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Conceptual and numerical model of groundwater flow for a coastal plain (Piana di Sibari, southern Italy)

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ABSTRACT *The large Sibari Plain (southern Italy) is crossed by 24 rivers with mouths on the Ionian Sea. On the basis of a huge analysis of tens of boring, geophysical studies and many hydrogeological surveying campaigns, the conceptual model of the whole plain is defined. The shallow and phreatic aquifer and the deep and confined aquifer can be distinguished. The numerical model of flow is calibrated considering climatic, river yield and piezometric data and it is utilised to evaluate the effect of current groundwater discharge by wells. The numerical results are compared and validated considering a time series approach based on the utilisation rainfall, temperature and piezometric data collected from the thirties until 2006 in-situ measurements.*
The numerical simulation of the current stage of groundwater discharge shows it is not sustainable in the case of shallow aquifer and it can be improved in the case of deep aquifer.

KEYWORDS: *Porous coastal aquifer, modelling, groundwater/surface-water interaction*

1. INTRODUCTION

Over the last few decades, the alluvial coastal plain of Sybaris (Calabria, Southern Italy) has seen considerable agricultural development and tremendous urban and tourist expansion. This has led to an ever-increasing demand for water, only partly satisfied by reserves of water stored in an artificial lake. A great deal of groundwater has been tapped from wells. The use of underground water reserves was not planned with an eye to, for example, the as-yet unknown extent of recharge, or the sustainability criteria for its use.

The aim of this paper is to determine what will be needed in quantitative terms to define the criteria for the rational utilisation of this natural resource. This will involve defining the conceptual model for the aquifer, formulating the most likely hypotheses in respect of the complex modalities of groundwater flow, the interchange of water with nearby aquifers and the potentialities of the aquifer under examination. Lastly, groundwater numerical modelling, together with the many measurements taken on site, will be used to verify the conceptual model.

2. GEOLOGICAL AND HYDROLOGICAL FRAMEWORK

The carbonate Mount Pollino to the north, metamorphic rocks of the Coastal Chain to the west, the granitic Sila Mountains to the south and the Ionian Sea to the east, where sandy beaches constitute the coast, bound the Sibari plain (Figure 1). The plain includes the downstream part of the Crati River valley, 40 km long and with a SW-NE orientation, and the upstream sector, a Plio-Holocene graben N-S oriented. Its width increases from inland to the coast, where it is about 40 wide. The maximum length of the plain (about 30 km) is measured along the bed of the Crati River; the length decreases up to about 10 km outside the basin of Crati River.

The upshot of the last phase of deformation to affect the area, a marked regional uplift, was that wide bodies of sand and fluvial-deltaic conglomerates were deposited inside the sedimentary basins, directly overlying the clay of Pleistocene. Along with these deforming phenomena, major tectonic discontinuities play a fundamental hydrogeological role (Ghisetti & Vezzani, 1983; Guerricchio, 1991). Apart from the changes wrought by the tectonic discontinuities, the current condition of the plain also derives from the glacioeustatic Quaternary sea-level fluctuations which influenced the continual evolution of the coastline and the current path of the watercourses (Cotecchia et al., 1996; Guerricchio & Ronconi, 1997).

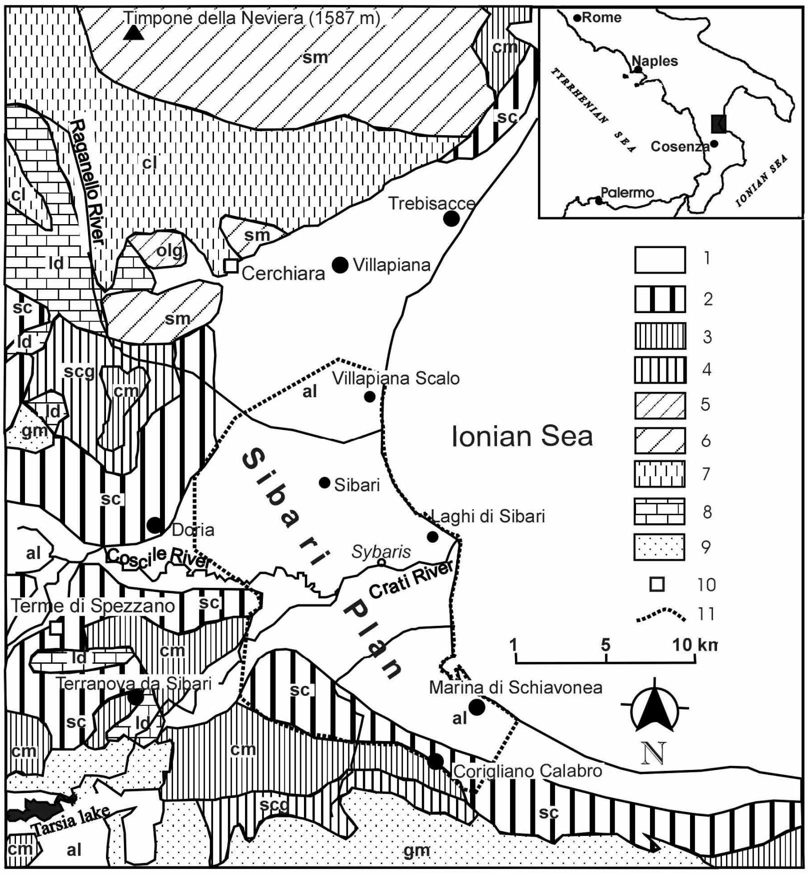

Figure 1 – Geologic map of Sibari plain and location of study area. 1=al) alluvial, fluvial, lacustrine and shore deposits, actual shore (Holocene); 2=sc) sand and conglomerates (Pleistocene); 3-cm) clays and marls (Pliocene); 4-scg) sands and conglomerates (Pliocene); 5-olg) organic limestones and calcarenites (Middle Miocene); 6-sm) sandstones and sandstones/marls (Paleocene); 7-cl) clays (Cretaceous); 8-ld) limestones and dolomites (Mesozoic); 9-gm) granites and metamorphites; 10) thermal springs 11) boundary of study area.

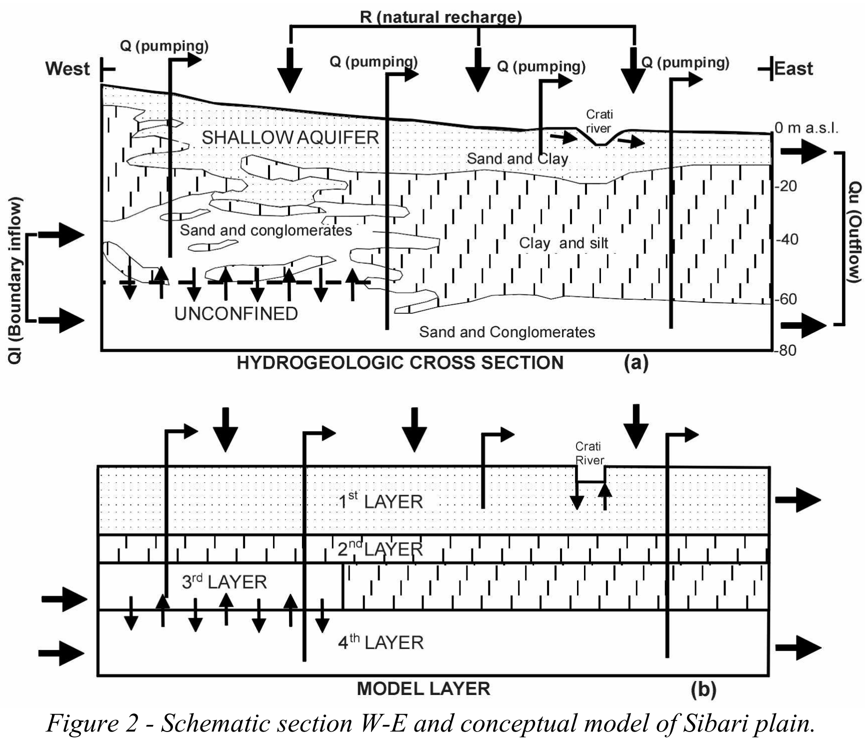

Figure 2 - Schematic section W-E and conceptual model of Sibari plain.

The Quaternary soils are sandy conglomerate deposits from the Pleistocenic Era, made up of sand, cobble-and-sand and polygenic conglomerates interbedded with layers of clay in places; Holocene sedimentary deposits, made up of sands, gravel and local peaty outcrops, of continental provenance and layers of clayey silt and sandy clay, of marine provenance. The bottom layer of the Quaternary deposits is composed of clays and Pliocene conglomerate deposits.

The plain is crossed by 24 rivers, 5 of which being tributaries of the Crati River. Their drainage area ranges from 3 to 82 km2, the only exception being the Crati River, which has a basin of 2460 km2, about 177 km2 of which extend into the Sibari plain.

The findings from previously conducted hydrogeological studies (Guerricchio et al., 1976; Tazioli, 1986; Guerricchio, 1992; Polemio et al., 2004) have been integrated with data gathered from one hundred or so boreholes and geophysical investigations. Two fairly well-defined aquifers can be distinguished in the plain: one superficial or outcropping phreatic aquifer and one underlying aquifer, referred to as deep. The clayey and impervious layer between the two aquifers downstream from the plain is well defined, facing the coast, where the clays and silty clays can be up to one hundred or so metres thick, while the layer between the two aquifers is less well-defined upstream, near the Pollino and Sila Massifs (Figs. 1 and 2). The alternation of fine impervious soils (lagoon deposits) with coarser ones (detrital deposits located along the watercourses) only goes some way towards explaining this dual hydrogeological situation.

It is, in any case, realistic to suppose that, upstream, along the belt of piedmont plain, the deep confined or semi-confined aquifer is fed by various different groundwater sources, both long and short, the latter being produced by the rocky aquifers that constitute the ranges surrounding the plain. The phreatic aquifer is made up of a series of Quaternary deposits, both continental and marine deposits. The average thickness of this aquifer is approximately 20-30 metres.

The shallow groundwater is characterised by water tables that reach maximum levels of 35 m asl in the North East sector. In this area, the presence of clayey impervious strata has a marked effect on the groundwater flow, which circulate at a depth of just a few metres from the ground surface; the water table adapts itself to the morphology of the ground surface and to hydrographic network; the groundwater flow is from West to East, towards the sea (Figure 3).

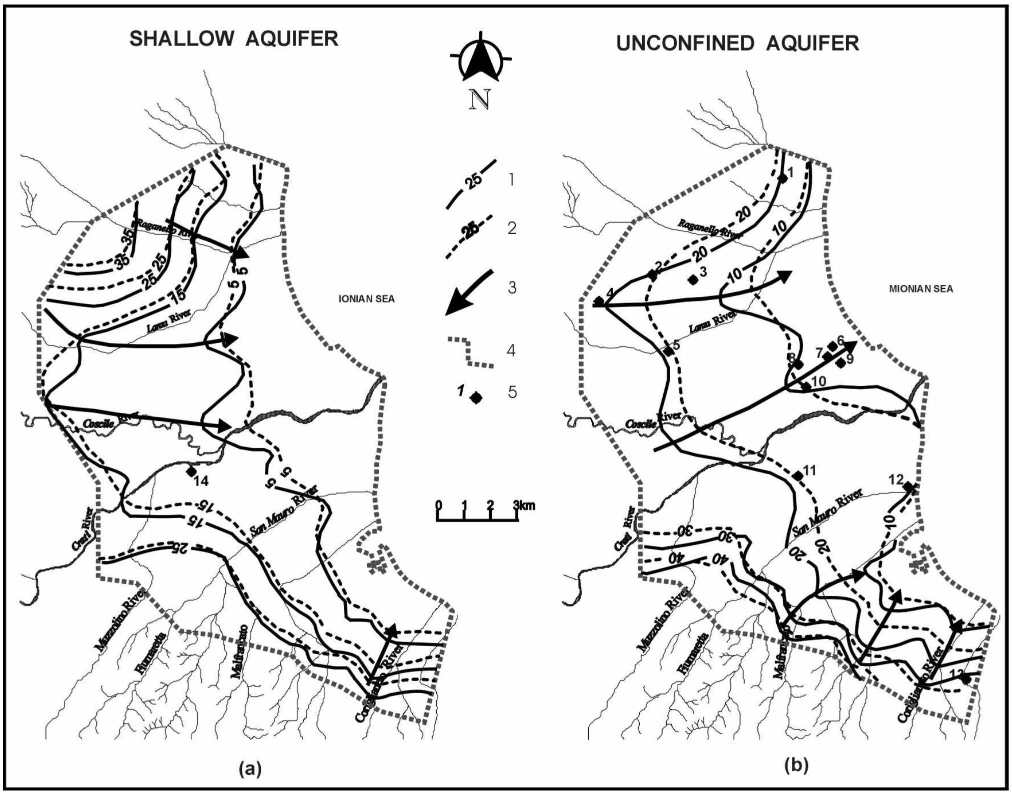

Figure 3 – Piezometric map (m asl) of shallow aquifer (a) and of deep aquifer (b) obtained by in situ measurements and by numerical modelling. 1) Piezometric contour line 1) by measurements and 2) by modelling; 3) main path flow; 4) aquifer boundary and 5) observation well.

The aquifer is predominantly fed by direct rainwater infiltration. Groundwater feeds the rivers running across the plain, the Coscile and Crati Rivers in particular, and vice versa, although the former is more prevalent upstream. The piezometric gradient is roughly 1% in the more inland areas, dropping to 0.25% towards the coast and near the Crati and Coscile riverbeds.

The shallow aquifer alone was used, mostly for irrigation purposes, up until the Seventies. Many wells, a large number of them sunk and generally only a few metres deep, although a few go down as far as 25m, now lie completely abandoned. The shallow aquifer is now used primarily in the floodplain areas of the Crati and the Coscile Rivers. The decline in the use of waters from the phreatic aquifer can be ascribed both to the higher transmissivity of the deep aquifer wells, now easily accessed by drilling, largely artesian and confined in any case and, in part of the territory, to the availability of superficial water resources of the Tarsia artificial lake.

Studies of the climate changes In the whole southern Italy have evidenced a falling rainwater trend over the last 80 years and an even more serious dropping trend in effective rainfall (Polemio & Casarano, 2004). Despite the steady decline of the wells into disuse, the piezometric level of the shallow aquifer appears to be dropping sharply, as observed starting form in the earliest data collected during the Thirties until 2004 (Polemio et al., 2004).

The deep aquifer is made up of cobble and sandy polygenic conglomerates and coarse sands. Some discontinuous strata of greyish blue silty clays, intercalated in places with silty/sandy Pliocene-Pleistocene soils, break up the continuity of the above-mentioned aquifer deposits. The impervious top of the deep aquifer (Figure 2) becomes increasingly continuous and thick moving downstream or eastward, away from the piedmont zone, where the aquifer should be regarded as semi-confined, towards its final destination, the sea, where the aquifer is confined; this affects the modalities of groundwater flow and recharge. Recharge is primarily achieved through outflows from the aquifers along the mountain edge. There are considerable NW/N inflow from the limestone aquifer of the huge massif of Pollino Mount and the fan deposits of the Raganello torrent (Guerricchio et al., 1976; Tazioli, 1986), while from S/SW, the inflow is guaranteed by the shallow granitic aquifer of the Sila massif and by the leakage of river waters through detrital sandy-conglomerate deposits, outcropping beyond the study area (Figure 1 and 3). The maximum piezometric levels of the deep aquifer are equivalent to approximately 40 m asl along the S-SW boundary and approximately 20 m asl along the NW/N boundary. The aquifer is artesian in a coastal strip approximately 3 km wide with piezometric levels between 5 and 10 m asl, which were a good 5-10 m higher in the past (Guerricchio et. al., 1976). The piezometric gradient varies from 1.00-1.25% along the piedmont belt to approximately 0.5% near the coast and the Crati and Coscile Rivers. As in the shallow aquifer, the main groundwater path runs from West to East, with the sea as final destination. The main groundwater path lines are similar to those of the shallow aquifer near the Crati River and in the southern portion of the plain.

Interchanges between the two aquifers in the piedmont belt should be a possibility: from the shallow aquifer to the deep one in the northern portion of the belt and the reverse in the southern portion. Later, due to a lack of definite qualitative factors, these interchanges were considered null.

From a qualitative point of view, the groundwater of the deep aquifer, on which this paper mainly focuses given the greater potentialities of this particular resource, is generally of a high enough level to qualify for use as drinking water, although they are strongly mineralised in some areas, with a high content of sulphurs, iron manganese, carbon dioxide and methane (Guerricchio et al., 1976). The wells in the floodplains of the Crati and the Coscile Rivers are generally unusable as the discharged groundwater is brackish. Various theories have been put forward as explanations for the elevated salinity, including the long age of groundwater (Tazioli, 1986), the effects of seawater intrusion and the added effects of the coastline withdrawal and the groundwater overexploitation or interactions with rocks containing rock salt (Guerricchio et al., 1976 and 1997). Our research results seem to exclude the first hypothesis and render the second unlikely; however further, on-going, assessments of a geochemical nature will enable this aspect to be clarified exhaustively.

3. MODEL DEFINITION AND CALIBRATION

The two aquifers were discretised into 3101 active cells, measuring 250 m per side, by means of the MODFLOW code (Mc Donald & Harbaugh, 1988), as shown in Figure 4.

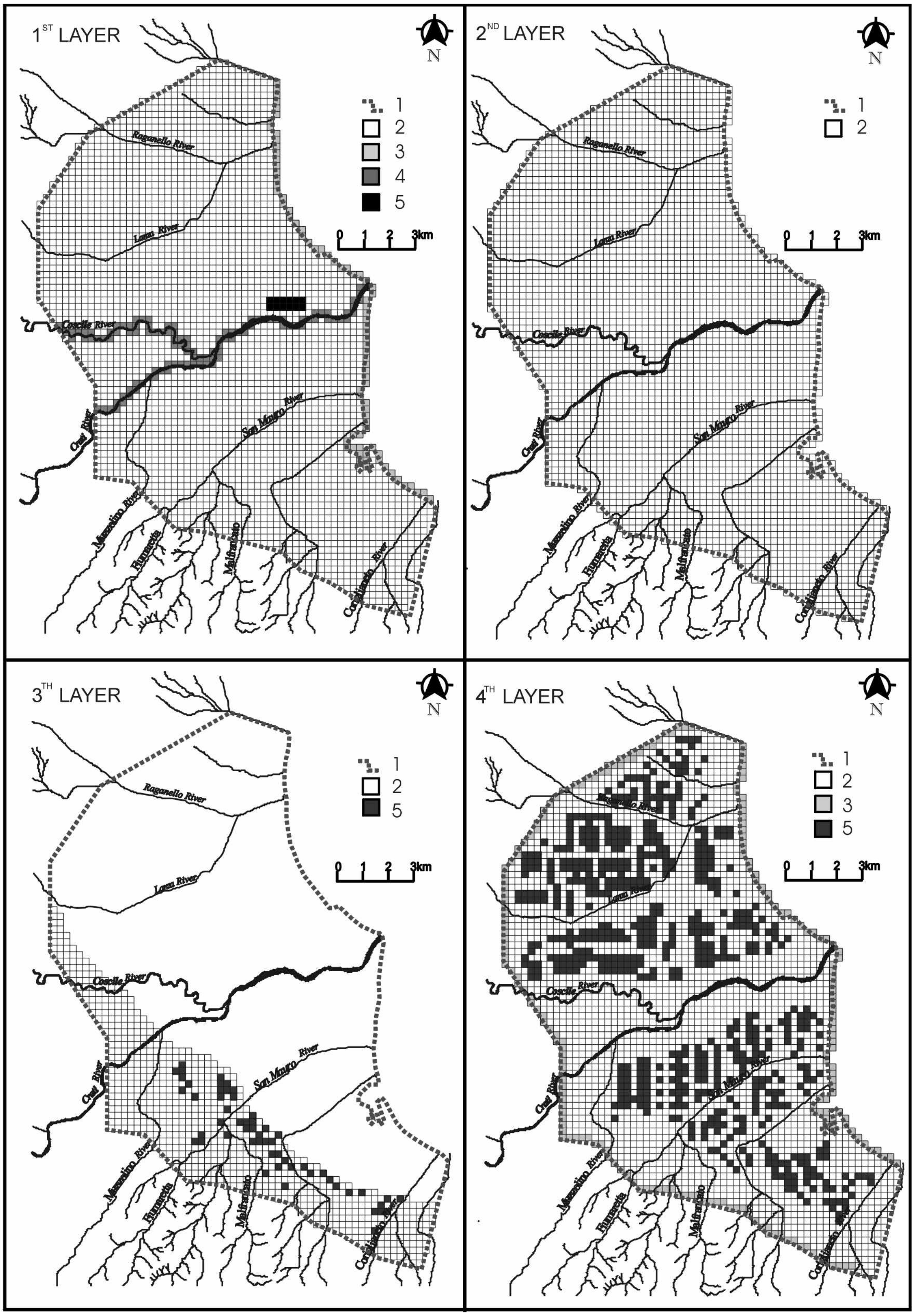

Figure 4 – Model grids and boundary conditions. 1) Aquifer boundary, 2) Active cell, 3) Constant head cell, 4) River cell and 5) Discharge well cell.

The hydraulic conductivity values were taken from in situ tests or, where this was not possible, from studies previously carried out on hydrogeologically similar soils. The hydraulic conductivity initially assigned to the model cells varied between 2 10^{-5} and 1 10^{-3} m/s for the shallow aquifer or top layer, and between 2 10^{-4} and 1 10^{-2} m/s for the third and fourth layers, which simulate the deep aquifer. The second layer had to simulate the absence of water interchanges between the first and third and fourth layers. The infiltration or vertical recharge is determined on the basis of climatic data provided by four Hydrographic Service Stations, over an observation period from 1921 to 2006; the result was an average recharge equal to 3.26 10^{-9} m/s for one cell and equal to infiltration over the entire area of 19.3 10^{6} m^3/year (Table 1).

The riverbed altitude and the river water height of the main rivers were obtained through on-site surveys repeated during different seasons.

The discharges from the shallow aquifer are both concentrated, in order to keep the archaeological excavations of the ancient city of Sybaris (Figure 1) dry, and widespread, particularly in the areas overlooking the Crati and Coscile Rivers (Table 1). The concentrated discharge is about equal to 2.5 10^{6} m^3/year. The widespread discharge is estimated at approximately 0.5 10^{6} m^3/year. It is largely carried out between July and August, and took in several wells; this sampling should be disregarded and was not taken into account during the later simulations under stationary conditions.

The discharges from the deep aquifer are for both irrigation and drinking purposes (Table 2). The drinking water discharge equated to approximately 5.8 10^{6} m^3/year, distributed cell by cell, based on the number of wells and the mean annual groundwater discharge of each well. The well discharge for irrigation purposes, estimated on the basis of agricultural demand, was reckoned to be 12.5 10^{6} m^3/year.

The model was calibrated using the PEST method (Doherty et al., 1994), later perfected by means of the *trial and error* method, which involved varying some of the input parameters used for constructing the model during the simulations. The calibration was developed mainly by working on the values of hydraulic conductivity, a parameter characterised by a rather lower degree of reliability. The calibration concluded with an absolute mean deviation between the calculated piezometric heght and the actual one of 0.59 m for the shallow aquifer and of 0.9 m for the deep aquifer (Figure 3). As regards the latter aquifer in particular, the high level of calibration was confirmed by the piezometric measurements taken in 40 verification wells (R^2=0.9713, gradient 0.96) and the transmissivity measurements obtained from pumping tests (r^2=0.8647, gradient 0.92) (Figure 5).

The calibration output in steady conditions and the piezometric measurements taken in 27 wells every 3 days during the period 1936-1940 allowed for the calibration of a transitory regime model of the shallow aquifer too. These 4 years were broken down into 12 *periods* of time, each split into 80 steps. During each of these steps, the recharge was articulated according to the climatic values observed in each of the 4 available climatic gauges.

The effective porosity adopted was equivalent to a mean value of 0.12, based on the stratigraphical characteristics observed at dozens of different points.

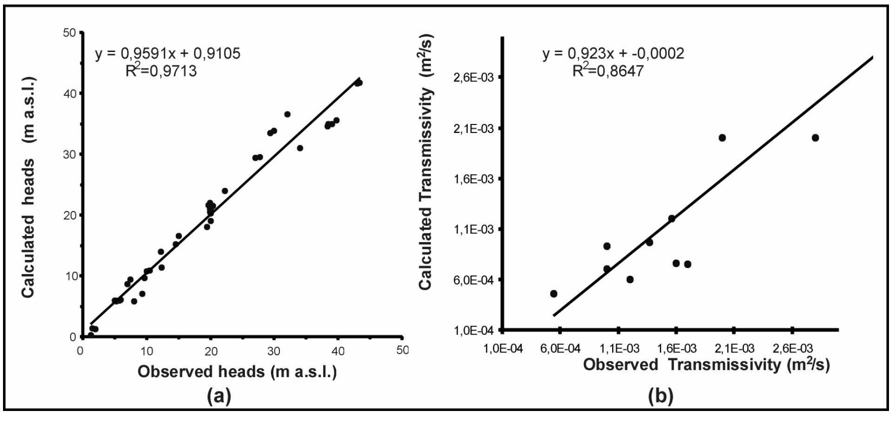

Figure 5 – Measured and simulated piezometric height (a) and transmissivity (b).

Table 1 – Main in/out of the shallow aquifer determined by steady conditions of modelling.

In or recharge	10^6 m^3/year	Output or discharge	10^6 m^3/year
rainfall infiltration	19.3	archaeological area	2.5
lekage from rivers	2.0	discharge for irrigation	0.5
		outflow into rivers	9.5
		outflow into the sea	9.8
Total	**21.3**	**Total**	**21.3**

Table 2 – Main in/out of the deep aquifer determined by steady conditions of modelling.

In or recharge	10^6 m^3/year	Output or discharge	10^6 m^3/year
lateral inflow from other aquifers	31.3	discharge for drinking	5.8
		discharge for irrigation	12.5
		out flow into the sea	13.0
Total	**31.3**	**Total**	**31.3**

The river water level was taken as variable, depending on rainfall. During the widespread period alone, the discharge was assessed in relation to agricultural irrigation demand at that particular time. The calibration ended with the application of an absolute mean error of the simulated piezometric levels with respect to those measured in 27 wells equal to 0.47 m. The variations produced by calibration mainly related to storativity, down to an effective porosity of 0.09 and, to discharge, up by approximately 6.8%.

The model thus showed that the groundwater of the phreatic aquifer is subject to stress during the summer irrigation season. In particular, between the months of June and September, the model calculates an inflow of seawater, the volume of which roughly equated to 0.7 10^6 m^3/year, by means of constant load cells; during the entire hydrological year, in any case, the outflow from the shallow aquifer towards the sea clearly prevails. The equilibrium condition between fresh groundwater and seawater was critical even during the Thirties, when more crops every year were not possible or conceivable as it happens over the last 30 years.

These results tally perfectly with the sharp downward piezometric trend over the last 80 years, as reported by Polemio et al. (2004), also thanks to direct surveys. Lastly, that the shallow aquifer is exposed to risks of salt contamination due seawater intrusion and that this phenomenon has already caused the quality of groundwater to decline in some areas was verified by means of detailed stratigraphical reconstructions, including the aquifer bottom altitude, along with chemical/physical tests.

4. CONCLUSIONS

This study has demonstrated the reliability of the conceptual model proposed for a coastal plain that is extremely complex in hydrogeological terms, but which has remained relatively unknown until now.
The main groundwater resources are hugely overexploited, especially in the past, in the case of the shallow aquifer as well as being affected by decreased recharge due to the current climatic trend, and subject to a not negligible risk of qualitative contamination by seawater intrusion in the coastal area.
The groundwater of the deep aquifer, on the other hand, show great potential and could cope with further extractions, as long as these were planned according to rational and sustainable management criteria, as illustrated by the model proposed.

Further on-site survey campaigns, laboratory tests and simulations are still on-going, aimed at clarifying some fairly important but as-yet not entirely characterised factors relating to leakage between aquifers, the amount of recharge due to upward aquifers, the explanations for particular chemical characteristics of groundwater of deep aquifer in certain specific areas and, finally, as regards the quality of groundwater of the shallow aquifer, in relation to the effects of anthropogenic pollution and marine intrusion.

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