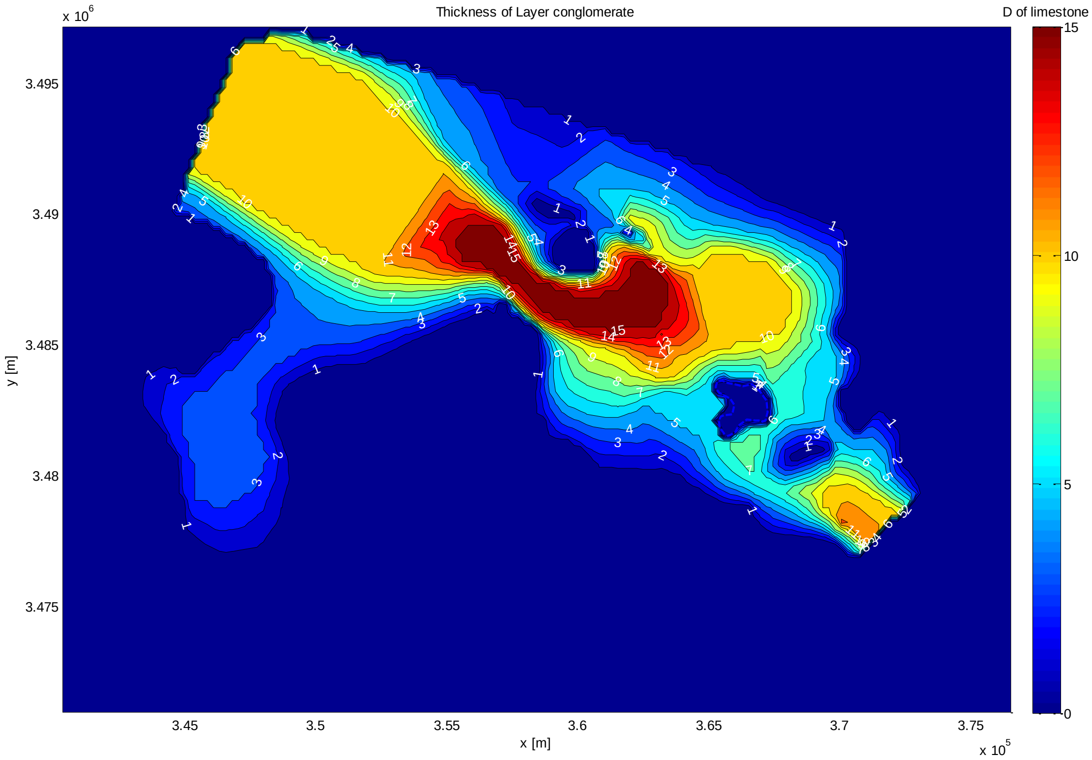


Figure 161: The thickness of the conglomerate layer in the model.

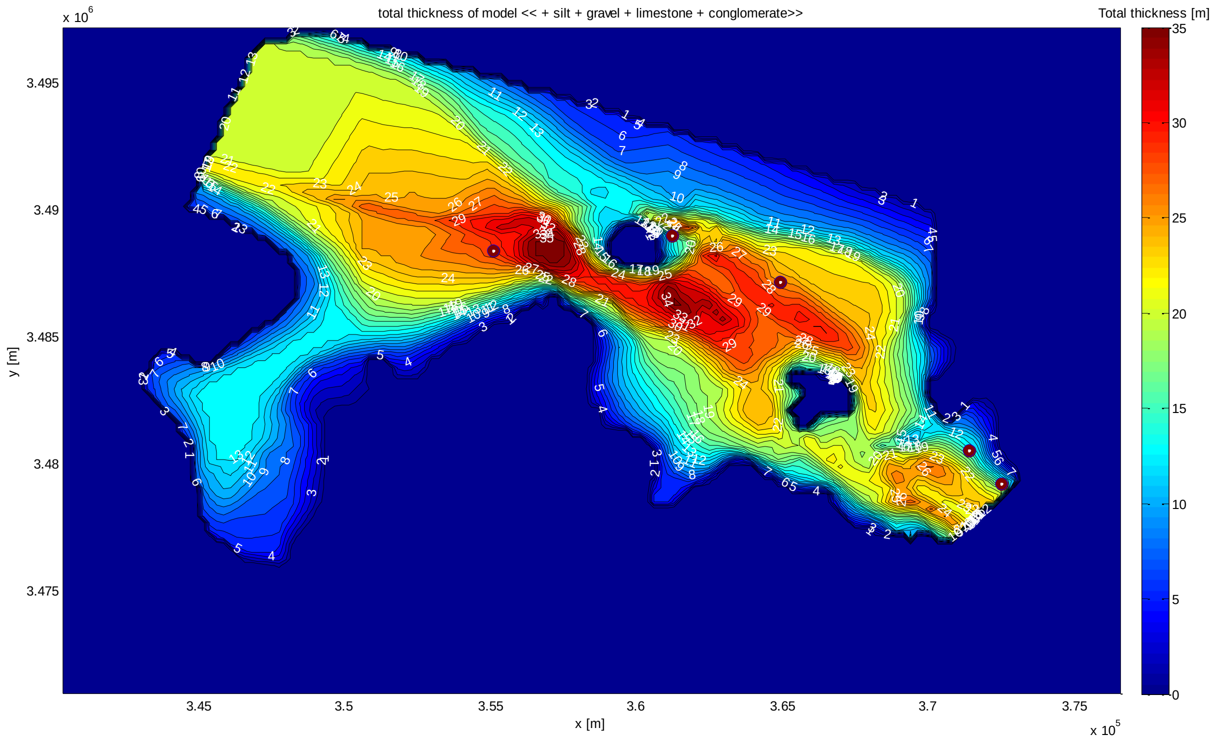


Figure 162: Total thickness of the sedimentary formations in the model.

Appendix K: Master plan agricultural areas

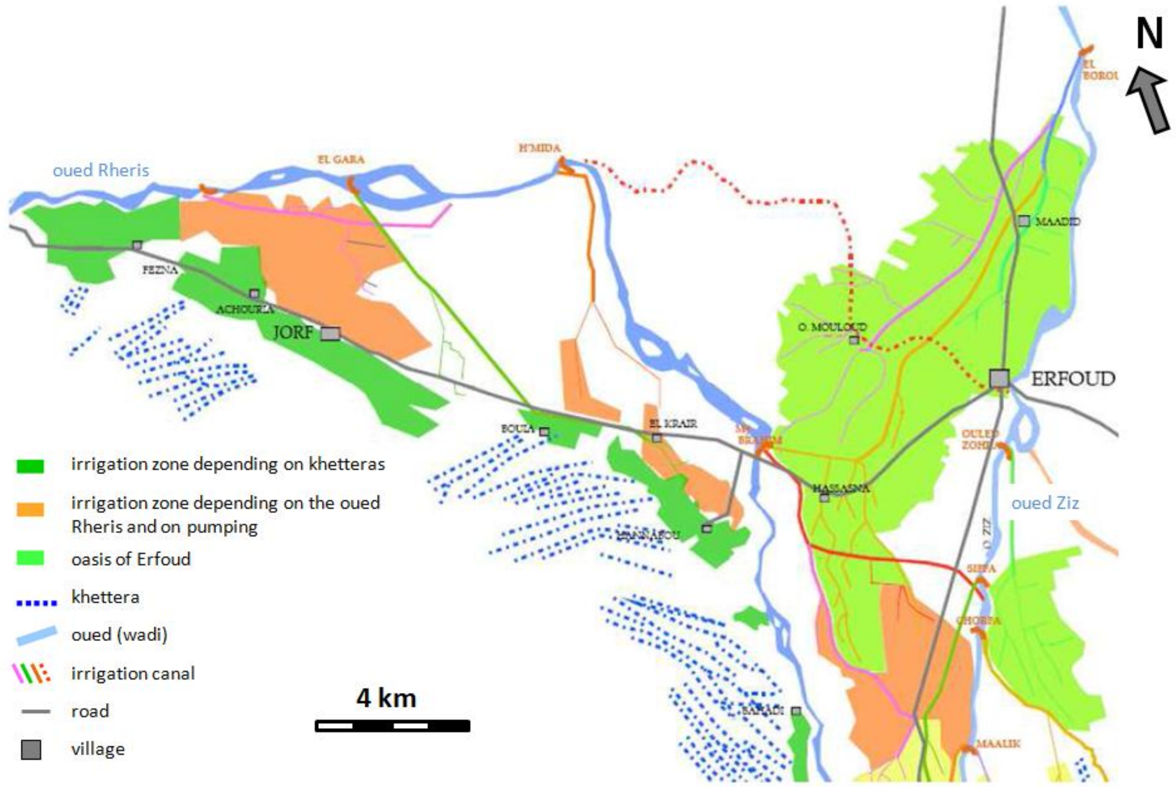


Figure 163: Master plan agricultural areas (Spoerry, 2007).

Appendix L: Hydraulic conductivities and transmissivites

Hydraulic conductivities from literature

Material	Hydraulic conductivity	
	cm/s	m/d
Gravel	10^{-1} to 100	100 to 10^{5}
Clean sand	10^{-4} to 1	10^{-1} to 10^{3}
Silty sand	10^{-5} to 10^{-1}	10^{-2} to 100
Silt	10^{-7} to 10^{-3}	10^{-4} to 1
Glacial till	10^{-10} to 10^{-4}	10^{-7} to 10^{-1}
Clay	10^{-10} to 10^{-6}	10^{-7} to 10^{-3}
Limestone and dolomite	10^{-7} to 1	10^{-4} to 10^{3}
Fractured basalt	10^{-5} to 1	10^{-2} to 10^{3}
Sandstone	10^{-8} to 10^{-3}	10^{-5} to 1
Igneous and metamorphic rock	10^{-11} to 10^{-2}	10^{-8} to 10
Shale	10^{-14} to 10^{-8}	10^{-11} to 10^{-5}

Figure 164: Typical hydraulic conductivity values for different type of formations (Fitts, 2002).

Comparing the transmissivities

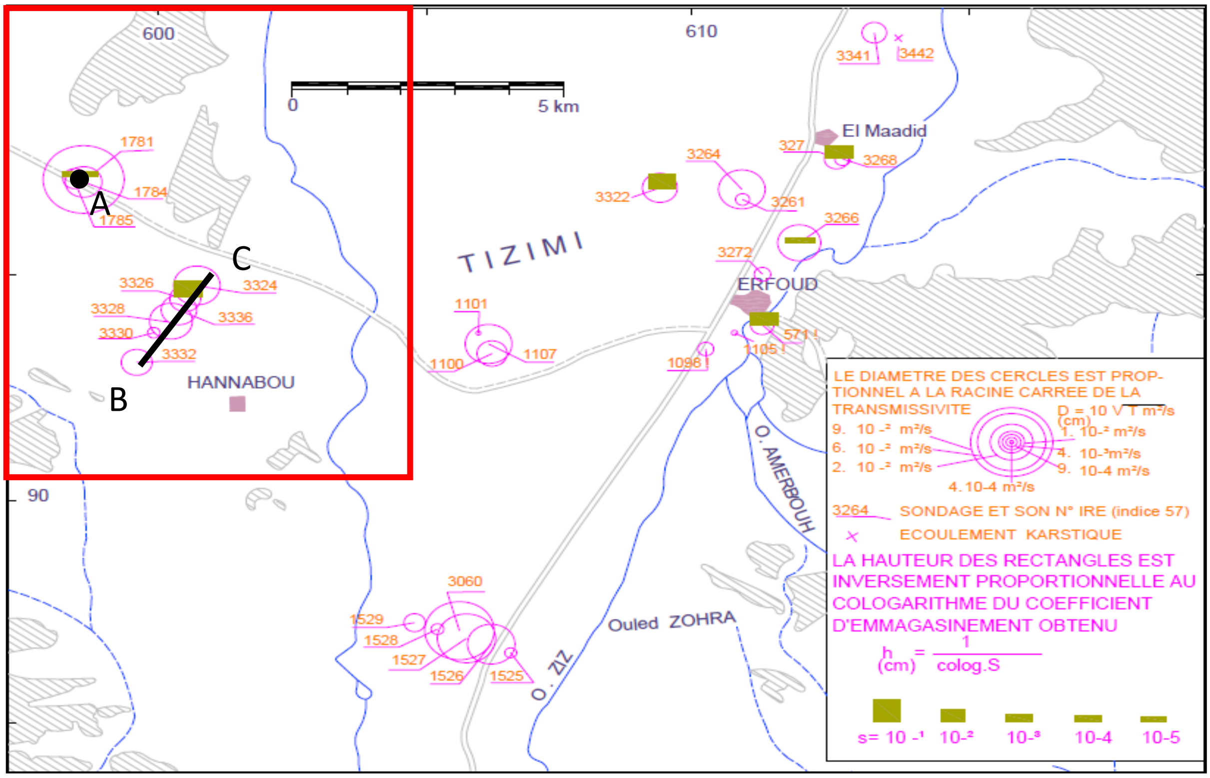


Figure 165: Transmissivities derived from pumping tests in the Northern part of the Tafilalet plain (Ruhard, 1977). The red box corresponds with the area presented in figure 166.

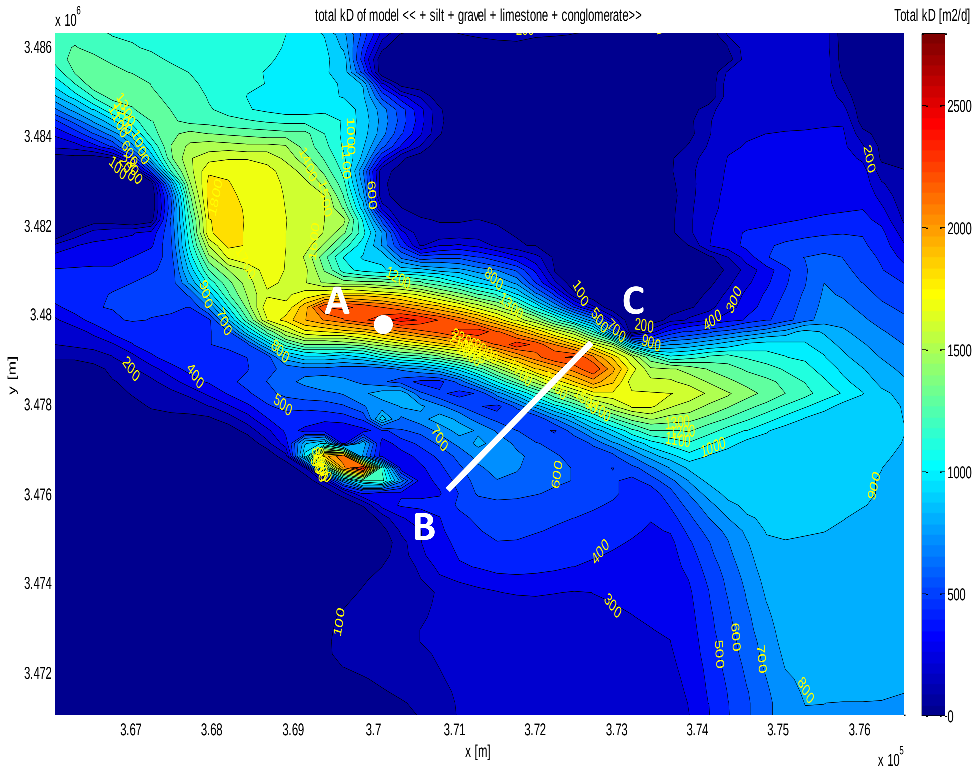


Figure 166: Transmissivities in the model using average hydraulic conductivity values of the ranges presented by Margat (Ruhard, 1977).

Appendix M: Comparing different cell sizes and model grid

In this appendix the importance of the cell grid size will be evaluated. Two difference cell sizes will be modelled: 180 by 180 m and 270 by 270 m. This will be done with the final model of the situation of the period 1959-1969. The calculated groundwater balances can be seen in table 54 and table 55.

Table 54: Comparison of the inflows with cell grid sizes 180 by 180 m and 270 by 270 m.

Inflow	Modelled		Ruhard/ Margat 1977	ORMVA 1998
	180 m	270 m		
	Mm3/y	Mm3/y	Mm3/y	Mm3/y
Groundwater inflow along outcrop Fezna	7.0	7.0	16	12.2
Recharge by precipitation and lateral inflow from Anti-Atlas	4.0	4.0	2	-
Groundwater inflow lateral Anti-Atlas	0.2	0.2		
River inflow Fezna-Jorf	0.9	0.9	5	2.2
Irrigation infiltration Fezna-Jorf	9.4	9.4	5	11
Total	**21.5**	**21.5**	**28**	**25.4**

Table 55: Comparison of the outflows with cell grid sizes 180 by 180 m and 270 by 270 m.

Outflow	Modelled		Ruhard/ Margat 1977	ORMVA 1998
	180 m	270 m		
	Mm3/y	Mm3/y	Mm3/y	Mm3/y
Groundwater outflow near Krayr	4.8	4.9	11	11
Pumping	7.8	7.9	2	8
Khettaras	9.4	8.6	12	3.7
Evapotranspiration	-	-	2.5	2.2
Drainage (Rheris)	-	-	0.5	0.5
Total	**22.0**	**21.4**	**28**	**25.4**

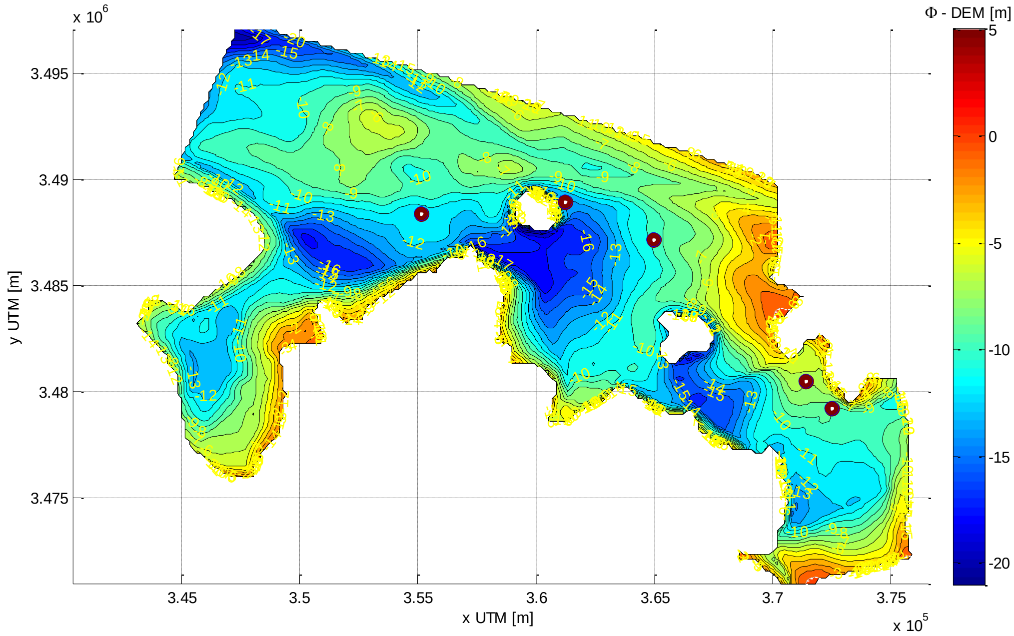


Figure 167: Calculated groundwater (with respect to the surface) with cells sizes of 180 by 180 m.

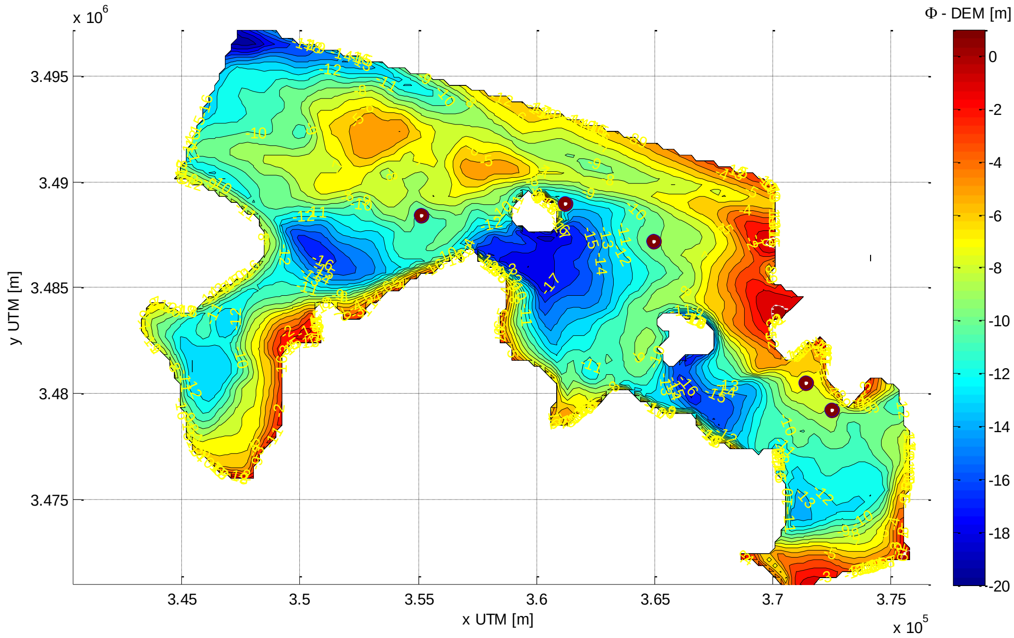


Figure 168: Calculated groundwater (with respect to the surface) with cells sizes of 270 by 270 m.

Both the groundwater balance and the groundwater levels show minor differences. With use of grid cell sizes of 270 by 270 m the khettaras extract 8.6 Mm^3/y compared to 9.4 Mm^3/y for the 180 by 180 m cell size. The water tables differ at most 1 meter.

Model grid

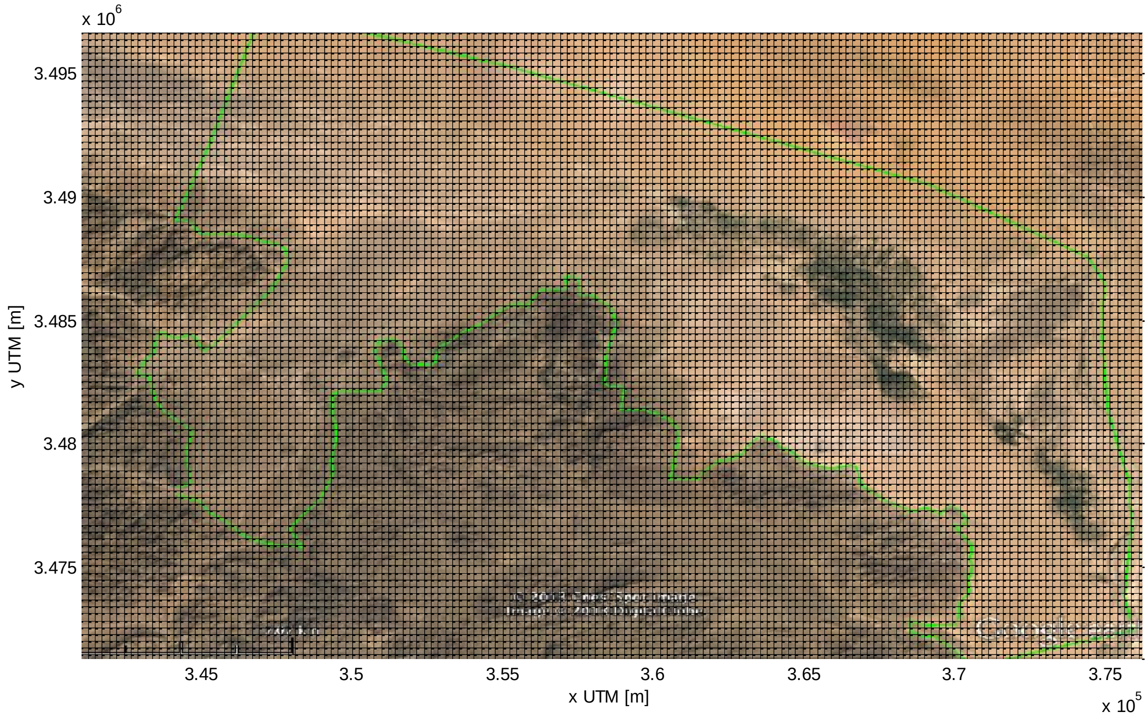


Figure 169: Raster of the model area. Only the grid cells within the model boundary (green line) are included in the model. The cells have a size of 270 by 270 m.

Appendix N: Modelled piezometric levels Hamada system

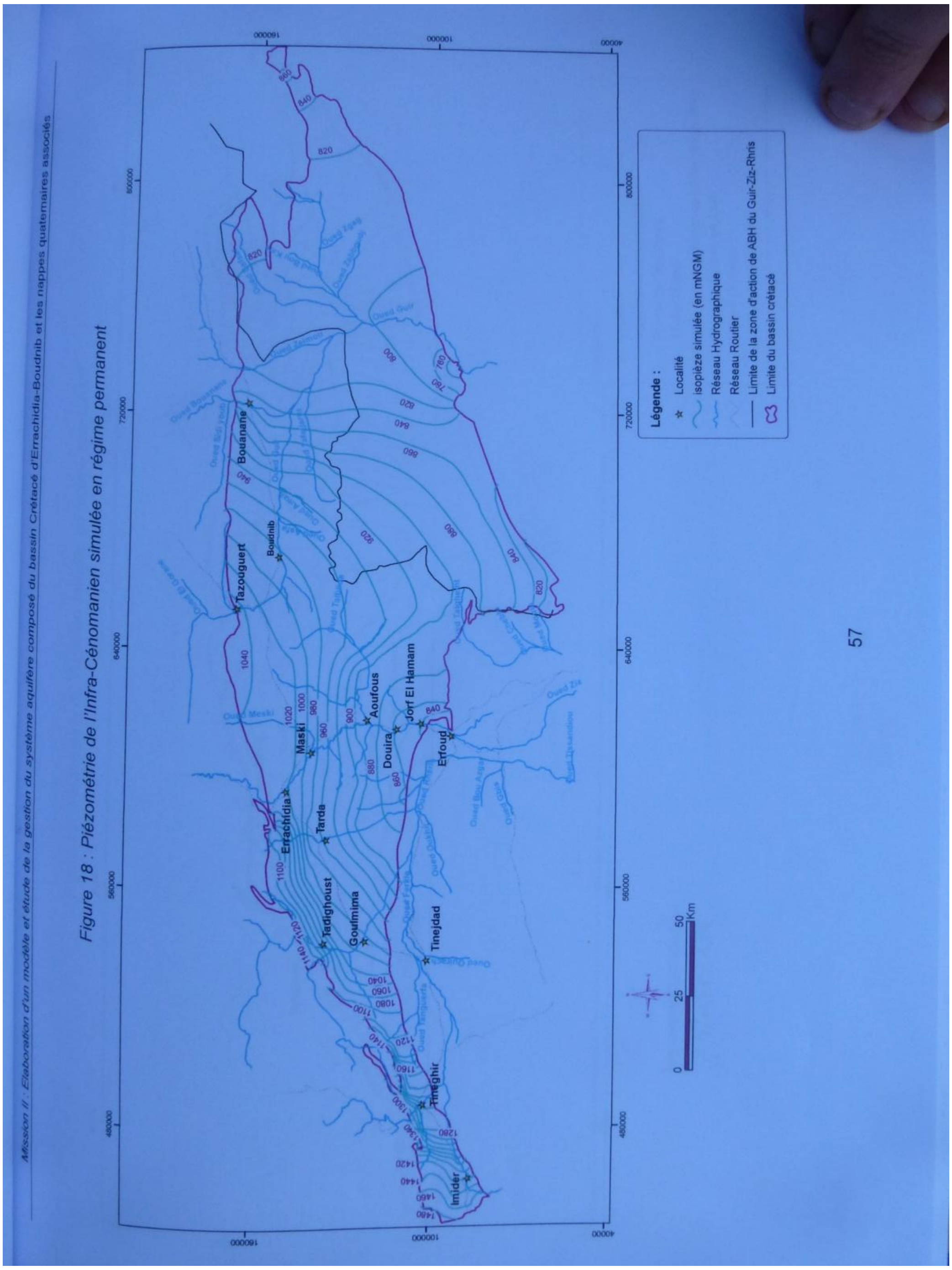


Figure 170 : **Calculated piezometric levels by the model of the Hamada system. The modelling is commisioned by the ABH Guir-Ziz-Rheris.**