SEAWATER INTRUSION IN THE PLAIN OF ORISTANO (SARDINIA, ITALY)

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ABSTRACT

The site under study covers an area of 273 km^2 in the Oristano plain on the west coast of Sardinia (Italy). Since 1950 the plain, formed during the Quaternary by alluvial deposits, has been under intensive cultivation and is an important dairy farming centre. In the coastal region, the large number of wells (25,000 tapped and not) some very close to each other, has resulted in over-exploitation of the aquifer system creating a circular circuit of water between the shallow phreatic aquifer and the deeper semi-confined aquifer. As a consequence, a significant deterioration of groundwater quality due to seawater encroachment has been observed in three successive monitoring campaigns (1989, 1995, 2000). This study aims to investigate the causes of saltwater intrusion by developing a model supported by a geographic information system. A three-dimensional finite element model (CODESA 3D) is used to simulate coupled flow and solute transport processes in variably saturated porous media. The data processing steps undertaken to set up the computational model are briefly described and available data are critically reviewed. One of the issues to be addressed is the importance of accurately describing the properties of the semi-confining clayey layer between the two aquifers, as its presence may create a barrier to saltwater intrusion but may also hinder attempts to replenish the deeper aquifer or, vice versa, its local discontinuities may have a strong impact in enhancing salt content.

INTRODUCTION

Water supply is one of the major problems afflicting Sardinia. The absence of permanent water resources, the losses in the distribution pipes which amount to more than 40% of the total water used and the prolonged periods of drought have substantially decreased available water reserves with the result that rationing of municipal, industrial, and agricultural supplies has had to be introduced. This is particularly critical in large agricultural areas where the water shortage is a major contributor to the high-level of contamination. Moreover Sardinia lacks a coherent water management policy in that more then 40 different local organizations are responsible for deciding water prices and when and whether to distribute it. Future water supply management policies will necessarily make strategic use of the important groundwater resources occurring in the region. Most of these aquifers are located close to the coast and, because of improper or inexistent management strategies, some of them are heavily contaminated by seawater intrusion. Careful management and exploitation of groundwater resources needs to be implemented, taking into consideration the effects that over pumping may have on seawater intrusion dynamics.

We have studied the coastal aquifer system of the Oristano plain (Campidano), western part of central Sardinia (Italy) that is one of the major sources of groundwater on the island, by means of a seawater intrusion model supported by a geographical information system.

DESCRIPTION OF THE STUDY AREA

The area under study is characterized by the typical climate of a Mediterranean island, with peak rainfall in December, minimum rainfall in July, and an average of about 610 mm/year, of which 65-70% is lost to evapotranspiration.

The morphology of the territory is predominantly flat, bounded to East by the Monti Ferru and Monti Arci hills (Figure 1). Several natural permanent pools (the Cabras, Mistras and S. Giusta lagoons), and some seasonal ones which dry up completely during the summer, for almost six months a year, are situated in the plain. The lagoons cover an area of about 60 km^2, and are one of the largest wetlands in the whole of Europe. The salt content varies significantly from one lagoon to another, the Mistras lagoon being the one with the highest salt content and the S. Giusta lagoon the lowest. The lagoons are recharged directly by the rainfall, surface runoff, groundwater and the sea.

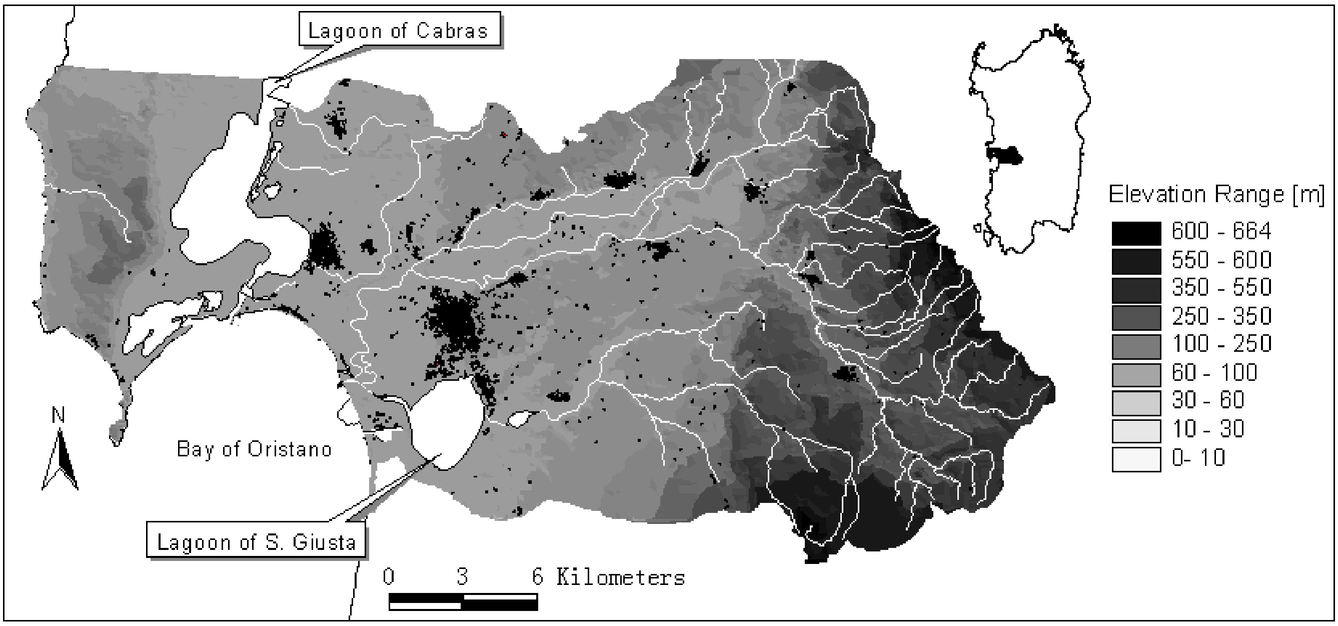

Figure 1 *Location map of the Oristano coastal plain with the digital elevation model and the main hydrography.*

The plain, that has formed on a tectonic trough of Tertiary age is characterized by Quaternary deposits with fluvial, lacustrine, marine and eolian facies. The Quaternary formation has a thickness of some hundreds of meters. The stratigraphic sequence, whose characteristics vary from one place to another, is generally characterized by gravelly, sandy, silty and clayey deposits.

The main river is the Tirso. Its basin covers an area of about 3300 km^2. Land is used primarily for cereal cultivation with rice fields in second place.

The groundwater formation is hosted in the Quaternary formations deposited by the river Tirso, and is formed of two main units, a shallow phreatic aquifer and a deeper multi layer semi-confined aquifer. These units are separated by a variable thickness aquitard that, in previous modelling studies, has been assumed as impermeable [5]. The available hydrogeological data do not enable, however, a precise characterization of the confining layer, but some of the data suggest that partial communication between the two units occurs. This communication has a strong influence on the hydrodynamics of the two aquifer units when subjected to intensive pumping.

Historical background.

In order to understand the current hydrogeological situation of the plain we have to consider the processes that have profoundly modified the Campidano plain over the last decades. The degradation that we see today is the product of many years of mismanagement, which gave little consideration to the problem of saltwater intrusion.

The Mistras, Marcedì and S. Giovanni lagoons were naturally connected with the sea, and as such are natural lagoons. Nowadays artificial canals, constructed to regulate properly the water balance of the system, also connect the Cabras and S. Giusta ponds to the bay. Therefore the salt content of the ponds has been altered, and today they can also be considered lagoons.

The plain was renowned in ancient times, for the richness of its dairy products. Up until the First World War the Campidano plain, was little populated and basically utilized for pastoral activities. It was an insalubrious morass that favoured the spread of malaria, about 43,13% of the population suffering from this disease (1934). The first reclamation started in 1812, with the drainage of an area called the "Cea 'e Cuccu" in the eastern part of Oristano. This terrain was then used to cultivate wheat and became so productive that it came to be known as the "Sardinian granary". In 1912 the Santa Giusta pond was dredged and the material was used to cover the extensive marshlands. But it was only after the enactment of the Serpioni laws of the 1924 and 1933, that reclamation was commenced in the whole plain. This also led to the construction of the town named Mussolinia, known today as Arborea. The morass, about 100 km^2, once drained, was very fertile and productive, and was converted to cereal cultivation and rice fields.

In those years the Arab open channel technique of irrigation was adopted, based on a turnover system. Only in 1976 did the "Consorzio di Bonifica", the organization responsible for water management policies, introduce modern irrigation practices (sprinkler systems). It has been estimated that, to irrigate the fields at least 40 % more water was used than today. The irrigation system used groundwater resources and the water stored in the Santa Chiara dam built in 1923. This altered profoundly the hydraulic regime of the Tirso River, originally characterized by natural seasonal variation as all the Sardinian rivers. As a matter of fact the Tirso River is today entirely controlled by the Santa Chiara dam, constructed at approximately 50 km from the coast, and its discharge is thus practically constant and has become a source of constant recharge for the aquifer system.

As a result hydrological dynamics has varied over the last 50 - 60 years. As a matter of fact, until 1930 the areas surrounding the lagoons and also a large part of the plain were characterized by a thin layer of water that created a constant total pressure head. This presumably acted as a hydrostatic barrier to seawater intrusion. Mostly due to the canalization of the rivers and the construction of the dam, there has been a loss of net recharge, which along with the withdrawal of large quantities of water from the aquifer system, after reclamation, presumably accelerated the natural salt intrusion process in the coastal areas.

Data analysis.

The Department of Land Engineering of the University of Cagliari has collected in three measurement campaigns (1989, 1995, 2000) data on water quality (pH, electric conductivity, and temperature) and the piezometric head measured from the well top. About 500 wells have been monitored, but it is estimated that more then 25000 tapped and disused wells are present. Over the last 5 years an increase in electric conductivity of about 20% has been observed in the wells located close to the sea. In some cases the electric conductivity measured exceeded 24000 μS/cm, indicative of seawater intrusion. Electric conductivity has been normalized at the temperature of 20° C, and then correlated with total dissolved solids (TDS). The interpolation method used is kriging with a linear variogram with no drifts. The boundary conditions of the system are the coastline that was set to a normalized concentration of 1, and the lagoons set to a 0.67 TDS normalized concentration.

The results are shown in Figure 2. The threshold for the seawater intrusion zone was set to 2500 μS/cm, value imposed by the Italian national law for water of the 4th quality class (law 152/99). This zone maintains its boundary basically parallel to the lagoons and to the coastline and varied little in the years 1989 and 2000. In August 1995, the boundary line (2500 μS/cm) varied from a minimum of 0.992 km to about 2.6 km from the coast. In January 2000, the same boundary line had shifted slightly. It is easy to observe the formation of a cone of intrusion located east of the Cabras lagoon, the minimum distance from the lagoon-sea line is 0.78 km and the maximum distance is about 3.5 km. The Sinis peninsula is instead characterized by high electric conductivity in all three campaigns. In this area the water has been presumably highly contaminated by seawater, and nowadays is unusable.

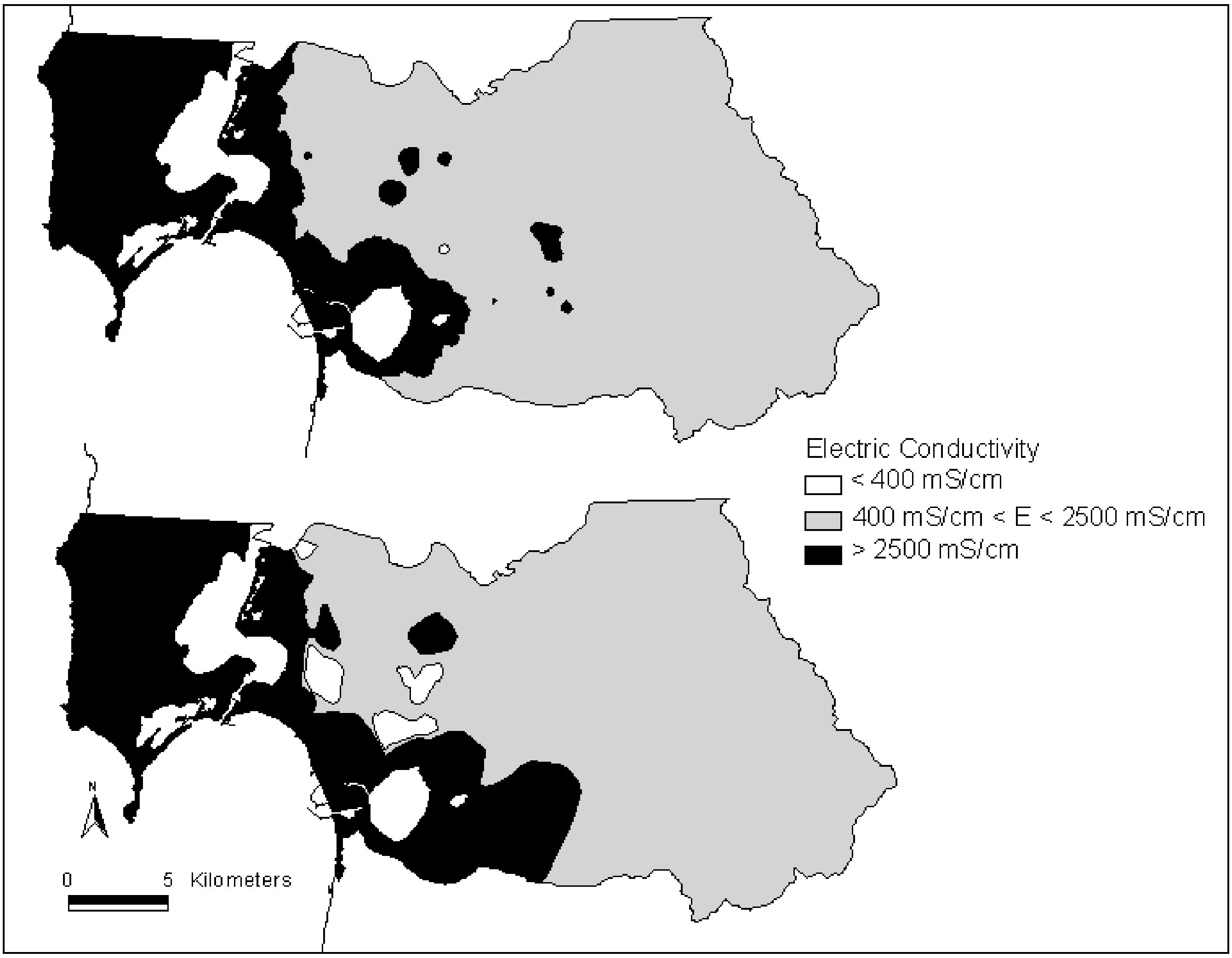

Figure 2 *August 1995 (above) and January 2000 (below) groundwater quality charts based on electric conductivity measurements.*

MATHEMATICAL MODEL

The CODESA-3D (COupled variable DEnsity and SAturation) code used in this study has been jointly developed by the CRS4 and the University of Padua [6]. It is a distributed, fully three dimensional, variably saturated flow and miscible transport model that accounts for spatial and temporal variability of parameters and boundary conditions. The wide applicability of the model allows investigation of a number of scenarios important for the Oristano study site, such as the effects of aquifer heterogeneity, location and rate of pumping, natural recharge, and unsaturated zone characteristics. The full coupling between water flow and salt transport components makes it possible to examine in detail density effects and interactions between pressure head and salt concentration fields, and, derived from these fields, water table levels, groundwater velocities and saltwater-freshwater mixing zone. The numerical model and its mathematical aspects are described in detail in Gambolati *et al.* [6] and are only briefly reviewed here for the purpose of introducing important simulation parameters to be subsequently presented.

The mathematical model of density-dependent flow and transport in groundwater is expressed here in terms of an equivalent freshwater total head $h = \Psi + z$, where $\Psi = p/(\rho_0 g)$ is the equivalent freshwater pressure head, p is the fluid pressure, ρ_0 is the freshwater density, g is the acceleration of gravity, and z is the vertical coordinate directed upward. The density of the saltwater solution is $\rho = \rho_0(1 + \varepsilon c)$, with ρ_0 the reference density, c [/] the relative salt concentration, normalized with respect to the maximum salt concentration of seawater (30 grams/litre [g/l]), and $\varepsilon = (\rho_s - \rho_0)/\rho_0 << 1$ the density difference ratio, being ρ_s the maximum density of seawater. With these definitions, the coupled system of variably saturated flow and miscible salt transport equations is:

$$\begin{cases} \sigma \dfrac{\partial \psi}{\partial t} = -\nabla \cdot \vec{v} - nS_w \varepsilon \dfrac{\partial c}{\partial t} + \dfrac{\rho}{\rho_0} q \\ n \dfrac{\partial (S_w c)}{\partial t} = \nabla \cdot (D \nabla c) - \nabla \cdot (c\vec{v}) + qc^* + f \end{cases}$$

with the Darcy velocity vector given by $\vec{v} = -K[\nabla \psi + (1 + \varepsilon \cdot c)\nabla z]$.

In the above equations *t* is time; $K = K_s(1 + \varepsilon c)k_r$ is the hydraulic conductivity tensor, with K_s the saturated hydraulic conductivity tensor at the reference density and $k_r(\psi)$ the relative conductivity; n is the porosity; $S_w(\psi)$ is the water saturation; $\sigma(\psi,c) = (1 + \varepsilon c)(S_w S + n\,dS_w/d\psi)$ is the general storage term, with

$S = \rho_0 g(\alpha + n\beta)$ the specific elastic storage at the reference density, and α,β the medium and fluid compressibility, respectively; q is the injected (positive)/extracted (negative) volumetric flow rate;

$$D = nS_W \tilde{D} = \alpha_T |\vec{v}| \delta_{ij} + (\alpha_L - \alpha_T) v_i v_j / |\vec{v}| + nS_w D_0 \tau \delta_{ij} \qquad \text{with } i, j = x, y, z\,,$$

is the dispersion tensor with $\tilde{D}$ defined as in Bear [1], α_L, α_T the longitudinal and transversal dispersivity

coefficients, respectively, $|\vec{v}| = \sqrt{v_x^2 + v_y^2 + v_z^2}$

δ_{ij} the Kronecker delta, D_0 the molecular diffusion coefficient, and $\tau = 1$ the tortuosity; c^* is the normalized concentration of salt in the injected/extracted fluid; and *f* is the volumetric rate of injected/extracted solute that does not affect the velocity field. Initial and boundary conditions are added to complete the mathematical formulation of the flow and transport problem. Non-linear coupling in system (1) is due to the concentration terms in the flow equation and the head terms that appear in the transport equation via the Darcy velocities. An additional source of non-linearity is introduced when the unsaturated zone is included in the saltwater intrusion model, as expressed through the flow equation coefficients S_w and k_r. The non-linear pressure head dependencies in the water saturation and relative hydraulic conductivity terms are expressed through semi-empirical constitutive relationships such as Brooks and Corey [2]:

$$S_w = [(1 - S_{wr})\left(\frac{\psi_s}{\psi}\right)^{\beta} + S_{wr}] \qquad \text{and} \qquad k_r = \left(\frac{\psi_s}{\psi}\right)^{2+3\beta}$$

with $\psi < \psi_s$, where ψ_s is the bubbling pressure head, S_w is the residual water saturation and β is the pore-size index.

The numerical model is a standard finite element Galerkin scheme, with tetrahedral elements and linear basis functions, and weighted finite differences are used for the discretization of the time derivatives. The system of non-linear algebraic equations arising from discretization is solved by an iterative scheme using either the Picard or Newton methods.

MODEL APPLICATION

Model set-up.

The 3D geometric model of the study site was obtained from the 400x400 m digital elevation model of the plain, with elevations ranging from –1.8 to 79 m above sea level ($z = 0$), and a reconstruction of the aquifer bottom, according to the occurrence either of an impermeable rock layer or a thick (>10 m) clayey sequence in 22 hydrostratigraphic units from drill holes in the plain [8], with elevations ranging from -18 to -214 m. The modelled domain covers an area of 273 km^2 with an average thickness of 123 m, ranging from 18 m in the central zone to 218 m in the southeastern zone. The domain was discretized into a 2D surface grid containing 3618 triangles and 1873 nodes. This non-uniform grid, constructed to have the smallest triangles (1400 m^2 as compared to 153056 m^2 for the largest) along the coast and around zones of heavy pumping, was then replicated vertically for 10 layers yielding a 3D mesh of 108640 tetrahedral elements and 20603 nodes (Figure 3). The aquifer system was subdivided into 3 units: a shallow phreatic aquifer, a thin semi-confining clayey aquitard, and a deeper semi-confined aquifer. The layers were defined to be of increasing relative thickness t from the surface to the base of the aquifer. The shallow phreatic aquifer was discretized into 3 vertical layers (t = 2 x 3, 4%), the thin semi-confining aquitard into a single layer (t = 2%); and the thick semi-confined aquifer into 6 layers (t = 2 x 14, 4x 15%) so as to have a sufficiently fine resolution in the upper part of the aquifer system. With this configuration of just over 20000 nodes, in the following referred to as *A-configuration*, a typical 50 year simulation with an average time step of 6 months on a high-range workstation (RS/6000 SP system 375 MHz Power3-II 16GB, *puccini.crs4.it*) required about 1 hour of CPU, a fast enough turnaround time for fine-tuning of the model and for generating scenarios.

The x, y, and z components of the saturated hydraulic conductivity tensor were assigned values of $K^I_x = K^I_y = 10^{-5}$ m/s and $K^I_z = 10^{-6}$ m/s for both the shallow phreatic and the deeper semi-confined aquifer units. The embedded clayey aquitard was assumed isotropic with $K^{II}_x = K^{II}_y = K^{II}_z = 10^{-8}$ m/s. Porosity n was set to 0.3, while the specific elastic storage S was set to 10^{-5} m^{-1} in all formations. Brooks-Corey parameters for water retention characteristics were assumed to represent a sandy soil with $\beta = 0.694$, $S_{wr} = 0.067$ and $\psi_s = 0.0726$ m. Homogeneous hydraulic conductivities and porosity were estimated using information from pumping tests and laboratory tests [7] and were subsequently reduced during model calibration to match the 2000 field observations. The solute transport parameters were $\varepsilon = 0.03$ and $D_0 = 0$. An isotropic value as large as 100 m, dictated by the adopted grid spacing, was taken for solute dispersivity coefficients α_L, α_T. In order to relax the constraints of the numerical scheme on the dispersivity values, a much finer resolution in space (with the smallest triangle of 2.5 m^2) was adopted for selected simulations on a refined vertical cross-section B-B of the 3D domain, placed between the Cabras lagoon and the Tirso river and oriented orthogonal to the coast line (Figure 3). This vertical slice of width 10 m, length limited to the first 5000 m from the sea and variable thickness, was considered to examine in more detail the density-driven flow in the mixing zone between saltwater and freshwater and the role of the semi-confining clayey layer in the spreading of saltwater. For this second configuration of 49200 nodes (referred to as *B-configuration*) the isotropic dispersivity value was reduced to 10 m and a typical 200-year simulation took about 6 hours of CPU with an average time step of 6 months.

Zero flux boundary conditions were imposed on the aquifer bottom and on the northern and southern domain boundaries regarded as groundwater divides. Prescribed lateral recharge flux Q = 0.63 m^3/s (20x10^6 m3/y) was set on the eastern boundary of the A-configuration, according to the water budget of the mountain sub-catchment of the Tirso river, while the eastern limit of the B-configuration, much closer to the coast, was taken as fixed head ($h = 1$) boundary, based on 2000 field observations. On the coastal vertical side a fixed actual total head $h^* = 0$ was assigned, corresponding to $h = -z\varepsilon$; while for the salt concentration, a zero gradient along the normal direction ($\partial c / \partial n = 0$) was imposed over an upper outlet window, of depth 20 m from the land surface, to mimic freshwater discharge into the sea and, below it, a prescribed seawater concentration $c = 1$ was imposed.

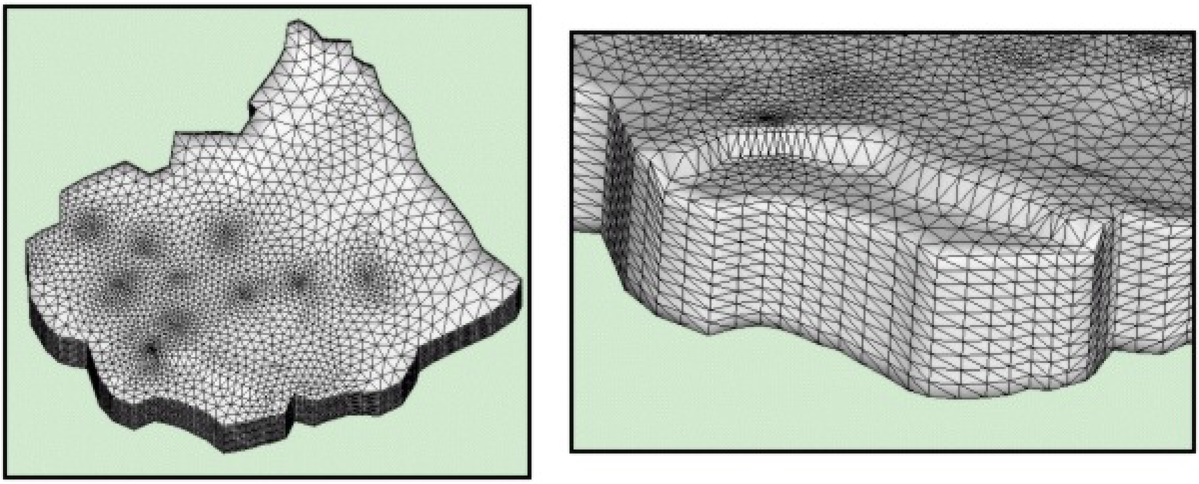

Figure 3 *The tetrahedral mesh of the 3D domain refined near the coastline and the 10 pumping zones (left) and a zoom of the coastal area (right) that includes a portion of the sea.*

The surface nodes were subjected to atmospheric forcing, with potential infiltration rate of 18% of annual rainfall, fixed in space but variable in time with a one-month resolution. Fixed head $h = 0$ was assumed on the Tirso River and on the two lagoons, where also a constant concentration $c = 0.66$ (20 g/l) was prescribed. Initial conditions for the simulation of aquifer exploitation were unperturbed, presumed to exist prior to the 1950s, as the steady state (no groundwater pumping) for flow and the null concentration field for transport.

Results.

Figure 4 shows the 2000 simulated relative concentration field c [/] on the water table after 50 years exploitation (1950 – 2000) of the aquifer system. A constant pumping rate at the 10 clustered wells, with penetrations at different depths (12-60 m), was imposed with a maximum total extraction of 50% of the aquifer lateral recharge Q. Isophreatic lines –10 and 0 m a.s.l. are plotted to delimit drawdown cones caused by intense pumping. The deflection of the saltwater front towards pumping zones is evident near the coastal area and around the lagoons.

The results of the simulation show that water withdrawals by pumping have caused a significant saltwater encroachment both from the sea and the lagoons. Comparing these results with 2000 measured electric conductivity field (Figure 2) we obtain a good match that shows model accuracy in capturing the essential processes of seawater intrusion. In the calibration process saturated hydraulic conductivities and pumping rates were the model parameters that most heavily influenced the behaviour of the system. The infiltration rate was not a critical parameter since actual infiltration rates were automatically computed by the model, according to the current soil water saturation conditions, as a fraction of the potential input rates. To examine the effect of aquifer heterogeneity with respect to the vertical permeability K^{II}_z of the semi-confining layer, selected simulations were run using the B-configuration. Two schemes were adopted: a first one with a uniform isotropic hydraulic conductivity $K^{II} = 10^{-8}$ m/s distribution (continuous scheme) and the second one with the presence of a discontinuity of length 20 m centred at 300 m from the coast line, which was given the same vertical hydraulic conductivity $K^{II}_z = 10^{-6}$ m/s of the upper and lower aquifers (discontinuous scheme). This second scheme can mimic the presence of an abandoned cluster of wells that constitutes a preferential vertical flow path between the two aquifer units. Figure 5 compares relative concentration fields c [/] of the two schemes after 200-year aquifer exploitation with a single well located at 150 m from the sea pumping from the phreatic aquifer (10 m penetration) at a constant rate of 2×10^{-4} m3/s.

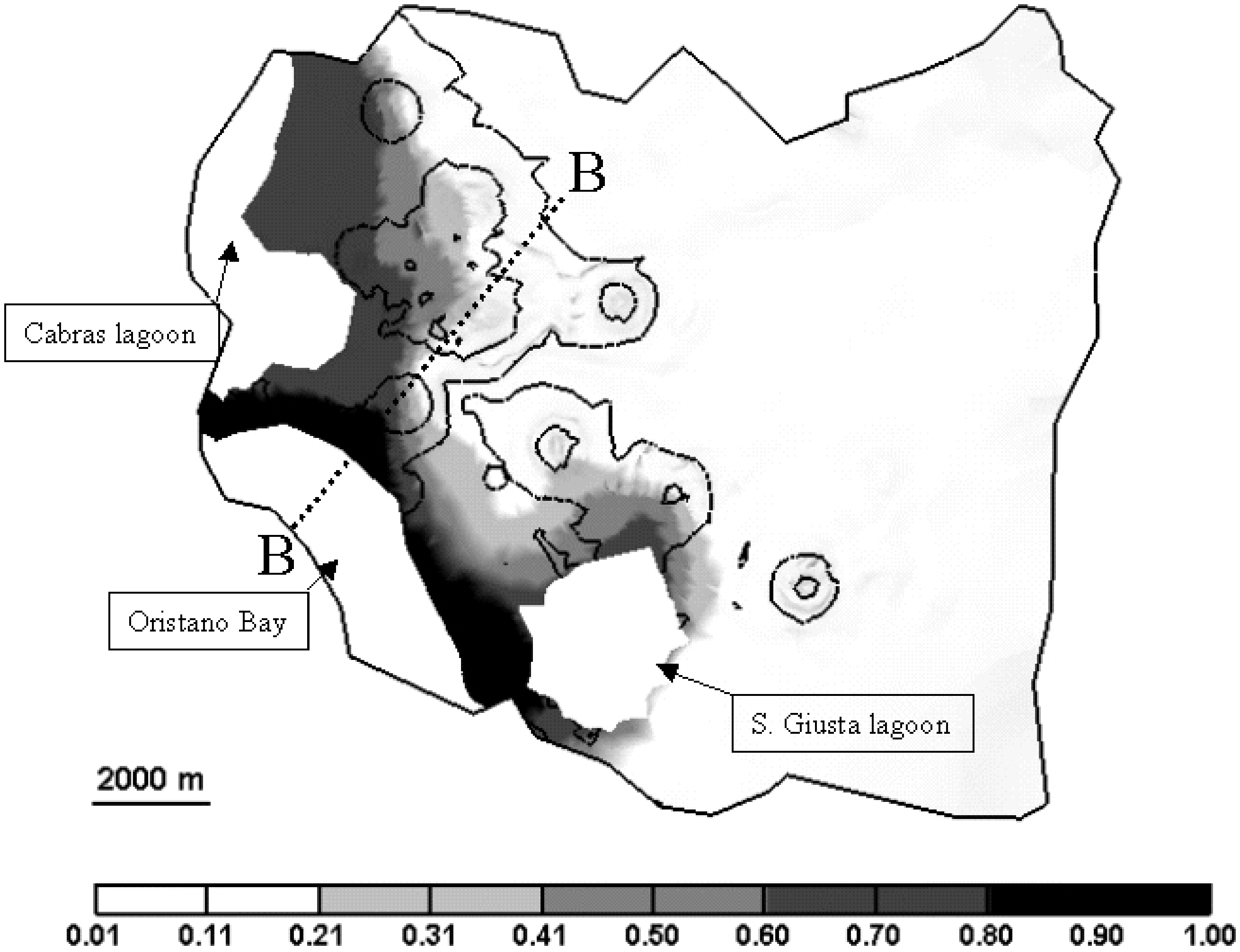

Figure 4 *A-configuration: simulated relative concentration field c [/] on the water table after 50 years exploitation of the aquifer system. Isophreatic lines 0.0 –10.0 m a.s.l., are shown to delimit drawdown cones. Note the deflection of the saltwater front towards pumping areas. The location of the vertical cross-section B-B (B-configuration) is also shown.*

The closeness of the well to the coast along with the high pumping rate (situation frequently found in the plain) caused the saltwater front to reach the well location in 3 years. For a well located at 1000 m from the coast the simulated saltwater front reached the distance of 150 m in 70 years (not shown). This supports the idea of the need for a buffer zone near the coastline and around the lagoons where pumping should be severely restricted. Moreover it can easily be seen from Figure 5 that local discontinuities in the semi-confining layer significantly alter the spatial distribution of salt throughout the aquifer system. Modelling results indicate that, during aquifer exploitation, areas of higher permeability in the confining layer (e.g., abandoned drilled holes, sandy lenses etc.) close to the drawdown zone create a faster vertical seepage flux from the threatened semi-confined aquifer to the phreatic aquifer, contaminating areas of clean freshwater due to salt upconing.

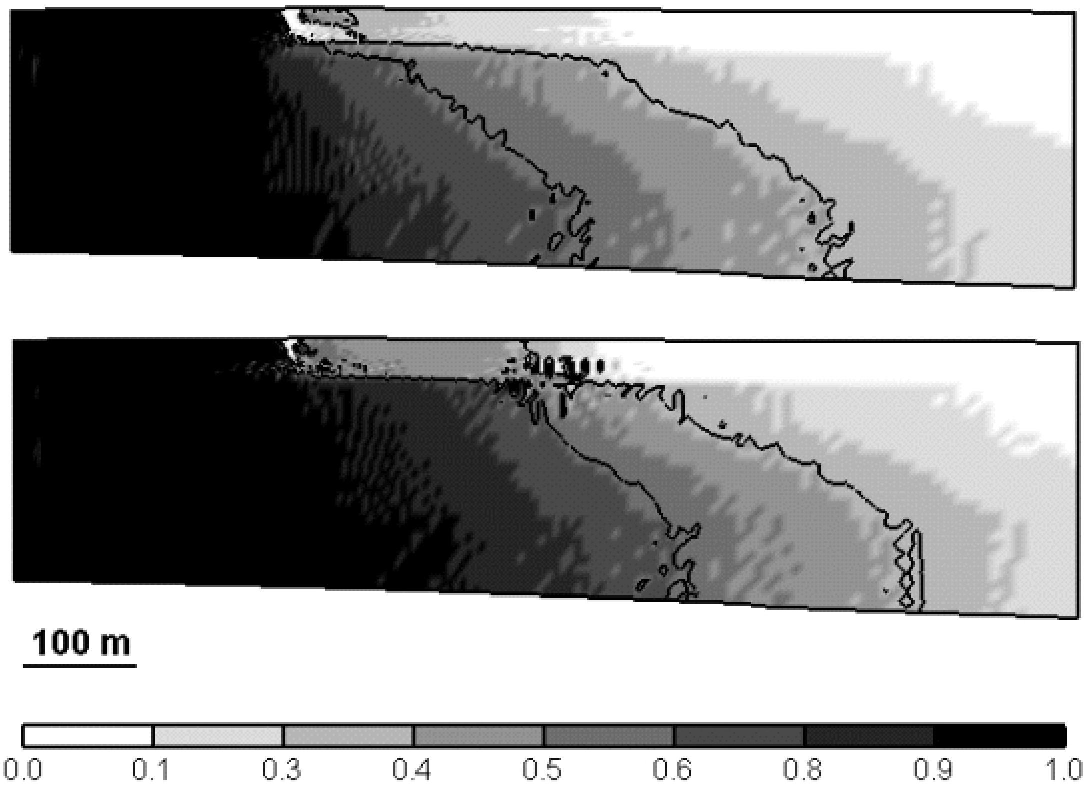

Figure 5 *B-configuration: simulated relative concentration field c [/] after 200 years exploitation for the continuous (above) and discontinuous (below) semi-confining layer schemes. Isoconcentration lines 0.4 and 0.6 are shown. Note the salt upconing due to heavy pumping in the discontinuous scheme.*

CONCLUSIONS

The management of the aquifer requires adequate tools and technologies for a better understanding of the phenomena taking place, and the dynamics of its degradation. In this context a multidisciplinary research has been conducted that enabled to place in time and to delimit in space the saltwater intrusion process. The changes in the hydrological pattern due to the reclamation of the Oristano plain at the beginning of the century, the construction of the Santa Chiara dam, and the canalization of the rivers along with mismanagement have strongly contributed to the degradation of the groundwater in the coastal areas. A critical analysis of available data has been carried out to obtain a rough estimate of the system's hydrogeological parameters and to get a critical viewpoint of the infield situation. In this context we set up a geographical information system and applied a groundwater model to study salt migration. The simulated hydraulic heads and the salt concentrations agree well with the field data, confirming the validity of the three-dimensional seawater intrusion model and the simulation procedure used. The application of such models can provide a scientific basis for predicting the movement of the freshwater-saltwater mixing zone and can be usefully employed to develop future scenarios. The hypothesis of a discontinuous clayey confining layer, due to the presence of abandoned wells and sandy lenses, has been investigated. Model results show that these discontinuities can act as a preferential path of communication between the lower and upper aquifer for salt migration and vice versa (circular circuit of water and salt) when the aquifer system is subjected to intense pumping.

Acknowledgement.

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