Uncertainty in exploitation rates and numerical modeling of its impact on seawater intrusion in the Korba aquifer (TUNISIA)

J. Kerrou, G. Lecca, P. Renard and J. Tarhouni

Abstract The Cape Bon peninsula, located 60 km South East of Tunis, is one of the most productive agricultural areas in Tunisia. At the same time, it suffers heavily from water scarcity and salinization due to seawater intrusion especially in the Korba aquifer. In 2002, the Korba aquifer was exploited from more than 9000 wells for a total volume of 54 106 m3.

Groundwater balance estimates in the area show that one of the major sources of uncertainty is the evaluation of the aquifer exploitation. Indeed, no precise information is systematically recorded by the local authority concerning either the current extraction rates or their evolution in time. Knowledge of spatial and temporal exploitation distribution is crucial to understand the dynamic of the aquifer to model the seawater intrusion and to investigate optimal management scenarios.

In this paper, we present a multivariate analysis to evaluate the uncertainty in the estimation of exploitation rates using secondary information including: aquifer geometry and physical parameters, surface water irrigation records and field measurements. Using direct measurements and secondary data, a geostatistical model of exploitation rates was constructed. The impact of the exploitation uncertainty on the seawater intrusion was evaluated with Monte Carlo simulations, based on a 3D density dependent variably saturated groundwater flow and miscible salt transport model. To circumvent the large computing time required to run multiple 3D simulations, the numerical model was run on the GRID infrastructure developed by the EGEE project (Enabling Grid for E Science in Europe).

Results demonstrated the possibility of using secondary information in a geostatistical framework to model the spatial distribution of pumping rates and its uncertainty. The Monte Carlo simulations showed that uncertain pumping rate localization led to a zone of 20.4 km^2 where the groundwater heads and concentrations were not known with accuracy. While the size of this uncertain zone remains small with respect to the size of the aquifer, it can be of high importance in terms of potential economic impact because of the risk of agricultural productivity losses when using this water.

Index Terms Monte Carlo simulations, Seawater intrusion, Pumping rates, Uncertainty.

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I. Introduction

The fundamental and applied research related to the understanding and management of coastal aquifers is very active worldwide [1], [2]. This is not surprising because coastal areas are the most densely-populated areas in our planet, about 70 % of the world's population dwells in coastal areas [1]. At the same time, groundwater resources in these areas are intensively exploited despite their extreme vulnerability to salinization by seawater intrusion. Consequently, many quantitative and qualitative problems affecting subsurface freshwater occur, especially in arid coastal zone. In this work, we present the case study of the Korba aquifer located in the Cap Bon peninsula (Fig. 1), 60 km South-East of Tunis (Tunisia), which suffers heavily from water scarcity and salinization due to seawater intrusion.

Many theoretical research and case studies [3], [4] show the validity and the interest of using numerical models to simulate the physics of seawater intrusion as a tool for sustainable management of groundwater resources. Nevertheless, the modelling of a real aquifer system remains an extremely delicate task for mainly because of the lack of accurate data allowing to characterize aquifer parameters and to estimate all the outputs and inputs of the system. Moreover, most of the input data are affected by a given uncertainty, which, in turn, affects the model outputs.

Recently, several authors started to develop techniques to quantify the uncertainty associated with sea water intrusion resulting from an incomplete knowledge of aquifer parameters [5], [6]. The results focus mainly on the uncertainty of the position of the interface between freshwater and seawater within the aquifer. The parameter of which the associated uncertainty is analyzed more often is the hydraulic conductivity [7]. Other model input parameters were studied stochastically to evaluate the effect of their inherent uncertainty on the consequent flow and transport processes. For example, [8], [9] studied the effects of the uncertainty associated with conceptual models and input parameters to evaluate the transport of radionuclide in a nuclear test site in Alaska. The results indicate that the mathematical solution to the flow and the transport problems are very sensitive to recharge rates and hydraulic conductivity. Unfortunately, stochastic models presented are often too simplified, and their applications to real cases remain rare.

The Korba aquifer is one of the most studied aquifer in Tunisia (Fig. 1). Two numerical groundwater models were developed previously [10], [11]. A particular difficulty encountered by both groups of authors was to obtain a reliable estimate of the extraction rates from the thousands of private wells in the region. As a consequence, the evaluation of the regional groundwater resources still remains uncertain.

Our interest is the global uncertainty over all of the Korba aquifer parameters. In this paper, we focus only on the uncertainty associated with the exploitation rates and its impact on the seawater intrusion. Indeed, in 2002 only a few data of pumping rates existed among the 9000 active wells in the region with a poor description of their time evolution. Therefore, the main objectives of this work are to estimate the pumping rates and the uncertainty associated with their spatial distribution by using multivariate regression of secondary data. In addition, using a probabilistic estimate we intend to evaluate the effect of this forcing term uncertainty on the 3D density-dependent flow and transport regional model results. Uncertainties originating from the interpolation as well as conceptual or mathematical errors are not studied here.

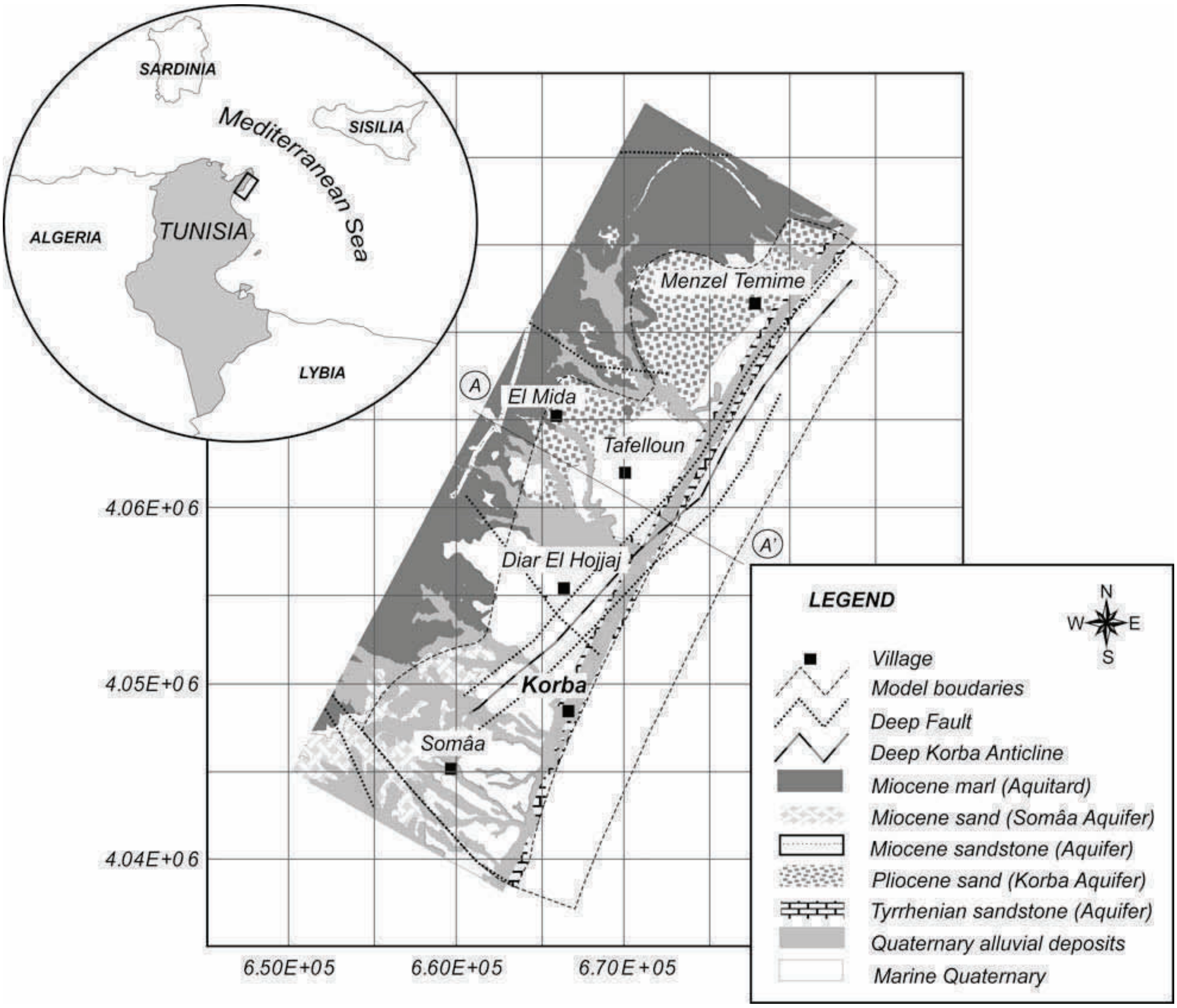

Fig. 1 Location map of the Korba aquifer and geological settings.

II. Hydrogeological Conceptual Model

The surface area of the Korba aquifer system is approximately 400 km^2, and its inland lateral extension is in agreement with the geological outcrops (Fig. 1). Two main geological units constitute the aquifer system. The first unit was formed during the Pliocene age by marine deposits in the Dakhla syncline in the north of Korba city. This geological formation corresponds to dominant shally yellow sand with alternating clay and sandstone levels and might be covered by Quaternary sandstone near the coastline. The second unit, called "the sands of Somâa", is of late Miocene age and is localised only in the south of the study area. This unit is composed mainly of thick fine sand layers of continental origin including conglomeratic levels and clay lenses. The Pliocene thickness might reach 120 m and decreases toward the west, while the Somâa formation thickness might exceed 420 m. Both units are underlined by Miocene marls which form the bedrock of the system. This aquitard contains lenticular sandstone bars of variable thickness and depth but often separated by thick layers of impervious marls (Fig. 2).

From a hydrogeological point of view, the two geological units are connected by the leakage from one to the other. The overall system represents a typical unconfined coastal aquifer structure (Fig. 2). The Plio-Quaternary deposits are hydraulically the most productive. They are characterised by the highest transmissivity ranging between 10^{-2} and 10^{-5} m/s. In this part of the aquifer, the water table is shallower than in the Somâa deposits, making the well implantation easier.

Naturally, groundwater flows toward the sea; however in the studied area, due to the intensive groundwater abstraction, hydraulic gradients are reversed mainly toward the central part of the aquifer leading to an acceleration of seawater intrusion. In 2004, the piezometic map showed a wide depression between Diar El Hojjej and Tafelloun villages where the hydraulic head lowered 12 m under the mean sea level. Vertical salinity profiles in the wells showed Total Dissolved Solid (TDS) values ranging between 2 and 15 g/l, confirming the landward seawater encroachment.

In the studied area, which is characterised by a semi-arid climate, natural recharge is highly variable in space and time. The infiltration rate is about 32 mm/year, ranging between 5 and 8% of the mean annual rainfall of 450 mm/y [10]. Although the lateral recharge and the leakage from the underlying layer have not yet been considered (Fig. 2), they are believed to be important. In additions, recharge from wadis and topographic depression is also expected to be important. Pumping, mainly for irrigation purposes, started in 1962 and reached a total estimated volume of 46.5 10^6 m^3 in 1996 and increased to 54 10^6 m^3 in 2002. Based on the land use map of 1996 and the plant water need, the groundwater abstraction (the unique source of agricultural supply in that time) is approximated at 75 10^6 m^3.

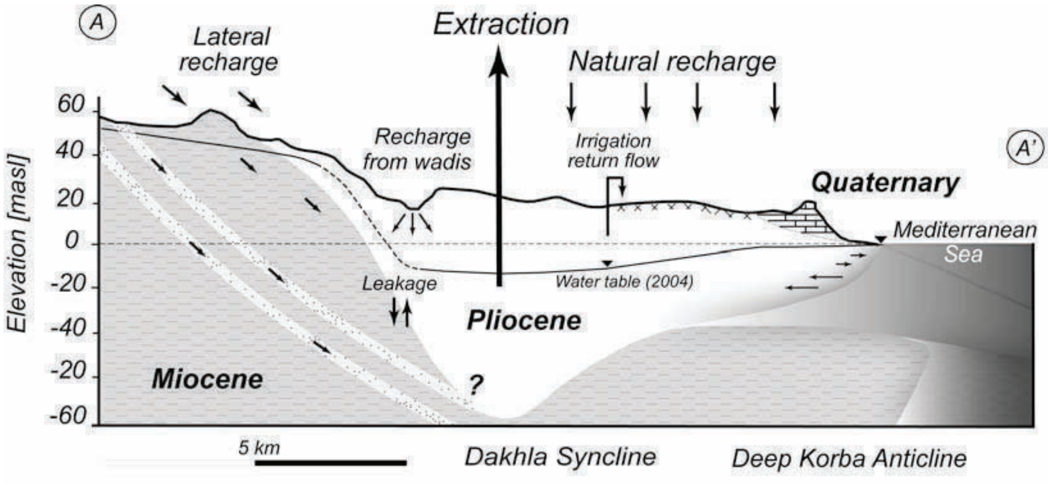

Fig. 2 Simplified geological cross-section of the Korba aquifer system sketching the conceptual model based on up-to-date geologic and hydrodynamic data. The aquifer surface and bedrock topography along with the August 2004 water table are also shown.

III. Methodology

A. Available Data

Most of the data used in this study were provided by the Institut National Agronomique de Tunisie (INAT) and the Local Groundwater Management Authorities (CRDA Nabeul) and were integrated in geographical information systems. The data set included rainfall and evapotranspiration records as well as the digital elevation model, soil distribution map, land cover map from 1996, and some geographic information (Wadis, Sebkha, etc.). Other punctual data, including stratigraphical logs, transmissivity values, and an incomplete record of historic head data and TDS measurements, were also available.

Regarding the groundwater abstraction, only two data sets were available. One data set was an exhaustive map of the locations of shallow and deep wells in the region, which was constructed in 1996 by the administration (CRDA Nabeul). It was based on the information from remote sensing analysis. This data set provided the information on the density and the location of the wells (Fig. 3) but it did not contain any information on the extracted volumes. The second data set came from a thorough survey of pumping rates (direct measurements) conducted in 1996 in 432 wells located in the central aquifer zone (Fig. 3).

Other data regarding the exploitation of the Korba aquifer were provided by the CRDA Nabeul. They consisted of 8 total groundwater exploitation volumes since 1962 which were estimated on the basis of the average seasonal head variation and the estimated aquifer porosity. Those values were used to derive the time evolution of the groundwater abstraction throughout the aquifer.

B. Linear regression model

Our starting assumption was that the pumping rates could be estimated using secondary information which could be mapped over the whole domain. For example, we expect the groundwater abstraction to be partly related to relevant parameters such as the transmissivity and the depth of the water table. Another such example parameter is the salinity of the pumped water: if the salinity increases, the saline water will no longer be used for irrigation; thus, pumping will decrease or stop.

8 parameters were selected as secondary information: hydraulic conductivity, electrical conductivity, thickness of the aquifer, seasonal variation of the head (1996), water table depth (1996), distance to the sea, well density, and digital elevation model. For each of these parameters, a distribution map was either already available or it was constructed by ordinary kriging.

The data from the 432 pumping rates (refer to Fig. 3) was used as reference data in order to estimate the parameters of a linear multivariate regression model whose error was minimized by the least squares method. The linear model allowed us to predict the measured values in the central part of the aquifer with a given error. It also allowed us to estimate pumping rates over the whole domain using the exhaustive maps.

Using the soil distribution map with relative field capacity on one hand and the rainfall and the pan evaporation data on the other hand, the infiltration rate on the top layer of the model was estimated from 1962 to 2004 by the Thornthwaite-Mather method. The recharge rate from Wadis was also assigned as source terms and calibrated using PEST.

The numerical model was built with CODESA-3D, a three-dimensional finite element simulator for coupled density-dependent flow and miscible transport in variably saturated porous media [12], [13]. The calibration of the steady state model was done iteratively and automatically (PEST) using all head data available starting from 1962, presumably representing the natural conditions [10]. Then, the calibrated steady state flow model was used to calculate the initial head and mass distribution for the 42-year-long transient simulations. The maximum time step to simulate inter-seasonal variations was 3 months.

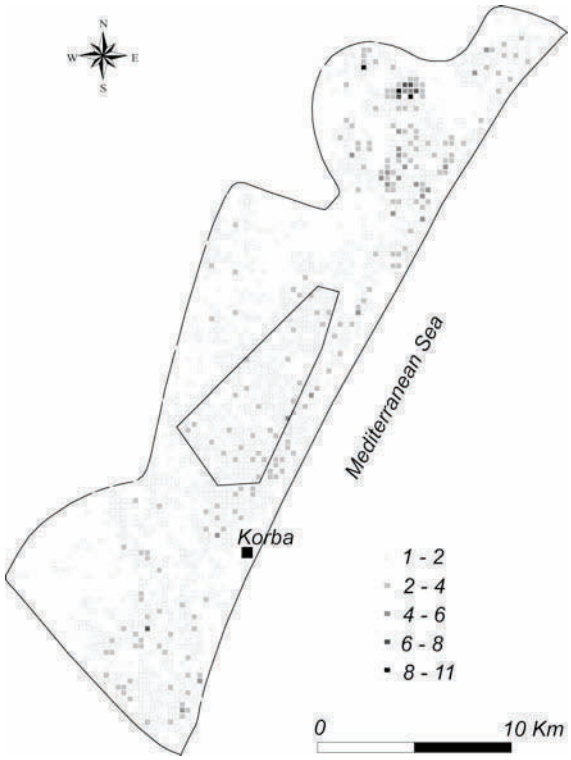

Fig. 3 Well density [in wells per 300 by 300 m cell] and area of the exhaustive pumping rate survey (internal polygon). Due to the density of the wells in the coastal area, pumping rates are grouped in 1521 well clusters on a regular 300 by 300 m cell size grid.

C. Geostatistical simulations

The spatial distribution of differences between the measured pumping rates and those estimated from the linear regression model was analyzed for the exhaustive data set (Fig. 4). We found that errors could be approximated by a Gaussian distribution (Fig. 4b). Those errors or residuals might as well be called ‘correction’. The experimental variogram (Fig. 4c) showed a clear structure, indicating error correlations for distances up to 800 m. The high nugget effect could be explained by the weak correlation between secondary and primary data sets corresponding to high micro-scale variability of the pumping rates. The experimental variogram was modelled using a spherical model with a range of 800 m in addition to a nugget effect.

Based on the variogram model and the Gaussian distribution, unconditional simulations using the turning band method were performed to generate 100 error maps over the whole domain. Each error map was added to the pumping rate map estimated by the regression model to obtain 100 maps on the pumping rate realizations.

D. Monte Carlo simulations

To evaluate the impact of the exploitation uncertainty on the flow and salt transport processes in the Korba coastal aquifer, the Monte Carlo method was used. Monte Carlo method (without modified sampling scheme) is commonly used to propagate uncertainties through numerical models as in [8], [9]. The method consisted of computing and storing model outputs (heads and relative salt concentrations) which corresponded to a set of pumping rate realizations, one at a time. The resultant outputs were, then, postprocessed to obtain statistics and probabilistic maps of heads and concentrations. These probabilistic maps reflected the uncertainty which would affect the model outputs, and it originated from pumping rate probabilistic estimates.

The 3D fully coupled density dependent flow and transport model for a 42 year transient simulation required more than 3 hours of computing time.

E. Grid computing

To circumvent the long computing time required to complete several 3D density-dependent simulations, the numerical simulations were run on the GRID infrastructure developed by the European EGEE (Enabling Grid for E-Science in Europe) project. The EGEE grid consists of over 30,000 CPU in addition to about 5 million Gigabytes of storage, and it maintains 20 000 concurrent jobs on average. EGEE grid includes more than 90 partners in 32 countries organized in 13 collaboration groups, depending on their research areas (virtual organizations), and they all have direct access to the computing power available (http://www.eu-egee.org). Such technology is possible owing to gLite Lightweight Middleware, and it allows running applications remotely on a large number of machines distributed all over Europe.

A particularly interesting aspect offered by this emerging technology is that even non-European partners, e.g. Tunisian academic researchers and water managers, could run, via a web portal, their groundwater simulations and uncertainty analysis on the GRID platform. This opportunity is offered by the EGEE companion project EUMEDGRID (http://www.eumedgrid.org).

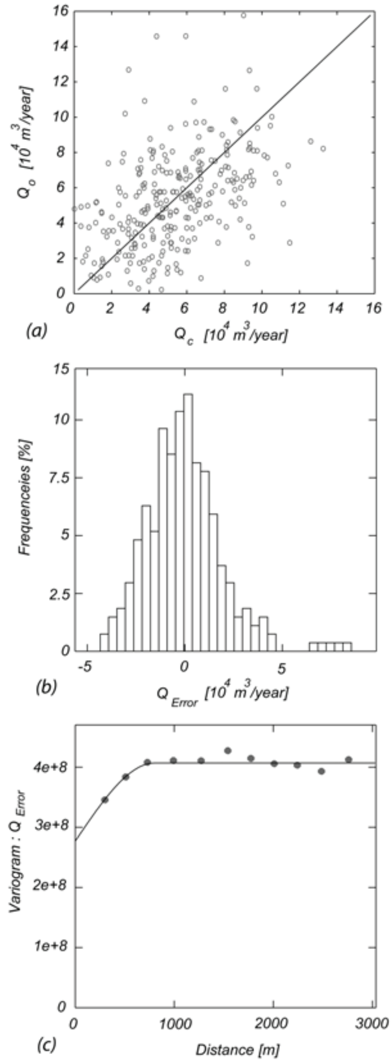

Fig. 4 Scatter plot of estimated (Q_c) versus observed pumping rates (Q_o) (a); PDF of the errors (Q_{Error}) (b) and experimental (black circle) and analytical (line) variogram of the error (c).

IV. RESULTS

The ensemble average of the 100 pumping rate realizations are shown in the Fig. 5 with the ratio of Q_{max}/Q_{min}. In 1996, the total estimated volume was 56.5 10^6 m^3. The 100 simulated pumping rate maps all had approximately the same total abstraction volumes as the average simulated error was insignificant. The magnitude of absolute errors, which were distributed randomly to all wells for each simulation over the whole aquifer, was 7.22 10^6 m^3 in 1996. It corresponded 12.5 % of the total abstraction. What is important is that in each point the groundwater extraction could be highly variable through the 100 simulations. The median value of the Q_{max}/Q_{min} ratio was 6.9, and it depended on the location of the point (Fig. 5b), and it could be as high as 10^5. The average pumping rate on a grid cell was 2.8 10^4 m^3/year.

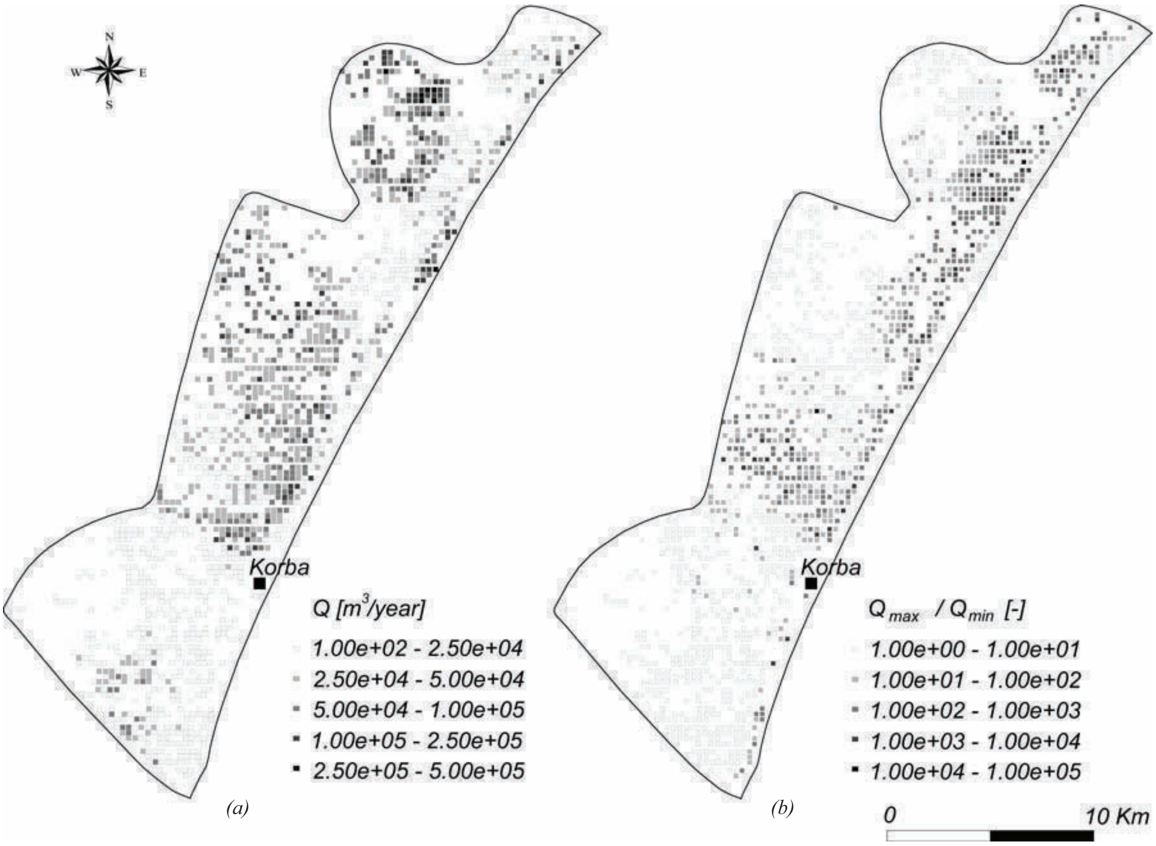

Fig. 5 Ensemble average pumping rates (Q) for the 100 simulations (a) and Qmax/Qmin rate distribution (b).

In order to facilitate a better understanding, we present the orders of magnitude of other inputs and outputs of the Korba aquifer. In 2002, the natural recharge was 36.7 10^6 m^3; the lateral recharge from the adjacent and deep aquifer was 13 10^6 m^3. For the outputs, pumping was around 65.6 10^6 m^3. The over-exploitation induced 4 10^6 m^3 seawater inflow into the aquifer and an overdraw of the aquifer waas 11.3 10^6 m^3. Note that this water balance was derived from the transient simulation; therefore, some of those values were not constant (e.g. the seawater inflow which increases regularly and rapidly).

The post processing of the Monte Carlo simulations led to the ensemble average head and concentration distributions in the aquifer (Fig. 6 and 7).

The probability distribution function of the head or concentration at any point as well as the probability map for exceeding a certain concentration or head value were calculated. The probability map for exceeding the relative concentration of 0.2 and that for falling under the sea level are shown in the Fig. 8 and 9.

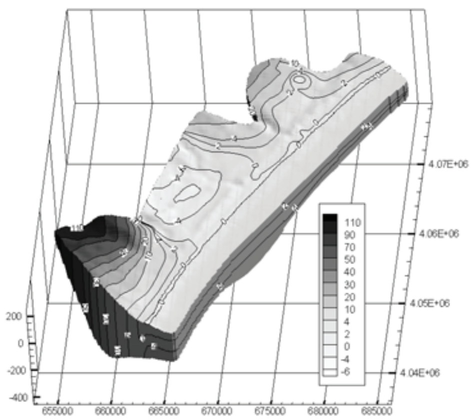

Fig. 6 Ensemble average head [m] map for the 100 realizations.

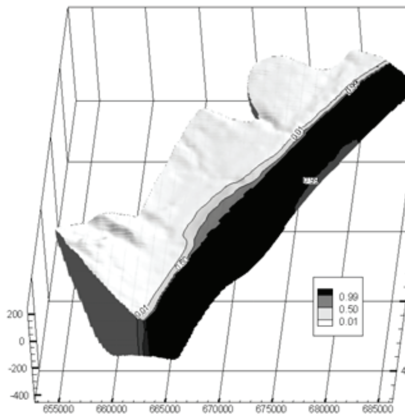

Fig. 7 Ensemble average relative concentration [%] map for the 100 realizations.

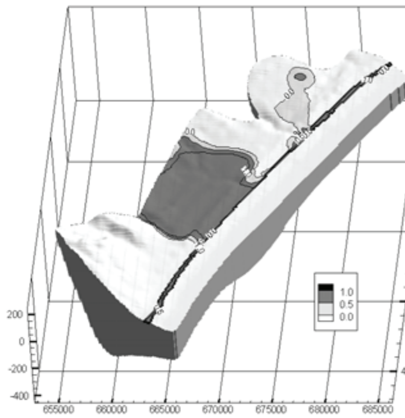

Fig. 8 Probability map for a point to be under the sea level.

The area delimited by the isoprobability contours of 0.2 and 0.8 for exceeding the relative concentration of 0.2 was 150 m in width all along the cost and reached 3.8 km^2 in surface area. The area between the probability lines of 0.2 and 0.8 for submerging under the sea level was 20.4 km^2. The vertical cross sections in Fig. 9 show the vulnerability of a shallow aquifer to the seawater intrusion and the natural protection of the deep aquifer due to the presence of confining layers.

V. Discussion and Conclusion

This work demonstrated the feasibility to construct a stochastic model on the exploitation rates when an exhaustive direct data set is not available for a real site. The proposed method enabled to model the uncertainty on the spatial distribution of pumping rates and to estimate its consequences on the sea-water intrusion. The method included a multivariate and geostatistical analyses of the spatial distribution of pumping rates coupled with Monte-Carlo simulations and GRID computing infrastructure.

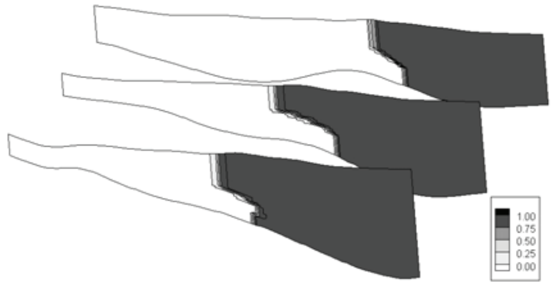

Fig. 9 Probability map for a point to exceed the relative concentration of 0.2, cross sections.

The main result of the study was rather surprising because the uncertainty of the predictions was relatively small. More precisely, Fig. 7 showed that the uncertainty was larger for the flow than for the transport processes. But even if the area surrounded by the isolines 0.2 and 0.8, for the probability of exceeding the relative concentration of 0.2, was small with respect to the size of the aquifer, it still covered an area of more than 20 km^2. Because all the coastal plain was heavily irrigated with groundwater, this zone represented a zone where there could suffer a potentially high losses in agricultural production. Therefore, even if the zone seemed small, it could result in a high economical impact on the local population.

There are several reasons for only a moderate level of predicted uncertainty. First, we kept all the other aquifer parameters constant to separate the effect of the uncertainty associated with pumping rates from the effect of the uncertainty associated with other parameters. The constant values for hydraulic conductivity and porosity led to the smooth shape of freshwater/seawater interface. Furthermore, the variogram model used to simulate the correction terms had a high nugget effect. As a consequence, two wells that were very close to each other might have very different pumping rates in the same simulation. Therefore, there were some compensation effects that reduceed the overall uncertainty.

To conclude this work, we must emphasize the fact that it is a part of a larger work that should also consider other sources of uncertainty. Just as a reminder, we have to pursue the work to consider uncertainties in the extracted volume that was not accounted for in this work. Impact of uncertain parameter distributions as well as boundary conditions should also be investigated.

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