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Estimating the impact of a discontinuous confining layer on the seawater intrusion using a stochastic approach: the Oristano coastal aquifer site (Sardinia, Italy)

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ABSTRACT

The study site covers an area of 273 km^2 in the Oristano plain on the western coast of central Sardinia (Italy). In the coastal area, since 1950, intensive agriculture and subsequent urbanization have resulted in overexploitation of the aquifer system and significant deterioration of groundwater quality due to seawater encroachment. The groundwater basin, hosted in the Quaternary alluvia released by the Tirso river, is formed of a shallow phreatic aquifer and a deeper semi-confined aquifer, separated by a possibly discontinuous thin clayey aquitard. Hydrogeological and hydrochemical data [Pala & Cossu, 1994; Barroccu *et. al*, 1995] do not allow for a precise characterization of this confining layer, but suggest that partial hydraulic connection between the upper and lower aquifer units occurs. In this study we assess the impact of the aquitard on the salt dispersion process by running simulations based on different realizations of its hydraulic conductivity (K) distribution. The proposed methodology consists in three steps: (1) a stochastic approach to generate synthetic realizations of random spatially correlated parameters K, (2) a modeling study, based on a three dimensional coupled flow and transport groundwater model, to simulate for each realization pressure heads and solute concentrations in the aquifer system, and (3) a statistical analysis of the simulated fields. With this strategy we attempt to cover the uncertainty of the model parameter K in the prediction of fluid and solute mass exchange between upper and lower aquifer units in the framework of a rational development on groundwater resources for the study site.

DESCRIPTION OF THE STUDY AREA

Adequate water supply is one of the major problems afflicting Sardinia due to the absence of permanent water resources and the prolonged periods of drought, which have caused in recent years rationing measures on urban, agricultural and industrial uses. As a consequence, a substantial increment of groundwater withdrawal has been observed especially along coastal areas. The study site is located in the coastal zone of the Oristano plain (Figure 1) in the western part of central Sardinia (Italy). The aquifer basin is formed of two main units, a shallow phreatic aquifer (few tens of meters) and a deeper aquifer (few hundreds of meters), separated by a variable thickness, possibly vanishing, aquitard. The groundwater reservoir is one of the more productive in the region: it is estimated that more then 25000, between used and disused, agricultural wells are present in the plain. Because of inadequate policies of water resource management, groundwater has been heavily contaminated by seawater intrusion due to aquifer overexploitation. Over the last 5 years an increase of about 20% in the electric conductivity measurements has been found in the wells located close to the sea [Cau *et. al.*, 2002(b)]. These measurements also showed high contamination levels both in the phreatic and confined aquifers, suggesting the existence of partial hydraulic connection between these units. The effect is presumably connected to the leakage of water through sandy lenses and corroded and failed casings of abandoned wells. Furthermore these preferential paths through the aquitard have shown to have a strong influence on the groundwater dynamics when subjected to intensive pumping [Cau *et al.*, 2002(a)].

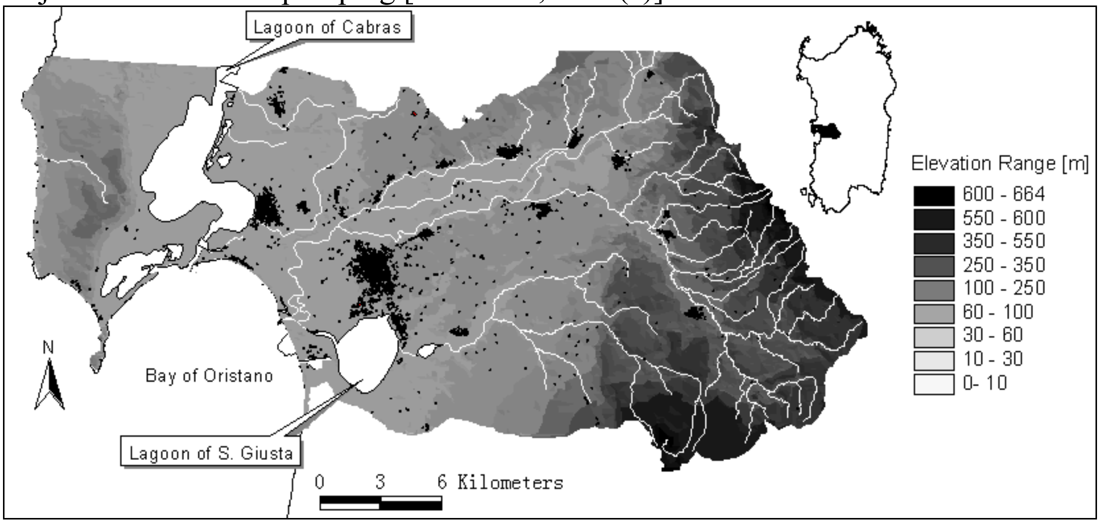

Figure 1. Location of the Oristano plain. Hydrography and topography maps are also shown.

THE MONTE CARLO SIMULATION

A preliminary modeling study [Cau *et al.*, 2002(b)] showed that the existence of localized areas of severe upconing or salt buildup largely depends, for the given spatial distribution of wells and their exploitation rates, on the heterogeneity of the aquitard hydraulic conductivity field K. In this study Monte Carlo simulation has been used to quantify the impact of the confining layer on the salt dispersion process in order to evaluate the potential risk of contamination due to different exploitation schemes. To this end we compare two modeling schemes for the aquifer system that differ only for the degree of spatial variability of the aquitard K field: the **homogeneous** and the **heterogeneous cases**. The former approach assumes an impervious confining layer with an isotropic conductivity of 10^{-8} m/s. The latter approach is based on stochastic realizations of the aquitard conductivity that mimic the random occurrence of spatial discontinuities in the confining layer. The K field generation has been carried out with the HYDRO_GEN computer code [Bellin & Rubin, 1996]. Let $Y = \ln(K)$ be a function with a Gaussian distribution of mean $\overline{Y}$ and variance σ_Y^2, Y was modeled as a stationary random space function with an exponential covariance function $C_Y = \sigma_Y^2 e^{-r}$, where $r = \sqrt{\left(\frac{r_x}{I_x}\right)^2 + \left(\frac{r_y}{I_y}\right)^2}$ with I_x, I_y and r_x, r_y are the x- and y-components of the integral scale and the two-point lag vectors, respectively. In our realizations we use a 85x73 rectangular grid with a constant spacing of 250 m that encloses the study area. The isotropic integral scale I was set to 500 m to guarantee that at least four adjacent grid cells have the same K value. The mean $\overline{Y}$ was selected such that $\overline{K} = 10^{-8}$ m/s, as in the case of the homogeneous/impervious layer, while the variance σ_Y^2 was set to 10 to ensure a high degree of spatial variability. All the zones characterized by conductivity values above the threshold $\overline{K}$ are effectively areas where the upper and lower aquitard units can communicate (aquitard "holes"). The stochastic fields obtained in this way on the regular grid have been then interpolated using the kriging technique with the same covariance function on the aquitard triangulation. This 2D mesh having 3618 triangles and 1873 nodes, constitutes the basis for the generation of the tetrahedral 3D grid of the numerical model. All the simulations have been performed with the CODESA-3D model, a distributed, fully three dimensional, variably saturated flow and miscible transport model, that accounts for spatial and temporal variability of physical parameters and boundary conditions [Gambolati *et al.*, 1999; Lecca, 2000]. The model nodal unknowns are the equivalent freshwater pressure heads $\psi = p/(\rho_0 g)$, where p is the fluid pressure, ρ_0 is the freshwater density and g is the acceleration of gravity, and the relative salt concentration *c* [/], normalized with respect to the maximum salt concentration of seawater (30 grams/liter). The 3D mesh of the domain, containing 20603 nodes and 108540 tetrahedra, was obtained by replicating vertically the land surface triangulation to form 10 layers of variable thickness. These layers discretize the three main hydrogeological units: upper and lower aquifers and the interbedded aquitard. Zero flux Neumann boundary conditions were imposed on the northern and southern boundaries (water divide) and at the bottom of the aquifer system. Dirichlet boundary conditions were imposed at the western boundary (seaside) and on the surface nodes corresponding to the Tirso river while an assigned recharge flux Q of 20 10^6 m^3/y was prescribed at the eastern border (land side). The surface nodes were subjected to atmospheric forcing with a net rainfall/evaporation rate constant in space and variable in time with a one-month resolution (average potential infiltration rate =139 mm/y). Pumping wells, with different penetrations ranging from 12 to 60 m, were clustered in 9 groups, with a total production of 50%Q. The groundwater flow model was calibrated against published piezometric data [Pala & Cossu, 1994] using the following values of aquifer hydraulic conductivity: $K_x = K_y = 10^{-5}$ and $K_z = 10^{-6}$ m/s. Porosity was set to 0.3, the specific elastic storage was set to 10^{-5} m^{-1} while the isotropic dispersivity coefficient was set to 100 m in all the formations. The following scenarios have been analyzed: the steady state ψ field with no pumping and pumping conditions and the 50-year transient state ψ and *c* fields with pumping from the phreatic aquifer. The number of Monte Carlo iterates (100) which guaranteed a stationary regime was first determined with the steady state simulations and then validated in the transient state runs. The quantitative behavior of the aquifer system has been analyzed by examining model unknown differences between the rank *j* heterogeneous and the rank *0* homogeneous cases: $\delta_{ij} = (x_i^j - x_i^0)$ with $x = \psi, c$; *i*=1, . . ., *nn*; *j*=1, . . ., *ns*, where *nn* is the number of nodes of the 3D mesh and *ns* the number of runs. In the statistical analysis the *nn* x *ns* rectangular matrix Δ whose generic element is δ_{ij}^2 has been evaluated. In particular, the ensemble indicator $\overline{\delta_j^2} = \sum_{i=1}^{nn} \frac{\delta_{ij}^2}{nn}$ has been used to represent the variance between the two considered cases. In addition the same summary statistics has also been considered to represent the partial response of the system at the scale of the single vertical grid layer.

RESULTS

Comparing the 100 heterogeneous runs with the homogeneous one we find that the maximum value of the standard deviation for the *c* field was equal to 7% (38-th simulation) proving how important the impact of the spatial variability of the hydraulic conductivity of the confining layer can be on the simulated concentrations.

Figure 2. Simulated concentration plots in the phreatic aquifer after 50 year exploitation for the case of the homogeneous (top left) and the 38-th heterogeneous (top right) runs. Isolines c = 0.1 (thick lines) are also shown. Spatial distribution of the aquitard hydraulic conductivity K for the 38-th realization (bottom left).

Figure 2 shows the comparison between the 50 year simulated *c* [/] in the phreatic aquifer for the case of the homogeneous (top left) and the 38-th heterogeneous (top right) runs. The model outputs indicate that water withdrawal causes a significant saltwater encroachment originating both from the sea and the lagoons. The difference in the saltwater intrusion mechanism due to the single effect of the K spatial variability is clearly visible. In particular it has been found that the course of the 0.1 isoline (saltwater front) for the heterogeneous case greatly differs from the homogeneous one. A maximum relative distance of 1.5 km was evaluated between the two simulated saltwater fronts, subtending a contaminated area of 4.96 km^2. Figure 3 represents the mean of the normalized variance $\overline{\overline{\delta_L^2}}$ evaluated in a layer by layer fashion for the transient runs. It illustrates how the effect of the aquitard "holes" tends to be negligible far from the confining layer and also how the dynamics of the two aquifer units is differently affected by its heterogeneity. Indeed, it shows a monotonic trend that increases with the layer number in the phreatic aquifer (first 3 layers), with a maximum occurring at the aquitard interface (4-th layer) and then decreases in the semi confined aquifer (last 7 layers) both for pressure and concentration fields. Steady and transient simulations show that consideration of the K spatial heterogeneity, even if in the case of a very thin confining layer, can be very important for the realistic prediction of the groundwater circulation and salt dispersion. Furthermore, the transient simulations show that the buffer zone adjacent to the sea and the lagoons is where higher accuracy in the hydrogeological characterization of the impervious layer is needed and also where the construction of capturing wells should have been strongly limited. Thus, predicting the effect of local discontinuities of the aquitard on water and solute mass transport is essential to evaluate the potential risk of contamination due to different exploitation schemes.

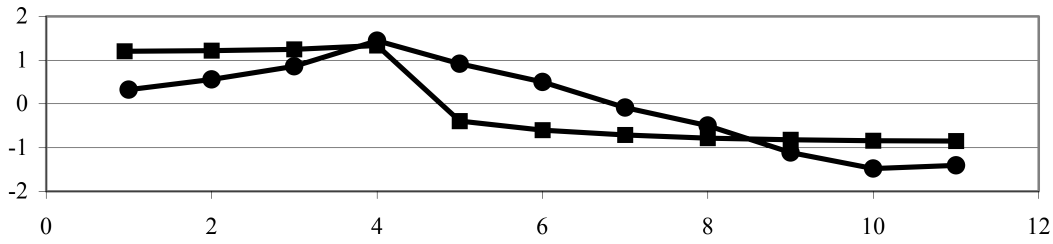

Figure 4. Layer by layer normalized $\overline{\overline{\delta_L^2}}$ versus layer number for pressure (square symbol) and concentration (circle symbol) fields after 50 year exploitation. The maximum difference between the homogeneous and the heterogeneous case always occurs at the aquitard interface (4-th layer). It can be noticed the different behavior of the upper (first 3 layers) and the lower (last 7 layers) aquifer units.

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