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Grid-Enabled Simulation of the Impact of Exploitation Uncertainty on the Seawater Intrusion of the Korba Aquifer (Tunisia)

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Abstract: In this paper, we present a grid-enabled subsurface hydrology application to quantify the impact of the groundwater exploitation uncertainty on the seawater intrusion of the Korba coastal aquifer (Tunisia). A suite of methods and tools are developed and applied for decision support of sustainable costal development with special emphasis on groundwater resources. First, a geostatistical model of exploitation rates is developed to represent the spatial and temporal distribution of the aquifer withdrawal under uncertainty. Then, a Monte Carlo analysis, based on multiple runs of a 3D density-dependent groundwater flow and salt transport model, is carried out to propagate the uncertainty affecting model inputs to the outputs, namely aquifer drawdown and salt contamination. The numerical simulations have been run on the European GRID infrastructure developed by the EGEE (Enabling Grid for E-Science in Europe) and the EUMEDGRID (Empowering eScience across the Mediterranean) companion projects. Results show that understanding exploitation variability and its effects is a key factor to plan and manage measures to stop degradation of groundwater and land in the littoral and sub-littoral zones and thus to avoid compromising the socio-economic development.

Keywords: Seawater intrusion, coupled groundwater flow and contaminant transport model, Monte Carlo simulations, and grid-computing.

1. Introduction

The fundamental and applied research related to the understanding and management of coastal aquifers is very active worldwide [1], [2]. It is not surprising since coastal areas are the most densely-populated areas in our planet, with approximately 70% of the world's population dwelling there. At the same time, groundwater resources in those 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 zones.

Many theoretical research and case studies [3], [4] showed the validity and the interest of using numerical models to simulate the physics of the seawater intrusion and the advantages they present as a tool for sustainable management of groundwater resources. Nevertheless, the modelling of a real aquifer system remains an extremely delicate task for several reasons, especially, the lack of accurate data allowing to characterize aquifer parameters and to precisely estimate inputs and outputs of the groundwater budget. Moreover, since most of the input data of a groundwater model are known only with a given uncertainty, the outcomes of the modeling are uncertain as well. Recently several

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authors started to develop techniques to quantify the uncertainty associated with seawater intrusion resulting from incomplete knowledge of aquifer properties [5], [6], [7] and forcing inputs [8],[9].

In this work, the case study of the Korba aquifer (Figure 1), located 60 km South-East of Tunis in the Cap Bon peninsula (Tunisia), is described. The Korba aquifer, that is one of the more productive in Tunisia, is suffering heavily from water scarcity and salinization due to seawater intrusion. The World Bank analysis (1996) shows that agricultural productivity levels are still increasing in the region while available water resources are already fully exploited, prospecting major water problems in the next decade.

Two numerical groundwater models were built for the Korba aquifer [10], [11]. A special difficulty encountered by both groups of authors was to obtain a reliable estimation of extraction rates in the thousands of private wells of the region. To overcome this difficulty a probabilistic groundwater model has been set up where the pumping rate distribution is assumed as a stochastic input parameter with assigned geostatistical properties. This work is focused on (i) the estimation of the aquifer pumping rates and their uncertainty using secondary exhaustive information, and (ii) the evaluation of the impact of pumping rate uncertainty on the aquifer drawdown and contamination, simulated by a 3D groundwater flow and density-dependent salt transport model. To reduce uncertainty in the pumping rate distribution a multivariate analysis has been conducted on the basis of secondary data including: aquifer geometry and physical parameters, surface water irrigation records and other field measurements. To propagate the input uncertainty to model outputs, Monte Carlo simulations have been carried out. Results show that understanding withdrawal variability is a key factor in the planning and management of remedial measures to stop the degradation of groundwater and land in the littoral and sub-littoral zone and thus to sustain future socio-economic development.

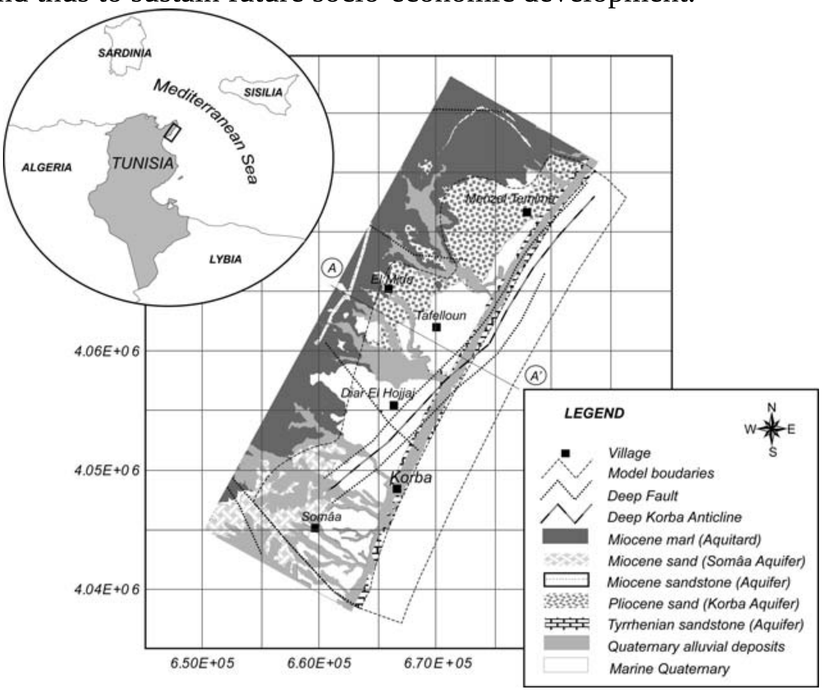

Figure 1. Location Map of the Korba Aquifer and Geological Settings.

2. Objectives

The final goal of this work is to contribute to better policy and decision making for groundwater resources management in the coastal zone. The practical objective of the study is to assess the impact of the imperfect knowledge about spatial and temporal distribution of aquifer exploitation on the groundwater drawdown and contamination resulting by seawater intrusion. The adopted approach is based on integrated quantitative simulation models and data analysis tools to generate and explore impacts and outcomes of aquifer development scenarios. The objective is achieved in two distinct steps: (i) estimation of pumping rates and of the uncertainty associated with their spatial distribution by using multivariate regression of secondary data; and (ii) evaluation of the impact of this forcing term uncertainty on groundwater flow and salt transport regional model results, by means of Monte Carlo analysis.

3. Methodology

The adopted methodology is based on the integration of georeferenced databases (GIS/DB), advanced spatially distributed and dynamic numerical models and data analysis tools.

3.1 Data Analysis

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, the soil distribution map, and the land cover map from 1996. Other punctual data, including stratigraphical logs, transmissivity values, and an incomplete record of historic head and salt concentration measurements, were also available. Using the soil map along with the relative field capacity and the rainfall and pan evaporation data, the infiltration rate was estimated from 1962 to 2004 using the Thornthwaite-Mather method. The recharge rate from ephemeral rivers was also calculated.

Only two data sets were available for groundwater abstractions. The first one is the 1996 map of the locations of shallow and deep wells in the region based on remote sensing analysis (Figure 2). The second data set is a 1996 field survey of pumping rate measurements conducted in the 432 wells located in the central aquifer zone (Figure 2, internal polygon). Additional aggregated data consist of 8 overall aquifer exploitation volumes since 1962, estimated on the basis of the average seasonal head variation and the estimated aquifer porosity. These values were used to derive the time evolution of the overall groundwater abstraction.

3.2 Linear Regression and Geostatistical Simulations

The starting assumption is that pumping rates can be estimated using secondary information available over the whole aquifer. To this end, eight parameters were selected: hydraulic conductivity, electrical conductivity, aquifer thickness, seasonal head variation (1996), water table depth (1996), sea distance, well density, and soil elevation. For each of these secondary data, a distribution map was either already available or created by ordinary kriging. The 1996 abstraction rates, measured in the 432 wells, were used as the reference data to estimate the parameters of a linear multivariate regression model, whose error was minimized by the least squares method. The spatial distribution of the difference between measured and modelled pumping rates was then analyzed (Figure 3). Results show that the error can be approximated by a Gaussian distribution (Figure 3b) with an experimental variogram (Figure 3c) showing correlation for distances up to 800 m and a high nugget effect. This effect corresponding to the high micro-scale variability of pumping rates can be explained by the weak correlation existing between primary and secondary data sets. Based on the geostatistical model, unconditional simulations were performed, using the turning band method, to generate 100 error maps over the whole domain. Each error map was then added to the pumping rate map, estimated by means of the regression model, to obtain 100 pumping rate equiprobable realizations.

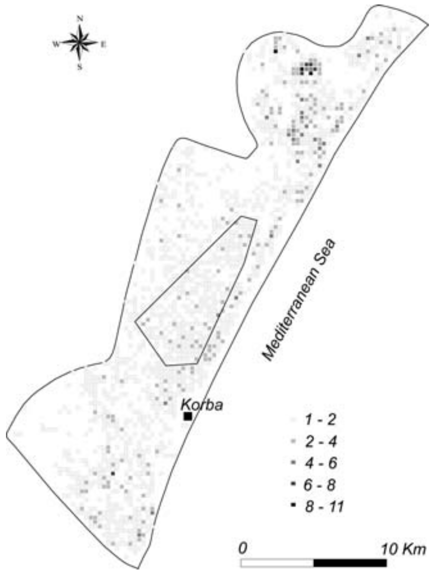

Figure 2. Well Density Map Obtained by Clustering the Wells in Cells of 300 by 300 m Size. The Area of the Exhaustive Pumping Rate Survey (Internal Polygon) is Also Shown.

3.3 Groundwater model and Monte Carlo analysis

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 automatically performed using all head data available since 1962, presumably under pre-development conditions [10]. Then, the calibrated steady state flow and transport model was used to provide the initial conditions for the 42-year transient simulations with aquifer pumping [14]. The maximum allowed time step in order to simulate inter-seasonal variations (recharge and pumping) was 3 months, producing a total simulation time of about 3 hours on a high performance PC.

To evaluate the impact of the exploitation uncertainty on the flow and salt transport processes for the Korba coastal aquifer, the Monte Carlo method was used. The method consists of computing and storing model outputs (heads and relative salt concentrations) corresponding to a given set of pumping rate realizations, one at a time. The stored outputs are, then, postprocessed to obtain statistics and probabilistic maps of heads and concentrations. The probabilistic maps reflect the uncertainty affecting model outputs that originates from pumping rate probabilistic estimates [14].

4. Technology Description

The information and communication technologies used here in a integrated framework are GIS/DB, advanced numerical models and data analysis tools. Another technological ingredient is the GRID computing. Indeed to circumvent the long computing time required to complete several 3D density-dependent simulations and to postprocess model outputs, 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).

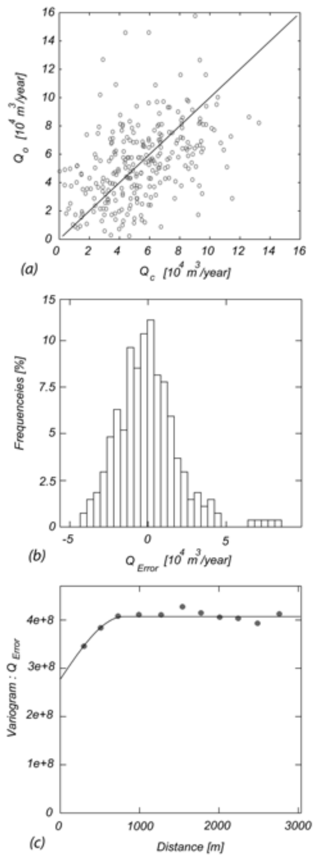

Figure 3. (a) Scatter Plot of Estimated (Q_c) Versus Observed Pumping Rates (Q_o);(b) PDF of the Errors and (c) Experimental (circle) and Analytical (line) Error Variogram.

Such a technology is possible owing to gLite Lightweight Middleware as 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 non-European partners, e.g. Tunisian academic researchers and water managers, can participate to the work running, via a web portal, their uncertainty analysis on the GRID platform. This opportunity is offered by the EGEE companion project EUMEDGRID (http://www.eumedgrid.org). The effort required to enable the application to run via command line on the GRID platform consisted mainly in recompiling the source code with free software compilers (GNU g95), integrating it with open source visualization tools (ROOT, and Paraview) and launching the resulting application on the computational queue by means of a job description language (JDL) script interface. The CODESA-3D GRID web service, accessible via the GILDA testbed, was designed and developed, in collaboration with the CRS4 partner, by the INFN GRID group in Catania (Italy).

5. Results

Monte Carlo analysis led to ensemble average head and concentration distributions in the aquifer shown in Figure 4 and 5, respectively. Figure 6 and 7 show the probability for water of exceeding the relative salt concentration of 0.2 in three aquifer transects and the probability of the water table to fall under the mean sea level, respectively.

Groundwater budget terms in 2002 are calculated as follows: natural recharge is 36.7 10^6, lateral recharge from the adjacent, deep aquifer is 13 10^6, and pumping is 65.6 10^6 m^3. Thus aquifer overexploitation induces 4 10^6 m^3 seawater inflow into the system with an overdraw of 11.3 10^6 m^3. Since the water balance was derived from the transient simulation some of its terms are not constant in time (e.g. seawater inflow which increases steadily).

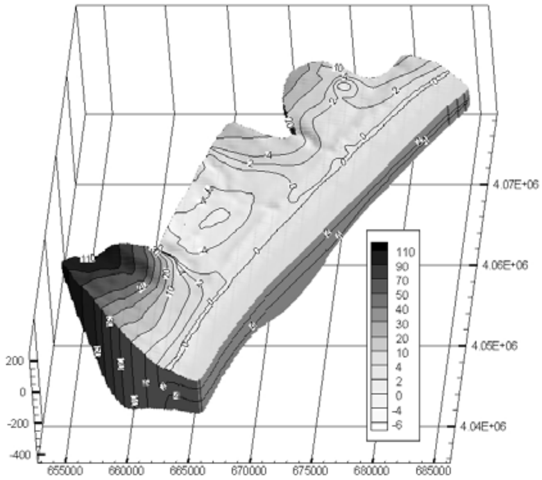

Figure 4. Ensemble Average Head [m].

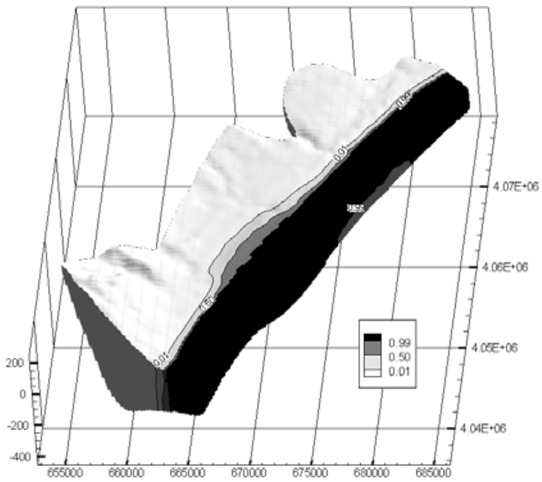

Figure 5. Ensemble Average Relative Concentration [/].

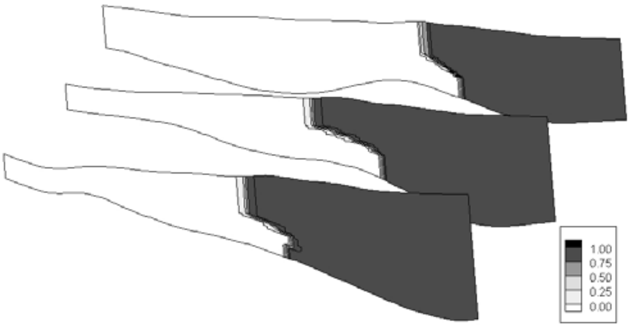

Figure 6. Probability Map for a Point to Exceed the Relative Concentration of 0.2 for Three Aquifer Cross Sections.

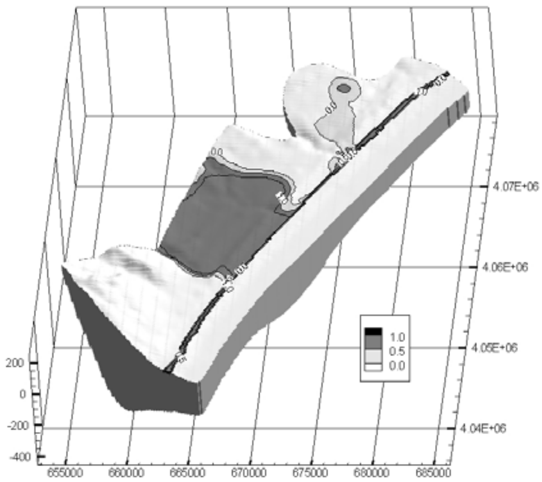

Figure 7. Probability Map for a Point to be Under the Mean Sea Level.

6. Business Benefits

The primary objective of this work is to contribute to better policy and decision making for resource management in the coastal zone. Coastal zone experience dramatic demographic and socio-economic development, especially in the Mediterranean area, with growing and conflicting demands on natural resources from different economic activities (e.g. tourism and agriculture). This leads to often irreversible degradation of natural resources that severely limit the basis for further development.

The work offers a contribution in terms of advanced software tools and data analysis tool to support long-term policy analysis and strategic decision making for integrated and sustainable coastal development. Further developments will necessarily include a detailed analysis of environmental and socio-economic constraints and costs (e.g. to meet water standards and to mobilize surface waters for irrigation) to tailor the system to the real problems faced by local water managers. To this end the integration of an optimization engine to rank the optimal scenarios satisfying specified, and often competing, objectives will provide decision makers with a more powerful tool.

7. Conclusions

This work demonstrates the feasibility of a stochastic model on exploitation rates when an exhaustive direct data set is not available for a real site. The proposed approach enables the modeling of the uncertainty in the spatial distribution of pumping rates and assessment of its outcomes on the seawater intrusion for the Korba coastal aquifer. The method included a multivariate and geostatistical analyses of the spatial distribution of pumping rates coupled with Monte Carlo simulations, performed on a GRID computing infrastructure.

The main result of the study may be rather surprising because the area affected by the uncertainty of model predictions is relatively small compared to the aquifer domain. But, considering that the area delimited by isolines 0.2 and 0.8 in Figure 7 is more than 20 km^2, we can easily realize the economic impact of potential losses in the agricultural production due to contaminated groundwater. Future developments will include into the model other sources of uncertainty like aquifer hydrogeological properties and boundary conditions.

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