PREDICTING GROUNDWATER SALINITY CHANGES IN THE COASTAL AQUIFER OF ARBOREA (CENTRAL – WESTERN SARDINIA)

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Abstract

The area of Arborea, extending over roughly 70 km^2, is located in the Northern Campidano plain (central-western Sardinia - Italy). The plain, that was formed in a tectonic trough of the Tertiary, is characterised by Quaternary deposits of fluvial, lacustrine, marine and eolian facies. The Quaternary formation is several hundred meters thick. The stratigraphic sequence, whose characteristics vary from one place to another, is generally represented by gravelly, sandy, silty and clayey deposits. The aquifer basin consists of two main units, a shallow phreatic aquifer (around ten meters thick) and a deeper semiconfined - confined unit, separated by a variable thickness aquitard. The system is recharged by rainfall, irrigation and by lateral inflow from the volcanic rock aquifers bordering the plain. Owing to inadequate water management policies, the Arborea coastal aquifer system has been contaminated by seawater intrusion as a result of overexploitation during the frequent droughts that affect Sardinia. Groundwater withdrawals have caused saltwater to encroach landward and upward toward the withdrawal points. Periodic monitoring, carried out for several years by the Department of Land Engineering at the University of Cagliari showed a varying degree of salt water intrusion along the coast. High electrical conductivity values were found mostly in the deeper aquifer, as it is locally overexploited, whereas lower values were recorded in the shallow phreatic aquifer. Nevertheless, in the shallow aquifer the extension of contaminated areas is larger than in the deep aquifer. In this work an extensive quality assessment of the data was performed to characterise the area overlying the Arborea aquifer system. In this context we set up a geographical information system and applied an environmental model to study the migration of the contaminants. A preliminary model, elaborated with the CODESA 3D code, was implemented to simulate the impact of land management (different groundwater abstraction schemes, artificial recharge etc.) on the salt dispersion process.

Keywords: saltwater intrusion, coastal aquifers, simulation, Sardinia

Introduction

The section of Applied Geology and Geophysics of the Land Engineering Department at the University of Cagliari has been studying salination of coastal aquifers in the Oristano Plain (Central-Western Sardinia, Figure 1) for more than 15 years. The research area, at the beginning covering roughly 142 km^2, has been gradually extended up to the current 470 km^2. During the last three years, all data collected in periodic field measurements have been organized into a data base together with a series of information related to geological, stratigraphical, pedologic, thermometric, pluviometric and hydrochemical aspects. This made it possible to reconstruct the time variation of aquifer salination and to identify the most likely sources of contamination and the most vulnerable areas.

Recent investigations have focused on the reclaimed area of Arborea (Figure 1), extending over roughly 70 km^2 in the most productive region in Sardinia, in terms of agriculture and animal raising. Further investigations and measurements carried out in this area allowed to define the conceptual model and to implement a preliminary numerical model for identifying a series of scenarios deriving from different conditions of external stress.

All collected and processed data have been organized into a Geographic Information System (GIS).
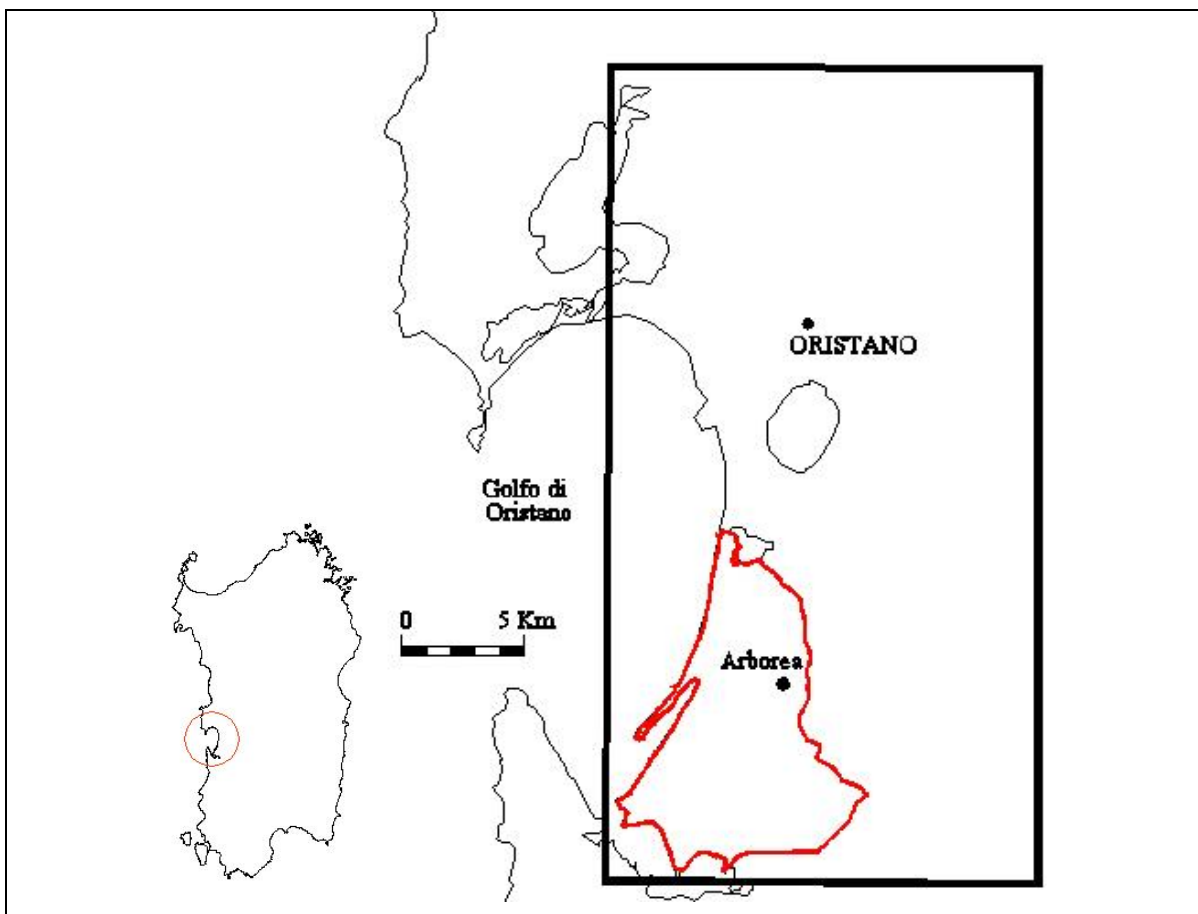

Figure 1: Location of the study area.

Hydrogeological features

The study area is part of a deltaic alluvial plain, whose hydrography is characterized, from North to South, by the rivers "Rio Mannu di Santu Lussurgiu", "Tirso" (the largest river in Sardinia), "Rio di Mogoro" and "Flumini Mannu di Pabillonis", and by numerous coastal ponds, the most important being "Cabras", "Santa Giusta", "s'Ena Arrubia" and "San Giovanni" (Figure 1).

The rainfall regime is highly variable, intense rainfall events alternating with long periods of drought. The temperature regime is typically Mediterranean, with mild winters and long, hot and dry summers.

The outcropping geological formations are composed of gravelly-sandy deposits of the Quaternary (AA.VV., 2001) and the stratigraphic sequence is generally represented by an alternation of permeable formations, largely gravel and sand, and silty and clayey formations.

Two main aquifer systems have been identified in the plain: a shallow phreatic aquifer located in the sands and a deeper multi-layer aquifer of variable artesian pressure. The shallow aquifer is no more than 10 m thick and is separated from the underlying multi-layer aquifer by a clayey or silty-clayey aquitard 2 or more meters thick (Barrocu et al., 1995; Soddu, 2004). The system is recharged by rainfall, irrigation waters drawn from river Tirso reservoir (not included in the investigation area), stream drainage and by lateral inflow from the volcanic rock aquifers bordering the plain. Following the damming the river Tirso and paving of numerous stream beds and minor canals (for example the "Rio Mogoro"), groundwater recharge of the system has been drastically reduced. Moreover, to satisfy the high water demand, chiefly for agricultural use and mainly during the dry periods, a large number of wells has been drilled. Preliminary estimates of the water budget (Staffa, 2003; Soddu, 2004) show that the quantities of water withdrawn far exceed effective groundwater recharge, resulting in overexploitation problems. Processing of data collected for water table levels and electrical conductivity as well as chemical determinations, has confirmed the critical state indicated by the water budget data.

Evolution of salt contamination

Figures 2 and 3 show groundwater levels and electrical conductivity measured in the field in spring 2003 for the shallow and deep aquifer (Soddu, 2004).
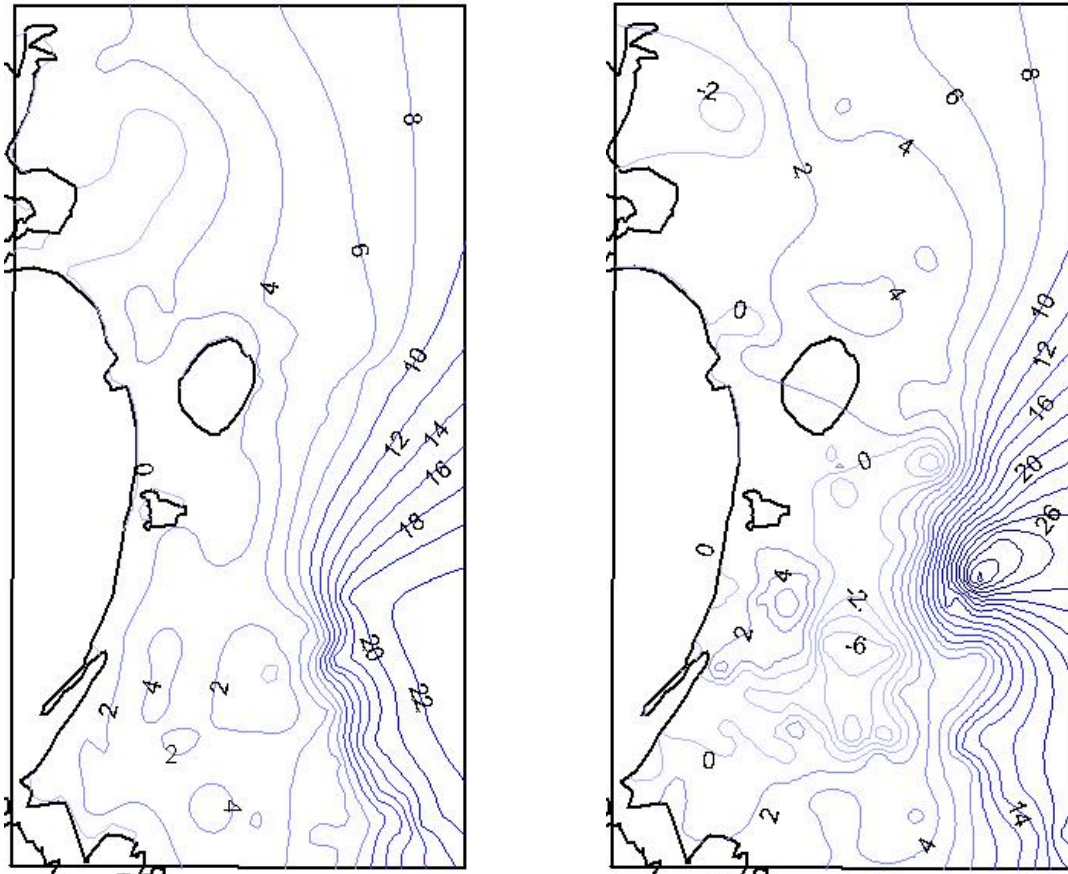
Figure 2. Groundwater levels (m) for the shallow (left) and deep (right) aquifers.
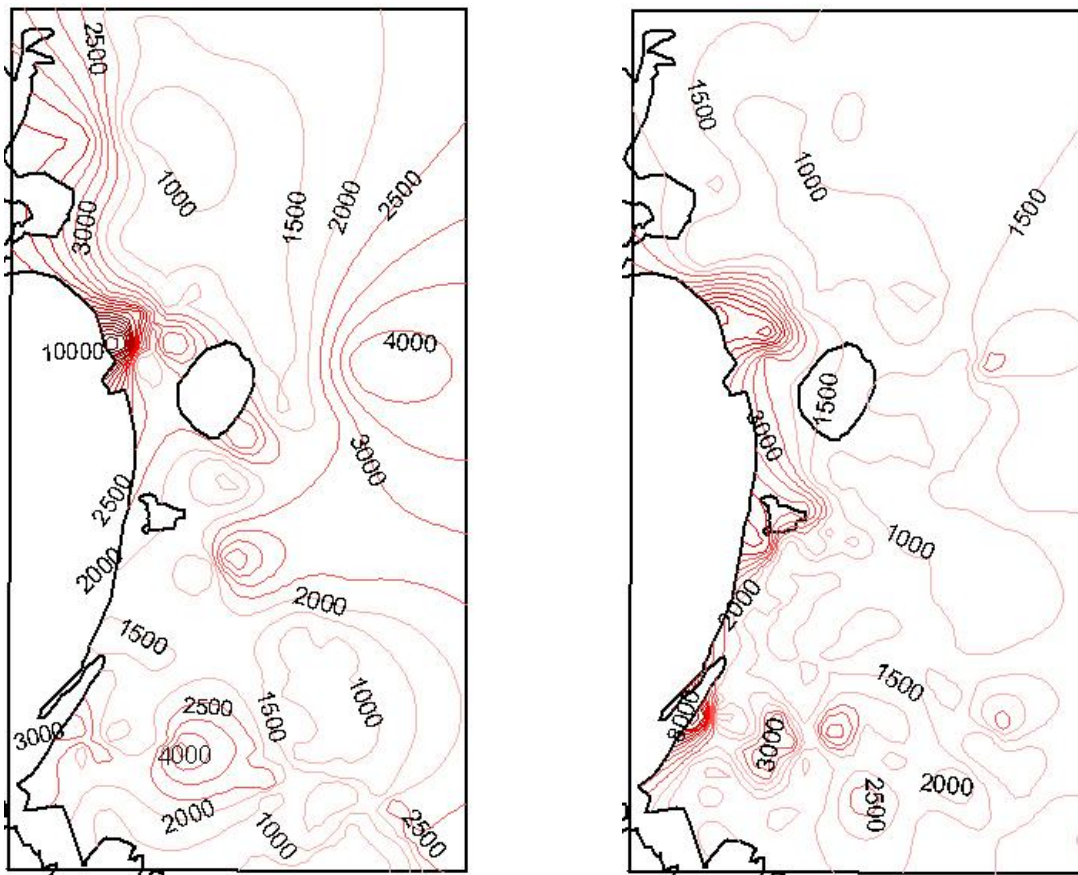

Figure 3: Electrical conductivity at 20°C (µS/cm) for the shallow (left) and deep (right) aquifers.

The groundwater levels show, for both the shallow and deep aquifers, an average flow coastwards, with local inversions mainly due to the presence of pumping wells. The hydraulic gradients tend to diminish coastwards, facilitating seawater encroachment. The highest groundwater levels in the shallow aquifer are lower than those of the deep aquifer, but are generally above mean sea level, while inverted cones of −6 m are attained in the deep aquifer. One likely explanation for this is that the phreatic aquifer has far lower yield than the multi-layer one, where pumping rates are much higher.

As for electrical conductivity, referred to 20°C, Figure 3 shows that in large areas values exceed 2000 μS/cm, the limit for the majority of crops cultivated in the plain. The electrical conductivity contours are rather irregular in both aquifers, but, on average, the highest values are observed along the coast, with peaks around the coastal ponds. Interestingly, some inland anomalies were recorded at the latitude of the "Santa Giusta" pond and in a belt more or less perpendicular to the coast located near the Corru de S'Ittiri fish farm (Arborea plain). The areas with highest electrical conductivity in the Arborea area correspond almost exactly to those having lower groundwater levels and the areas with highest conductivity in the two aquifers also match very closely. Electrical conductivity in the shallow aquifer is on average lower than in the deep aquifer, but in the former areas where electrical conductivity exceeds 2000 μS/cm are observed more frequently. The above observations suggest the causes of groundwater salination to be seawater intrusion and interaction with coastal ponds as well as other phenomena in inland areas (such as upconing, salt dissolution processes involving non-leached formations or ancient marine waters penetrated into the subsoil in past geologic eras). The chemical composition of groundwater sampled in some of the drilled wells (data supplied by the Genio Civile office in Oristano) seem to substantiate this hypothesis: chloride contents are particularly high (195-603 mg/l) and groundwater hardness (on the whole very hard) can also indicate the presence of brackish waters.

To understand in what way abstraction has changed the regime and quality of groundwater, the groundwater levels and electrical conductivity values for the years 1990, 1995, 2000 (Cau, 2000) and 2003 (Soddu, 2004) are compared.

Groundwater in the phreatic aquifer has on average maintained the same piezometric levels over the years and locally levels have even increased. These apparently unchanged levels do not however match the mean electrical conductivities of the groundwater which remain substantially unvaried but have increased locally.

By contrast, the groundwater levels of the deep aquifer show a certain lowering, whereas the electrical conductivity values on the whole have increased, especially along the coast.

In the light of the above remarks and of field observations, the unchanged (or local rise) piezometric levels in the shallow aquifer may be attributed to the progressive abandonment of dug wells in favour of the more productive drilled wells and to irrigation waters withdrawn from drilled wells and from the Tirso reservoir. Intensive groundwater abstraction has progressively aggravated contamination of the deep aquifer without improving salinity conditions in the shallow aquifer. The reasons for this are to be sought in a combination of the following factors:

1. overexploitation may have irreversibly contaminated groundwater in the shallow aquifer;

2. salinity in the shallow aquifer may also be due to artificial fertilizers;

3. shoddily constructed wells cause mixing of groundwater from the two aquifers;

4. the abstraction of part of the groundwater from the deep aquifer for irrigation reduces the benefits produced by non saline recharge water, such as infiltrating meteoric water and water from the Tirso reservoir and from stream drainage.

The factors under points 3 and 4 may also explain the general coincidence between the highest electrical conductivity areas in the two aquifers, especially in the southern part of the study area.

Reclaimed area of Arborea

Over the last year studies have focused on the southern portion of the plain, namely the reclaimed area of Arborea (Figure 1), which was not included in the monitoring network prior to 2003. The problems outlined above are particularly critical in this area, which was marshland up until 70 years ago. The study area is bounded to the N by the "s'Ena Arrubia" pond, to the W by the sea, to the SW by "San Giovanni" pond and to the E and SE by the "Acque Medie" canal and by the "Rio Mogoro". The "Acque Medie" canal and the "Rio Mogoro" beds have been paved, making them impervious. There are no natural watercourses in this area supplying the aquifers, which are replenished primarily by meteoric and irrigation waters and by lateral recharge. With a view to developing the conceptual model of the area, in January 2004 electrical conductivity monitoring and chemical analyses were carried out. Water samples were collected from both aquifers at the most significant points. A total of 29 samples were collected, at the sites shown in Figure 4. Electrical conductivities of the samples confirm the trends observed in 2003.

Figure 4 shows the contour lines for chloride in the shallow and deep aquifers. There is a remarkable correspondence between the highest chloride concentrations and the highest electrical conductivity, especially in the deep aquifer for which a linear relationship has been found (Soddu, 2004). High concentrations of lithium and strontium have also been found in wells with high electrical conductivities and chloride concentrations. These observations suggest that high electrical

conductivity values, especially in the deep aquifer, are directly related to the presence of waters of marine origin.
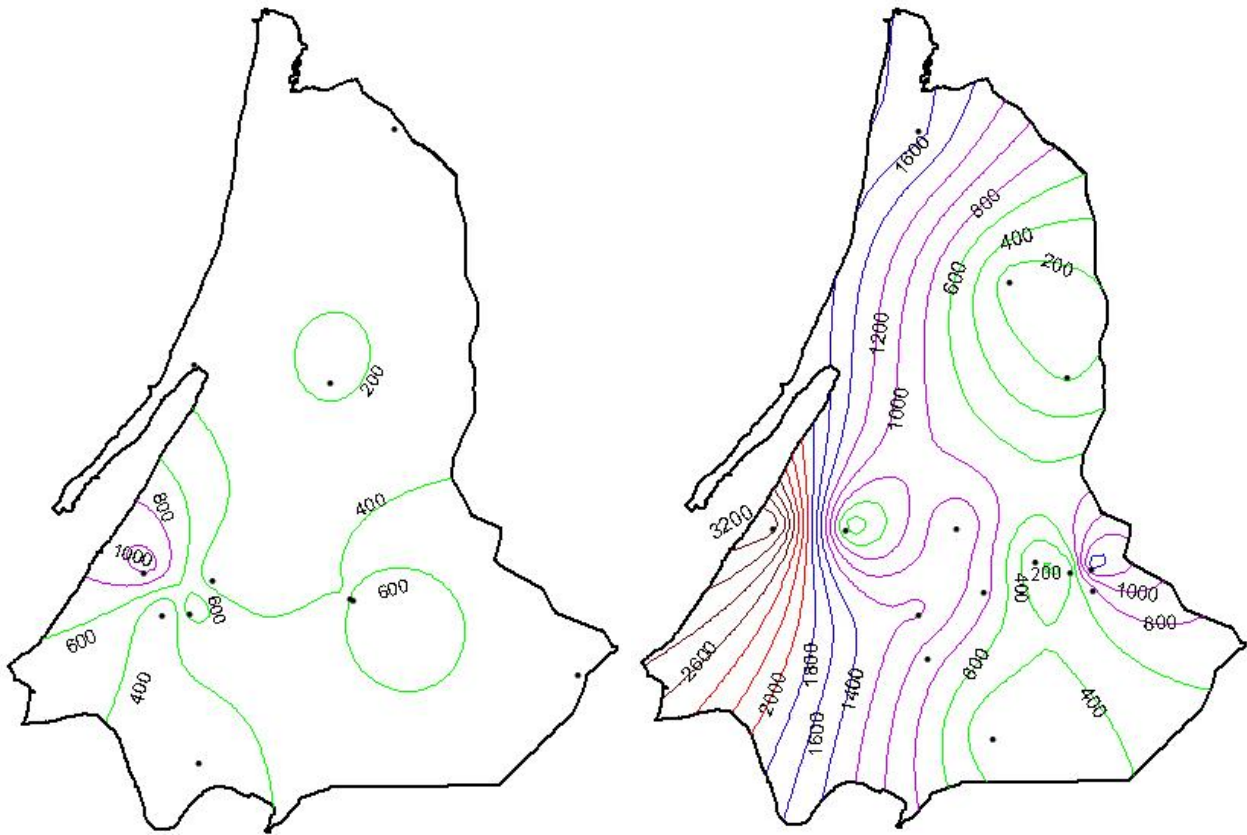

Figure 4: Chloride contour lines (mg/l) for the shallow (left) and deep (right) aquifers.

Conceptual model of the Arborea area

The first step in building the numerical model, developed using the CODESA-3D code, was to define the conceptual model of the area. The hydrogeological system has been represented by two aquifers of the same areal extension as the study area: a shallow phreatic aquifer and a deep confined aquifer, separated by a clayey aquitard. The average thickness of the formations containing the shallow aquifer, whose top coincides with ground level, is 10 m, while the aquitard is around 2 m thick. The hydraulic conductivity values are 10^{-3} m/s for the shallow aquifer and 10^{-8} m/s for the aquitard. The deep aquifer is considered around 48 m thick. The model area is larger than the study area since it also incorporates the sea and the coastal ponds. As far as the shallow aquifer is concerned, the sea and the lagoons are taken as surfaces with zero pressure head and given salinity and the "Acque Medie" Canal and the "Rio Mogoro" are in practice impermeable boundaries. Wells have been introduced into the model as representative points of groups of wells, according to zoning based on groundwater levels and conductivity values.

Mathematical model

CODESA-3D is a Fortran code that simulates 3D flow and transport (Gambolati et al., 1993; Gambolati et al., 1994; Gambolati et al., 1999; Lecca, 2000). The flow module simulates water flux in the porous medium, accounting for external contributions like infiltration, evaporation, pumping, recharge etc., while the transport module calculates the displacement of salt water due to advection and dispersion. The model takes into account the presence of both saturated and unsaturated zone and assumes a diffuse interface between fresh and salt water. The mathematical model is based on two coupled differential equations which, for a given control volume, express the mass conservation principle for water and dissolved salts (Gambolati et al., 1999; Lecca, 2000). These equations are formulated in terms of two unknowns which, at a point of coordinates x, y and z and at time t, are defined as follows:

$$\psi(x, y, z, t) = \frac{p}{\rho_f g} \quad (1) \quad c(x, y, z, t) = \frac{c'}{c'_s} \quad (2)$$

where ψ represents the equivalent freshwater pressure head, p is water pressure, ρ_f is fresh water density and g is the gravitational acceleration. The normalized concentration c is defined by the ratio between the actual salt concentration c' and maximum salt concentration c'_s and varies between 0 and 1. The flow and transport equations comprising the mathematical model can be written:

$$\sigma \frac{\partial \psi}{\partial t} = -\nabla \cdot \mathbf{v} - \phi S_w \varepsilon \frac{\partial c}{\partial t} + \frac{\rho}{\rho_f} q \quad (3)$$

$$\phi \frac{\partial(S_w c)}{\partial t} = -\nabla \cdot (c\mathbf{v}) + \nabla \cdot (D\nabla c) + qc* + f \quad (4)$$

The symbol $\mathbf{v}$ represents Darcy velocity, $\sigma(\psi, t)$ is the storage coefficient, ϕ is porosity, S_w is water saturation, q is the injected (positive) or extracted (negative) volumetric flow rate, $\mathbf{D}$ the hydrodynamic dispersion tensor, $c*$ is the normalized salt concentration in the injected (positive) or extracted (negative) fluid, f is the volumetric rate of injected (positive) or extracted (negative) solute in a limited quantity unable to affect the flow field.

Equations (3) e (4) form a coupled system due to the concentration and the piezometric head (that appears in the transport equation via the expression of Darcy velocity). Both equations contain non-linear expressions in the unknowns. An additional source of nonlinearity is due to σ and to the permeability of the medium, that appears in Darcy velocity, which are non-linear functions of ψ when the flow takes place in the unsaturated zone ($\psi < 0$). The mathematical formulation of the model is completed by the initial and boundary conditions (Lecca, 2000).

Numerical model

The CODESA-3D code is a standard finite element Galerkin scheme (Gambolati et al., 1999; Lecca, 2000). The domain discretization leads to a system of ordinary differential equations in the nodal unknowns $\hat{\psi}$ and $\hat{c}$. The system is integrated in time using the finite differences method, leading to a system of nonlinear algebraic equations to which Picard or Newton linearization techniques are applied. The final system is solved by a successive substitution scheme through a cyclic process that ends when the solutions fall within the prescribed tolerance.

The spatial domain discretization starts with the creation of the superficial triangular mesh that, in the present case, contains 1406 nodes and 2694 elements. The mesh has only been thickened in high gradients areas (coast, lagoon shores, some wells). The 3D tetrahedral grid is created through a CODESA-3D subroutine that replicates the 2D mesh in the vertical direction, according to the user defined number of layers. In the present case, we defined five layers: one for the shallow aquifer, one for the underlying aquitard and three for the deep aquifer.

Simulations

In the present paragraph only the most emblematic results obtained for the shallow aquifer will be discussed. The numerical modelling of the deep aquifer requires a more detailed analysis and involves greater difficulties as CODESA-3D does not include automatic calibration.

Steady state flow simulations

Steady state simulations have been carried out assuming a fully saturated system as initial condition. The three most representative simulations have been performed in the following conditions:

1. natural conditions (no pumping, no irrigation, mean yearly infiltration of 134.5 mm);

2. as for simulation 1, but considering recharge by irrigation waters coming from the Tirso reservoir (mean yearly infiltration of 200.6 mm);

3. as for simulation 2, but considering pumping from wells (average real conditions of the system). As mentioned, pumping rates in the shallow aquifer are very low and much less than in the deep aquifer. For this reason only three wells have been activated (note that each well represents a set of wells belonging to a homogeneous area) with constant pumping rates of $0.3\text{-}0.5 \times 10^{-2} \text{m}^3/\text{s}$.

Analysis of the results shows what follows (Soddu, 2004):

- The groundwater level contours show an inland/seaward and an inland/coastal lagoons direction of the water flux;

- Comparison of the first two situations examined allowed to quantify the average rise of groundwater levels due to infiltrating irrigation waters, that can attain 50 cm. The differences between the nodal values in the two simulations tend to increase inland, especially in the south.

- Comparison of the second and third simulation show that wells have not a strong influence in the piezometric contours, that are regular like those deriving from field measurements. However in pumping areas groundwater drawdown at the nodes is calculated to be 30 cm or more. For the same pumping rate, the effects of pumping are more evident inland than near the coast because of the effect of boundary conditions.

Transient flow simulations

The fourth simulation has been carried out in transient conditions taking into account the seasonal fluctuations infiltration and, consequently, of aquifer recharge.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
33.8	30.3	17.7	18.4	0.0	0.0	0.0	0.0	0.0	10.1	50.4	40.0

Table 1: Mean monthly infiltration (mm).

The calculated values (Table 1) have been cyclically imposed over a period of 18 years and it was decided to print a monthly output at year 18 so that iterations could become stable. The initial flow condition is the one obtained with simulation number three (steady state regime, average real conditions of the system). Figures 5 and 6 show the groundwater level contours obtained for the months of March, August and December.
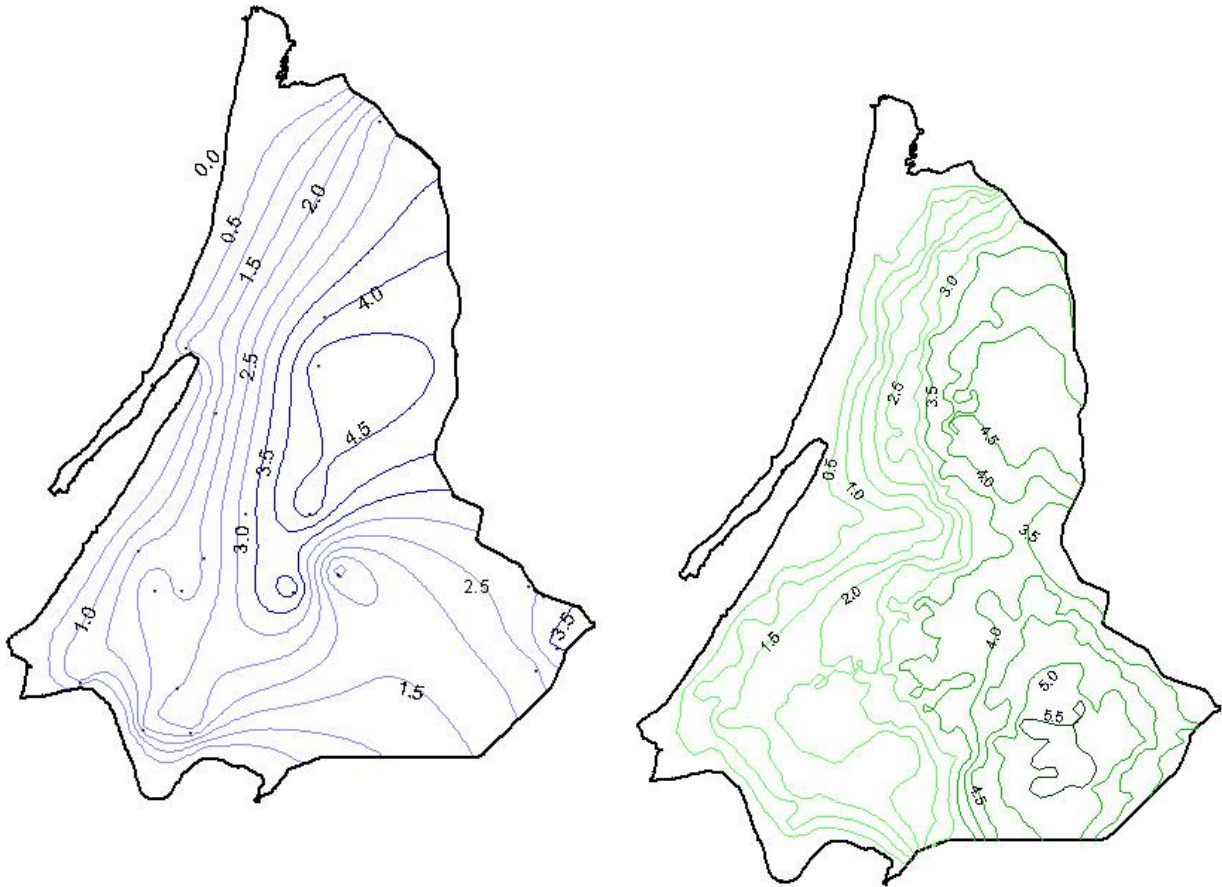
Figure 5: Comparison of calculated (right) and measured (left) groundwater level contours (m) for the Spring period.

Figure 6: Calculated groundwater level contours (m) for the month of August (right) and December (left).

The shape of the Spring contours matches the field data fairly well. The most significant differences are observed in the south-east portion, an area where there are no wells and consequently no field measurements were available to draw a meaningful comparison. Groundwater levels fall visibly in the month of August (minimum condition), while the maximum levels are observed in December.

The transport problem

Having analyzed how the model responded to the flow problem, next the flow and transport problem was addressed. The results presented here concern the most meaningful simulation, performed in the following conditions:

- Initial flow conditions derived from steady state flow simulation in actual conditions of the system (simulation number three);

- Presence of the actual recharge (rain and irrigation) and of pumping wells as for the third simulation;

- Normalized concentrations of zero at time zero (initial condition for the transport problem);

- Normalized concentrations of 1 and 0.6 for salt water (sea) and brackish water (ponds) respectively (boundary conditions for the transport problem);

- Simulation time of 30 years.

Figure 7: Thirty-year evolution of saltwater intrusion (normalized concentrations): contamination at 5 (left) and 30 (right) years.

Figure 7 shows contamination in terms of normalized concentrations (equation (2)) at 5 and 30 years from the base year. The advance of the saltwater front is clearly visible, but it is worthwhile noticing that the largest withdrawals from the coast line are those of the minor concentration curves. Figure 8 shows the withdrawal of the 0.5 concentration line, which may represent the location of the ideal sharp interface. The position of the line is fairly stable, bounding a contaminated belt extending from 250 m in the central coastal area to 1600 m near the coastal ponds. Contrarily to the field data, simulations of transport do not indicate the presence of contaminated inland areas. This result strengthens the hypothesis that salinity of the shallow aquifer in those areas farthest from the coast can be attributed to three causes that are not represented by the model: the use of artificial fertilizers, the mixing of waters coming from the two aquifers due to shoddily constructed wells and the use of saline waters coming from the deep aquifer for irrigation purposes.
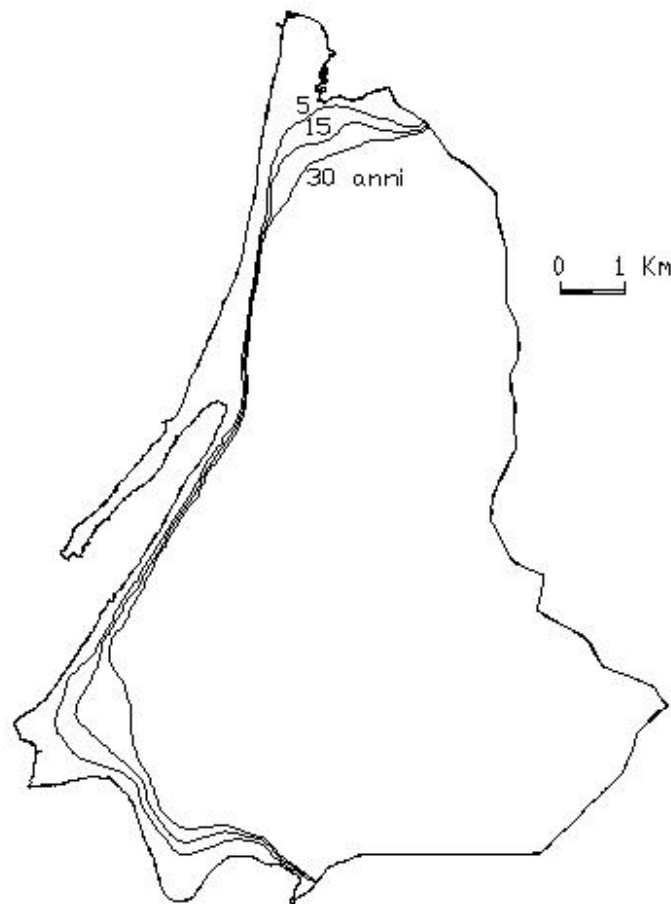

Figure 8: Thirty-year displacement of the ideal sharp interface.

Conclusions

The hydrological calculations performed for the Oristano plain indicate that the quantities of water pumped from the aquifers far exceed groundwater recharge. Chemical analyses have shown that high electrical conductivity values, especially in the deep aquifer, are associated with high

concentrations of chloride and of other minor elements typically contained in seawater. In the shallow aquifer this matching is less manifest. Temporal analysis of contamination has revealed an alteration of the equilibrium between salt and fresh waters, resulting in saltwater intrusion processes along the coast and other contamination phenomena in inland areas. The highest salinity peaks were recorded in the deep aquifer, currently more intensively tapped, but in the less productive shallow aquifer, where pumping rates are very low, a larger number of areas were observed to have electrical conductivity values higher than 2000 µS/cm. The areas of highest salinity in the two aquifers, especially in the Arborea area, also coincide inland. This can be very likely due to contamination of the shallow aquifer by infiltrating irrigation waters pumped from the deep aquifer and to shoddily constructed wells which cause groundwater mixing.

Implementation of the numerical model of the Arborea area allowed to reconstruct the shape of the groundwater levels for the shallow aquifer under different conditions, and to evaluate the effects of irrigation, pumping and seasonal fluctuations in recharge. The model has shown that the abstraction regime of the shallow aquifer is such as to cause saltwater intrusion in a coastal region extending over a maximum width of 1600 m, in agreement with the hypothesis, suggested by field observations and chemical analysis, that inland contamination is mainly due to mixing of waters between the two aquifers and artificial fertilizers.

The results of the study have demonstrated that the investigation method adopted for the Oristano plain is adequate for addressing the specific hydrogeological problems. Consequently field measurements and numerical processing will be integrated in the future in order to achieve the following targets:

1. Complete the model for the deep aquifer in the Arborea area. This will enable a study of the interactions between the two aquifers as a function of external stresses, pumping rates and the degree of mixing of groundwater from the two aquifers.

2. Continue model validation using monitored data and perform isotopic analyses in order to better define the origin of saltwater.

3. Extend the model to the entire research area.

4. Identify the limitations of the model and perform a comparative analysis with other numerical codes.

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