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G.I.S. and Modeling for Studying Saltwater Intrusion in the Capoterra Alluvial Plain (Sardinia - Italy)

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ABSTRACT

Previous experience at a regional scale has demonstrated that the greater the possibility of analyzing and managing information utilized for saltwater intrusion modeling in coastal aquifers, the more comprehensive and reliable the end results are likely to be. The contribution offered by Geographical Information Systems (G.I.S.) for achieving this goal is crucial.

A G.I.S. allows to acquire, store, process and represent spatial information in real time and in a form suitable for further use in different application contexts. A wide range of problems can be addressed within the philosophy of a G.I.S., thematic mapping, land planning, environmental impact studies, natural resources management, location of environmental risk areas, demographic studies, modeling.

The information acquired during earlier hydrogeological studies in the Capoterra alluvial plain have been organized into a G.I.S. for the purpose of modeling saltwater intrusion. The paper describes the modeling procedure adopted.

INTRODUCTION

A comprehensive study of the Capoterra alluvial plain has been conducted by the Engineering Geology and Applied Geophysics Section of the Department of Territorial Engineering at Cagliari University within the frame of the international projects ME.D.A.L.US. and AVICENNE 73 funded by the European Union. The purpose of the investigation was to gain a deeper insight into saltwater intrusion in the coastal aquifer system and to numerically simulate this phenomenon. (Sciabica M.G., 1994; Barrocu et al., 1997; Barrocu et al., 1998).

The considerable amount of data collected suggested setting up a G.I.S. To this end an alphanumerical database was created, along with a geographic database, so as to enable integrated methods to be applied for modeling saltwater intrusion in the coastal aquifer system..

THE CAPOTERRA ALLUVIAL PLAIN

The Capoterra alluvial plain lies in the southwestern portion of the Campidano tectonic trough in southern Sardinia (Italy). It comprises, to the S, the delta of the Rio Santa Lucia delta, a torrential watercourse, and is bounded eastwards by the Santa Gilla lagoon and northwards by the Rio Cixerri. To the West it is interrupted by a series of hills aligned en *échelon*, representing the extension of the tectonic block that west of the Sardinian graben is split up by two main sets of NW-SE and NE-SW trending fractures (Fig. 1).

On the grounds of information concerning the geology, hydrogeology, geomorphology and soils of the area, the following hydrogeological units have been recognized (Barrocu et al., 2000): fluvial and lacustrine sediments, recent and ancient terraced alluvia of the Quaternary and fractured granites and metamorphic schists of the Paleozoic. The recent alluvia are highly permeable and contain a phreatic aquifer, overlaying a second multi-layer aquifer, semi or locally confined.

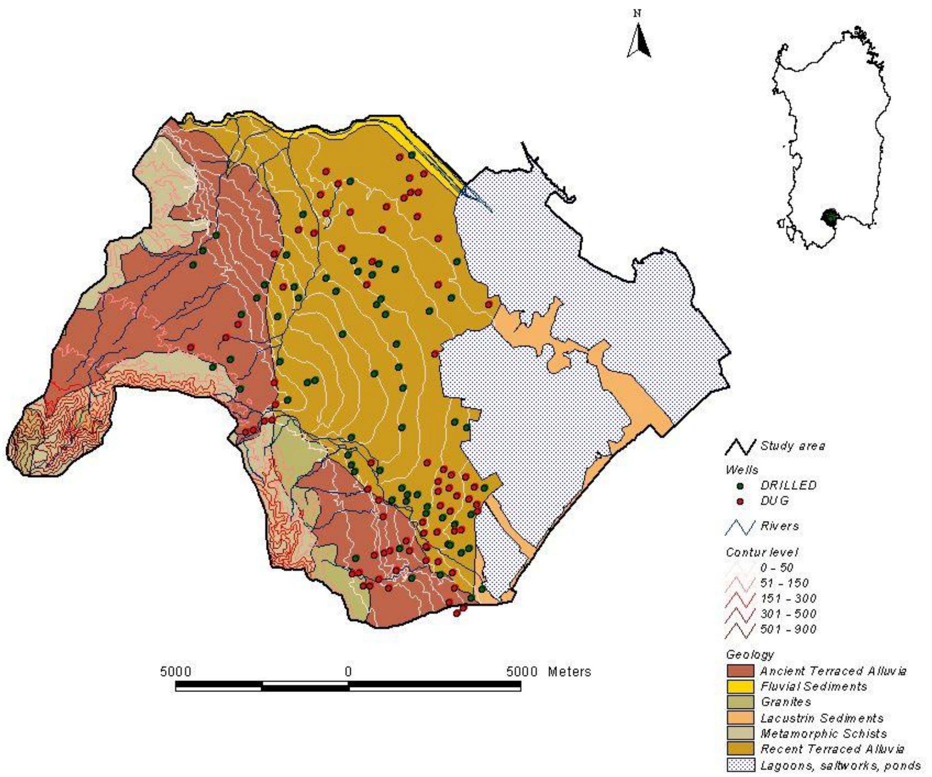

Figure 1: Alluvial plain of Capoterra in Sardinia

Over the last two decades, the area has undergone profound transformations due to the ever-increasing agricultural and industrial expansion and water demand has risen accordingly. The particular climatic condition of the area, characterized by frequent, prolonged periods of drought and the natural or human-related presence of a variety of sources of salt (sea spray, sea water, lagoon, evaporation ponds of the salt-works and salt-hills), combined with the uncontrolled overexploitation of the groundwater resources, has resulted in the depletion of groundwater resources and in the widespread salination of groundwater, with more serious consequences in the shallow part of the coastal aquifer system.

A monitoring network for controlling water quality and groundwater level was set up in June 1991 initially in the southern portion of the plain, near to the Rio Santa Lucia, and then extended northwards in April '92 to include the area nearer the Rio

Cixerri. The network comprises 132 wells, 74 wide-diameter, but relatively shallow wells, dug into the superficial aquifer and 58 wells drilled into the deep aquifer.

For each well in the monitoring network, assigned an identification code, the following information was gathered:

- type of well, dug or drilled;
- Gauss-Boaga coordinates [m];
- ground level with respect to mean sea level [m]
- elevation [m] of the reference point marked on the well with respect to mean sea level;
- height [m] of the reference point marked on the well with respect to ground level.

In 1991, '92 and '93, groundwater levels were measured each month in all the wells and water samples collected from some significant wells were chemically analysed in the laboratory to determine:

- temperature (°C);
- pH;
- electric conductivity [μS/cm];
- total salinity [g/l];
- main cations and anions (Ca, Mg, Na, K, Cl, SO_4, HCO_3, CO_3) [meq/l].

In April '94 samples of water taken from the sea, from three evaporation stages of the saltpans, from the lagoon and from the Rio Santa Lucia and Rio Cixerri were chemically analysed in the laboratory.

Pumping tests were performed at selected observation wells or at purpose built wells and piezometers so as to evaluate the hydrogeological parameters for simulating saltwater intrusion.

Artificial recharge experiments were also carried out at purpose built wells and piezometers in the plain for the purpose of assessing the efficiency of a hydrodynamic barrier aimed at controlling saltwater encroachment and its spatial evolution (Barrocu et al., 1997).

More recently, in July 1998 a measurement campaign was carried out in the frame of a detailed study of the groundwater geology and geochemistry. (Vernier E., 1999).

MODELING SALTWATER INTRUSION

The modeling procedure for simulating saltwater intrusion in the Capoterra coastal aquifer system involves the definition of the hydrogeological and conceptual models, formulation of the mathematical model, its numerical solution and validation using field measurements and the results of laboratory chemical analyses (Sciabica M.G., 1994; Barrocu et al., 1997; Barrocu et al., 1998).

The hydrogeological and hydrochemical study, based on the information acquired from the monitoring network aimed at obtaining a better definition of the hydrogeological model of the Capoterra alluvial plain for improving validation of saltwater intrusion modeling.

The hydrogeological model was defined by identifying both the natural factors, such as geology, proximity of the sea, presence of the lagoon and saltworks, and anthropic factors including irrigated agriculture, and the urban and industrial development of the area concerned. By processing the piezometric data it was possible to establish the relationships between groundwater, the lagoon, the saltworks and the sea. Examination of the correlations between chemical elements present in the water samples allowed to elucidate the processes influencing water salinity in the coastal aquifer system.

The conceptual model was defined by simplifying the domain and the phenomenon under study, leading to a series of assumptions that were then mathematically formulated and introduced into the model.

According to the hydrogeological and conceptual models, the mathematical model can be formulated as a coupled system of two partial differential equations, one describing mass conservation for the water-salt solution (flow equation), and the other mass conservation for the salt contaminant (the transport equation). Flow and transport equations are coupled by means of the constitutive equation relating density of the freshwater-saltwater mixture to salt concentration.

The numerical solution code of these non linear equations involves spatial discretization with the finite element method following Galerkin's approach, and time discretization using finite differences (Paniconi et al., 1995). The results are expressed in terms of equivalent freshwater heads and normalized concentrations at selected time intervals and at each node of the three-dimensional mesh. The calibration-validation of the numerical solution code is performed by comparing the simulation results with hydrogeological and hydrogeochemical data obtained from the monitoring network.

Based on the geological features of the plain four homogeneous zones have been defined. The first two are composed of the recent and ancient terraced alluvia of the Quaternary, the third of fractured granites and metamorphic schists of the Paleozoic, and the fourth of fluvial and lacustrine sediments. Based on the aquifers' hydrogeological parameters determined through pumping tests, hydraulic conductivity has been set for each zone. On the other hand, to set longitudinal and transverse dispersivity values, it has been necessary to reach an acceptable compromise between stability requirements of the code and soil properties reported in the literature. Moreover, the Dirichlet boundary conditions for flow and transport have been defined on the basis of measured piezometric and salinity contour lines.

Based on the four zones identified in the domain and on the location of the wells within the monitoring network, a two dimensional mesh has been created with triangular elements. A three-dimensional mesh with tetrahedral elements is automatically generated by the numerical solution code.

ORGANIZATION OF THE G.I.S.

On account of the large amount of data collected on the Capoterra plain a G.I.S. was set up, creating an alphanumerical database together with a geographic database, so as to enable integrated methods to be adopted for modeling saltwater intrusion in the coastal aquifer system.

The alphanumeric database, created with Microsoft Access, is implemented according to relational principles. The information gathered in the monitoring network over the years of measuring campaigns were organized into files containing well coordinates and elevations, water levels and results of chemical analyses for each month of measurement, reference water samples and flow tests. Each file is composed of fields containing the information gathered for each well and records pertaining to the wells comprised in the network.

To facilitate input, modification and above all display of the information contained in the database, "masks" were created for "coordinates and elevations", "water levels" and "chemical analyses" for each month of measurement, for example July 1993, August 1993, etc., "reference water samples" and "flow tests", linked together by action keys.

In each mask it is possible to:

- search for information concerning a specific well;
- access the other masks;
- print the report of the data, after preview;
- return to the last mask displayed.

The geographic database, created with ESRI ArcInfo and ArcView software, organizes the information into "views" and "themes". A view is an interactive map that allows one to display, explore, query, and analyze geographic information; it is made up of layers of geographic information. Each layer, called a "theme" is a collection of geographic features. Using an SQL connection feature, it is possible to access and query the Access database to retrieve records therefrom.

The geographic database of the Capoterra plain consists of a number of views and themes:

- a view that contains levels of general information that have been created from .DXF files in AutoCad and imported and converted into ArcInfo coverages and ArcView shape, i.e., geology, elevation, surface hydrography, monitoring network;
- as many views as there are months of measurement, containing the levels of information on water level, T.D.S. and electric conductance contour lines of the phreatic and confined aquifers, and the spatial distribution of the principal chemical-physical parameters, such us temperature, pH, cations and anions;
- a view containing the levels of information created from the saltwater intrusion modeling results including the two-dimensional mesh, the equipotential and equiconcentration lines of the 1^{st} and 5^{th} layer of the three-dimensional mesh for the simulation times.

CONCLUSIONS

Implementation of the modeling procedure, intended both as the definition of the hydrogeological and conceptual models and the numerical solution of the mathematical model, in a complex physical and anthropic context such as that of the Capoterra plain presupposes a sound knowledge base consisting of real data obtained in the monitoring network purposely set up in the area, by means of field measurements and laboratory chemical analyses.

The numerical solution of the mathematical model has demonstrated that the significant computational capacity of the code can be fully exploited if the possibility of using a punctual data base exists, both for describing the geometry of the domain identified and for characterizing the phenomenon in physical terms.

The results obtained have pointed to the need to integrate modeling with G.I.S. systems for facilitating the collection, updating and interpretation of the real data and as an aid to model construction and implementation and to the critical evaluation of the results, in order to achieve an efficient decision support system.

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