Analysis of seawater intrusion phenomena in the Korba coastal aquifer of Tunisia

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ABSTRACT: A geographic information system and a three-dimensional coupled variable density and saturation numerical model are implemented for the Korba coastal aquifer of northeastern Tunisia, and preliminary simulations are performed to investigate seawater intrusion phenomena. The GIS provides an essential platform for data management, enabling the organization and merging of a large volume of data that has been collected in often ad hoc manner from diverse sources over many years. A critical assessment of data quality is provided and the usefulness of GIS and modeling tools is demonstrated, with an aim to encourage more directed and continuous monitoring and characterization of important parameters and processes involved in the contamination phenomena. This approach is currently being extended to two other coastal aquifers, in Sardinia (Italy) and Sahel (Morocco).

1 INTRODUCTION

A proper assessment of the environmental impacts and economic consequences associated with seawater intrusion phenomena requires monitoring and analysis of the short, medium, and long-term response of the threatened system (Sherif & Singh 1996; Bear, Cheng, Sorek, Ouazar, & Herrera 1999). It is important to adequately characterize the aquifer flow regime and its natural patterns of land recharge and sea discharge. For heavily-utilized aquifers in semi-arid regions, the flow regime will be particularly sensitive to replenishment by irrigation, artificial recharge, and the rainfall that effectively infiltrates and is not directly lost to surface runoff and evaporation. Such analysis and characterization of the dynamics of coastal aquifers, as with more general hydrologic systems, can be effectively carried out with appropriate tools such as geographic information systems (GIS), visualization and image processing software, and simulation models (Paniconi, Kleinfeldt, Deckmyn, & Giacomelli 1999).

The 438 km^2 Korba coastal aquifer is situated in the northeastern Cap-Bon peninsula of Tunisia (Figure 1). Effective infiltration (rainfall minus evaporation and surface runoff) is estimated to be less than 10% of the annual precipitation of 460 mm and as low as 5–7%. Increasing population and agricultural activities through the past four decades have led to a steady increase in the amount of water that is pumped from the Korba aquifer; there are currently over 7000 wells that supply the many small farms and communities in the region. Saltwater contamination was first observed in the early 1970s and was recognized as a serious problem in the mid-1980s.

The socio-economic consequences of piezometric drawdown, saltwater intrusion, and salinization in the Korba coastal plain include degradation of arable soils and abandonment of farms, a deterioration in the quality of water pumped from wells and used for irrigation, a decrease in aquifer yields from existing wells, and a migration of the local population in search of alternative freshwater sources (Khlaifi 1998). Several remediation options are being studied for the region, including rationalization and regulation of well pumping, artificial recharge of the aquifer (some pilot trials using treated wastewater have been conducted in a small area in the southern part of the aquifer), and construction of small reservoirs to serve as an alternative source of irrigation water, all within an overall view towards improved management and planning not only of the aquifer but also of land use practices, which clearly have significant impact on the subsurface water regime.

Modeling and data analysis will play a key role in the assessment of remediation alternatives and the definition of an appropriate management framework. This contribution is limited to more specific aims related to data organization with a critical assessment of the existing dataset and to model implementation with some preliminary simulations.

2 DATA PROCESSING

Aside from three observation-well measurement campaigns conducted over the past 35 years and rainfall records collected from five gauges, data acquisition aimed at monitoring the quality and use of the Korba aquifer has been sporadic until 1996, and no field studies aimed specifically at implementation and calibration of a groundwater transport model have been conducted. This is a common situation for the countries of the Mediterranean basin, and presumably in many other regions worldwide, where environmental protection is not a high priority and lack of funding has prevented systematic and coordinated monitoring efforts. Nonetheless, for the Korba site a large amount of data has been accumulated since the early 1960s from a variety of sources and surveys, and for this study a large effort was expended on the organization and manipulation of these data, and on deriving and inferring from them parameters and boundary conditions for the model discretization and implementation.

The available data for the Korba site include topographic and soil maps, geological and geophysical surveys, water level and water quality measurements taken from the monitoring wells, information relating to agricultural activities and water use, hydrographic and geomorphologic characterizations, and data from meteorological stations. A geographic information system was used to organize these diverse data and to support both pre- and post-processing tasks connected with the saltwater intrusion modeling (Giacomelli, Paniconi, Khlaifi, & Tarhouni 1999). Some of the processing, support, and analysis functions performed with the GIS include:

- Basic digitizing and manipulation to create data layers and thematic maps: all geographic data was initially available in paper format and at different scales and classifications, and required georeferencing, joining, and assigning of attribute information;

- Data conversion and formatting to adapt GIS-processed data for input to the simulation model and to enable GIS-based 2D visualization and comparison of model output. Scientific visualization software was used for 3D and 4D (space and time) analysis of simulation results, but also in this case GIS scripts and routines were used for data conversion and formatting;

- Multicriteria analysis for recharge optimization: a simple analysis was conducted to identify areas in the Korba region that might be most suitable for artificial recharge of the aquifer, based on a weighted combination of soil, aquifer transmissivity, geology, and terrain slope map features. This was a preliminary and heuristic analysis but illustrates a potentially important application for combining observation data and simulation results through GIS to produce qualitative or quantitative indices useful for remediation studies and more general water resources management.

The data most relevant to the modeling study and that required the most intensive GIS processing were the geologic and terrain maps and the historical data from the monitoring and pumping wells and rain gauges, as described below.

2.1 *Geologic data*

For modeling purposes, it was necessary to process extremely detailed geologic data and to identify and aggregate the features pertinent to the coastal aquifer. The resulting map is shown in Figure 2. The unconfined aquifer, formed during the Pliocene and Quaternary ages by deposition of eroded products from the Djbel Sidi AbedErrahmen anticline and the Dakhla syncline, is underlain by a Miocene marl formation and below this stratum by a small and less-exploited confined aquifer. The Pliocene formation is a sandstone with alternating marl units, while the Quaternary alluvium is composed of detrital sediment (sand, gravel, and silt) with thin clay lenses. The sandstone formation spans the entire aquifer and has a mean thickness of 85 m, while the detrital formation is less ubiquitous and has a thickness that varies between 20 and 25 m.

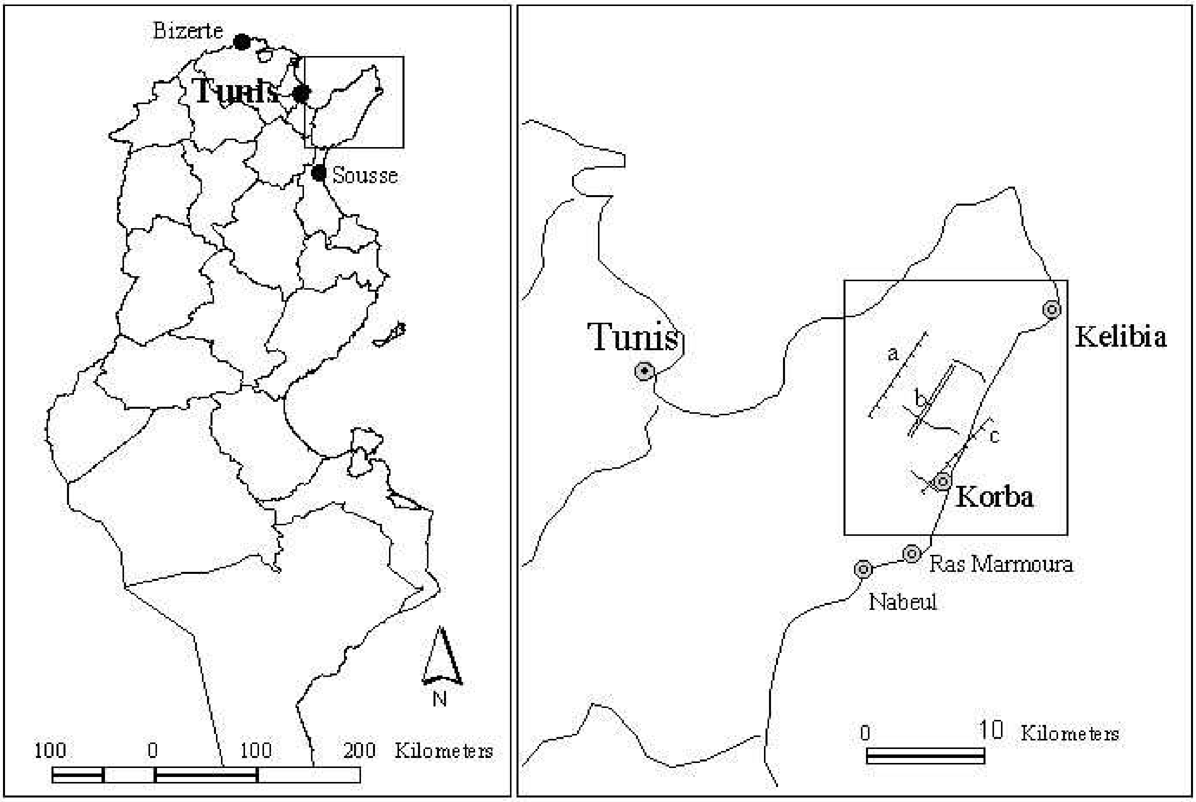

Figure 1: Location map of the Korba coastal plain in northeastern Tunisia on the Mediterranean Sea (left) and enlargement showing the population centers and the main hydrographic (ephemeral streams) and geologic (anticline and syncline) features (right).

An additional characteristic geomorphologic feature of the Korba plain is the dune formation that runs along part of the coastline just east of the second, smaller Menzel Temime anticline. This unit is composed of Quaternary sediments with high hydraulic conductivity, but was not modeled as a distinct block given its small vertical and lateral dimensions relative to the other two formations.

2.2 *Topographic data*

Topographic maps were used to interpolate a 50x50 m digital elevation model (DEM) for the study area, and, in conjunction with geologic data, to define the surface limits of the aquifer and its base configuration (Figure 3). The topography ranges from 0 to 161 m a.s.l., and the aquifer thickness is also highly variable, with a mean of about 85 m corresponding to the thicker and more extensive sandstone formation, a range from 151 m in the south to 24 m in the north, and a decreasing trend from east to west to nearly vanish at the Djbel Sidi AbedErrahmen mountains.

With the geometry and dimensions of the aquifer thus delimited, a triangulated irregular network (TIN) was constructed with the GIS and then used to generate the 2D surface grid for the model. The advantage of using GIS rather than standard unstructured grid generation software is that the GIS enabled a direct link to be maintained between the mesh structure and the geographic data on which it is based. For instance, distance from the coast, location and importance of pumping wells, and location of monitoring wells were all considered in determining the local grid resolution, and in the future other considerations (designated artificial recharge areas, characteristics of surface freshwater reservoirs and other water bodies) can also be easily incorporated.

2.3 *Forcing terms*

Imposition of surface boundary conditions was also assisted by the GIS, incorporating information from the pumping and monitoring well datasets, derived irrigation maps, and rainfall records into the nodes or triangles of the 2D grid. To the best available knowledge, the total volume of water pumped from the aquifer in recent years is close to 50×10^6 m^3/yr. Pumping volumes, together with irrigation rates, are difficult to estimate reliably for the Korba site, given also the abundance of small-farm private wells in the region. Irrigation rates estimated from available maps were lumped into the effective infiltration term.

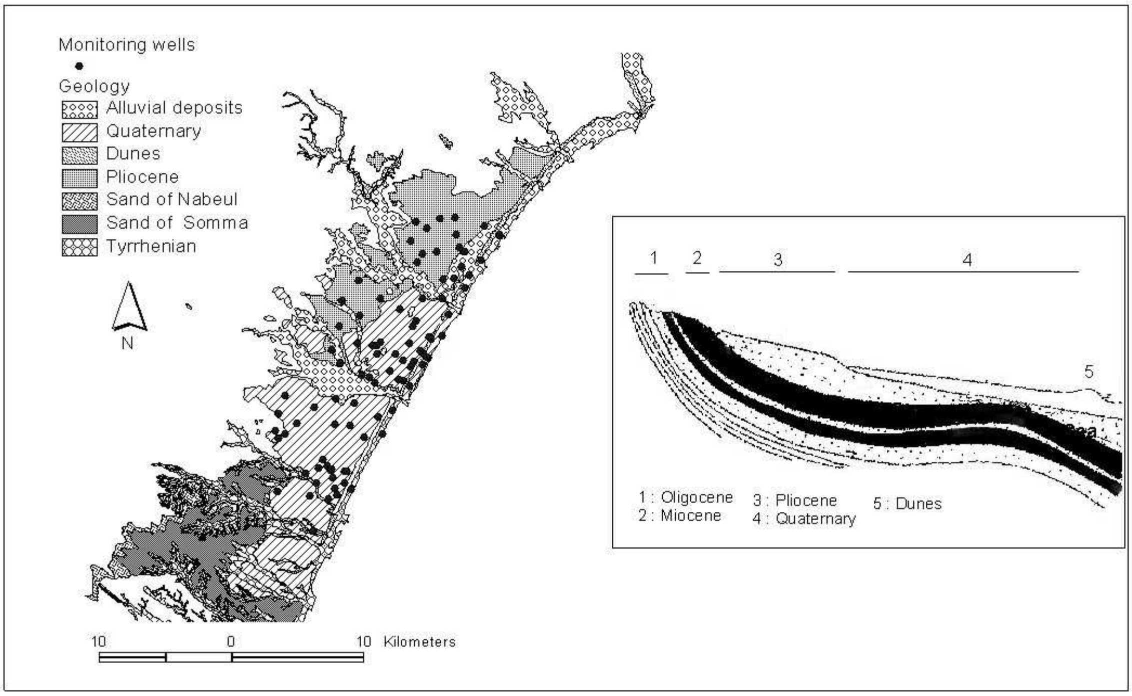

Figure 2: Simplified geologic map of the Korba study area derived by aggregation of surface geologic features into dominant units (left); vertical geologic cross section perpendicular to the coast and passing roughly midway through the aquifer showing the anticline, syncline, and dune formations that determine the shape and varying thickness of the Quaternary–Pliocene unconfined aquifer, along with underlying formations (right).

Figure 3: Digital elevation map (left) of the modeled area showing the hilliest southwestern portion (max elevation 161 m a.s.l.) and the comparatively flat central region of the coastal plain. The right image shows aquifer thickness contours overlain on a detailed map of the channel network. The aquifer thickness is highly variable, with minimum depth 24 m, maximum 151 m, and mean 83.5 m.

Annual rainfall data is more reliable, but the problem in this case is lack of detailed information on rainfall rates at small temporal scales (hourly and even finer resolution). This is critical if the unsaturated zone component of the model is to accurately simulate rainfall–runoff–infiltration partitioning and thereby reproduce an important natural recharge component of the aquifer's water balance. In absence of this detailed data, scenario simulations were run, and, in particular, the estimated effective infiltration of (less than) 10% of annual rainfall was relied on.

It is interesting to note that, based on these estimates and using 40 mm as effective annual infiltration, the volume of water recharged to the aquifer from a combination of rainfall and irrigation is approximately 18×10^6 m^3 annually; comparing this value with the 50×10^6 m^3 estimated annual pumping rate gives an idea of the degree of over-exploitation of the aquifer.

3 MODEL DISCRETIZATION

The numerical model used in this study is CODESA-3D (COupled variable DEnsity and SAturation), a distributed, fully three-dimensional saturated–unsaturated finite element code that makes no assumptions regarding the nature of the saltwater–freshwater interface or the flow regime in the aquifer and can account for spatial and temporal variability in parameters and boundary conditions (Gambolati, Putti, & Paniconi 1999).

3.1 *Grid*

The first step in the discretization of the study domain for model simulation was the generation of the DEM-derived TIN-based 2D surface grid described earlier, resulting in a mesh containing 2917 triangles and 1643 nodes (Figure 4). This unstructured grid, constructed so as to have the smallest elements (28.6 m^2 as compared to 1.48 km^2 for the largest) along the coast and around zones of heavy groundwater pumping, was then replicated vertically for 6 layers, yielding a 3D mesh of 52506 tetrahedral elements and 11501 nodes. The layers were defined to be of increasing thickness from the surface to the base of the aquifer, so as to have a sufficiently fine resolution for investigating unsaturated zone processes.

With this configuration of just over 10000 nodes, a typical 35-year transient simulation on a mid-range workstation required about 1 hour of CPU, a fast enough turnaround time for these first phases of the study where frequent runs were needed for fine-tuning the model and for generating scenarios. A much finer resolution (more than 100 000 nodes) will be needed in future simulations to examine in more detail the three-dimensional behavior of selected processes and to relax the dispersivity constraints.

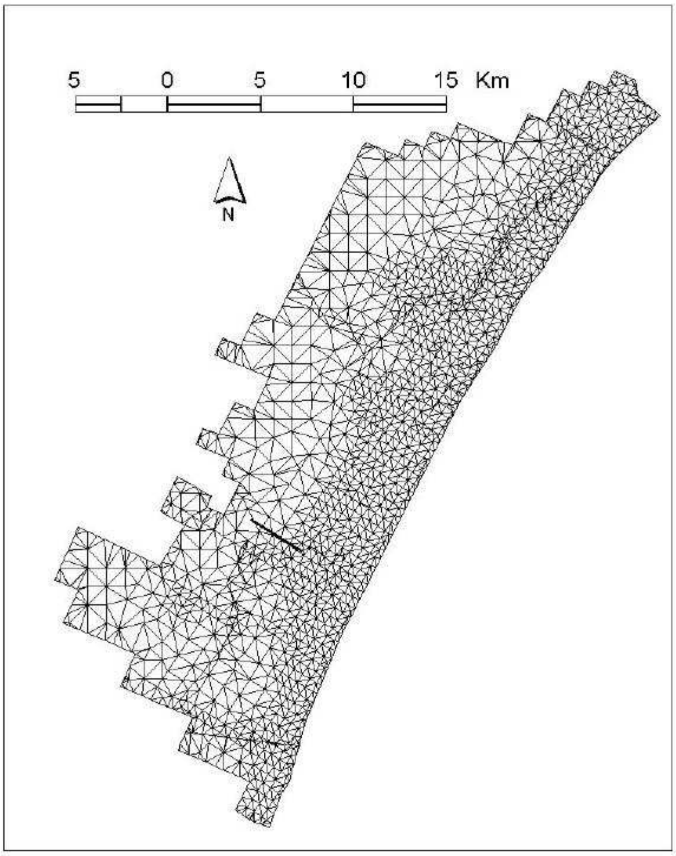

Figure 4: Surface discretization of the modeled area into 2917 triangles, with the smallest elements near the coast and around important pumping well clusters. This nonuniform surface grid was replicated vertically for 6 layers of varying thickness (thinnest layers near the surface) to yield a three-dimensional mesh containing 52506 tetrahedral elements and 11501 nodes.

3.2 *Parameters*

The CODESA-3D model can in theory assign different flow and transport parameters to each vertical layer and each tetrahedral element; for the Korba simulations only selected hydrogeologic parameters were treated as spatially variable, in a block heterogeneity sense according to the presence of either Pliocene or Quaternary formations: saturated hydraulic conductivities K_x, K_y, and K_z, porosity ϕ, aquifer specific storage S_s, and three fitting parameters in the characteristic relations describing the nonlinear pressure head dependencies in the relative hydraulic conductivity and general storage terms for unsaturated porous media.

The irregular geometry of the aquifer, in particular its nonuniform base and thickness arising from the syncline and dune formations, were considered important features in determining the response of the Korba coastal plain to groundwater exploitation and the dynamics of saltwater intrusion, and these features were thus discretized to conform as closely as possible to the available data. It would be interesting to quantify more precisely the effects and importance of variable aquifer thickness, comparing the current discretization with a series of hypothetical configurations including more uniform geometries as usually assumed in reported seawater intrusion studies. For the Korba site such sensitivity analyses could be useful for planning future hydrogeological field studies aimed at augmenting the quantity and accuracy of available data, and for adding additional information to be used in multicriteria assessments of remediation options.

3.3 *Boundary conditions*

The most important boundaries of the three-dimensional discretized representation of the Korba study site are the land surface (sources and sinks of fresh and/or salt-contaminated water from rainfall, evaporation, irrigation, pumping, artificial recharge, and streams and other surface water bodies), the eastern coastline (discharge of freshwater from the aquifer and source of saltwater from the sea or underlying seawater-saturated porous media), and the western edge of the Korba plain (natural subsurface recharge of the aquifer from adjoining formations). These three boundaries are critical both in the physical role they play in the dynamics between freshwater and saltwater in the aquifer and in the numerical effect they can have in determining simulation outcomes.

Imposing constraints on these boundaries which accurately mimic natural conditions is difficult due to lack of information and to the complexity of the boundaries, and there is ample scope here for experimentation and sensitivity analysis. The land surface, for instance, comprises a number of sources and sinks, each of them highly variable in space and time; the western edge may contain significant localized water transmission pathways such as fractures; the coastal boundary should require some prior knowledge of the position of the saltwater–freshwater interface and the extent of the freshwater outlet "window".

This window portion of the coastal edge is treated as a zero dispersive flux boundary for the solute, allowing lighter freshwater to discharge to the sea, while the nodes below it are assigned a fixed relative concentration value of 1, implying a continous source of heavier seawater that enters the aquifer at depth. The extent or thickness of the window is likely to vary over time, contracting or expanding depending on the hydrologic balance of the aquifer system. To capture this variation requires iterative treatment of the coastal boundary condition in the solute transport model, in a manner similar to seepage face handling in models of variably saturated groundwater flow. This is a feature still to be implemented in the CODESA code, so in the simulations reported below the window thickness was kept fixed.

Synthesizing, the vertical face corresponding to the coastline the boundary conditions for the transport equation were zero dispersive flux for the nodes of the window and maximum concentration for the nodes below the window, while vertical hydrostatic equilibrium was prescribed on all nodes for the flow equation. For the land surface, zero dispersive flux was assigned to all nodes for the transport equation, while for the flow equation the estimated irrigation values were incorporated into the effective infiltration rates. The western edge of the Korba plain was treated in a default manner as a zero flux boundary for both flow and transport, as were the remaining boundaries (the northern and southern edges and the bottom of the aquifer).

4 SIMULATION

The pressure head distribution and water table levels obtained from steady state calibration simulations with the flow model (Lecca, Khlaifi, Tarhouni, & Paniconi 1998) were used as the initial flow conditions for subsequent transient simulations using the fully coupled model, while for the transport component a zero concentration initial condition was used.

A 35-year (1962–96) transient simulation was run to examine, in vertical cross section, the behavior in time of the water table and the saltwater–freshwater interface as groundwater is pumped along the coast (1.4 km away) or further inland (about 3.6 km from the coast) (Figure 5). In this scenario a single well acts as a sink node drawing water from the aquifer at a rate that increases linearly over the 35-year simulation period from 0 to 0.91×10^6 m^3/yr.

A new equilibrium state in terms of the saltwater–freshwater balance is quickly established in the case of inland pumping, with the 0.5 isoline remaining stationary at about 150 m from the coast. On the other hand in the area around the pumping well it is apparent that the extraction rate exceeds the rate of natural

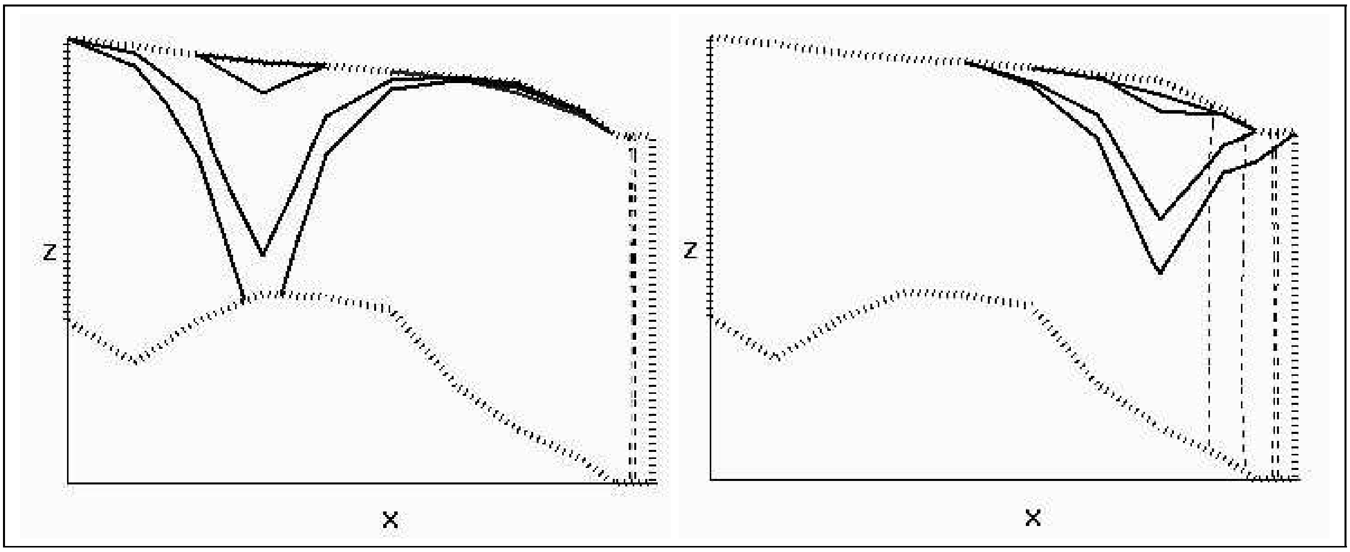

Figure 5: Simulation results for two experiments plotted as vertical cross sections perpendicular to the coast and passing through the town of Korba, comparing the groundwater drawdown and seawater intrusion from inland (left) and coastal (right) pumping regimes and illustrating the interaction between the unsaturated zone and the saltwater–freshwater interface. The two plots show water table levels and 0.5 normalized salinity isolines at times 1, 6, 25, and 35 years in response to pumping from a single well at a rate that increases linearly over the 35-year simulation period from 0 to 0.91×10^6 m^3/yr.

recharge (an effective infiltration rate of 22 mm/yr was used) as seen by the severe and non-steady drop in water table.

In the case of coastal pumping, under the same conditions of pumping and natural recharge, the reverse is true — drawdown is significantly less but seawater intrusion is much more pronounced. These effects feed back into eachother as the influx of seawater is spurred by the nearby high pressure head gradients in the unsaturated zone and around the drawdown cone, and in turn this seawater serves as a ready source of water for the pumping well.

5 CONCLUSIONS

An information management and modeling system has been set up for the Korba coastal aquifer of Tunisia, containing comprehensive (but far from complete) geospatial data from various sources. The production of the GIS-based geographic dataset for the study site, in addition to providing the data source for the numerical model, represents per se an important outcome of this study, since it has allowed the organization and analysis of the heterogeneous data and has facilitated pre-/post-processing interaction with the model.

Some of the important shortcomings of the current dataset that have been singled out include: more extensive monitoring data is needed concerning piezometric heads and aquifer salinity levels; spatio-temporal detail is lacking in the rainfall, runoff, evaporation, irrigation, and pumping records; and aquifer/soil properties (conductivity, dispersivity, leakage) need to be better characterized.

For model simulation, the 438 km^2 Korba study site, complete with nonuniform geometry, topography, and aquifer thickness, was discretized into 2917 surface triangles, and these were replicated vertically for 6 layers of varying thickness to produce a 3D mesh of 52506 tetrahedral elements and 11501 nodes. The thousands of pumping wells known to be active in the study site were aggregated into a representative handful of model sink nodes, and the complex geology was simplified into the dominant Pliocene sandstone and Quaternary alluvium formations, with hydrogeologic parameters assigned accordingly.

Boundary conditions at the land surface and on the vertical face representing the coastline were imposed according to the limited data and following standard practice, although there is scope here for much further study to determine how best to treat these complex boundaries in problems of coupled variably saturated flow and salt transport (e.g., the handling of the freshwater outlet or window; the importance of more accurate and fine resolution input data concerning rainfall–runoff–infiltration partitioning).

The data analysis and modeling approach described is currently being extended to two other coastal aquifer sites in semi-arid regions (Sardinia, Italy and Sahel, Morocco) that are highly sensitive to severe degradation by saltwater intrusion and where monitoring, modeling, and analysis of the risks involved are essential components of effective water resources management.

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