Saltwater intrusion in the Arborea area (central-western Sardinia)

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Abstract The reclaimed land of Arborea, covering some 70 km2, is the most productive area in Sardinia (Italy) in terms of agriculture and animal husbandry. The main outcropping formations in the plain are Quaternary sands and gravels. Two main aquifer systems have been identified, a shallow phreatic aquifer and a deep multi layer aquifer with varying degrees of confinement.

Both aquifers are now showing signs of intense over exploitation. Significant lowering of piezometric levels has been observed as well as salt water intrusion and groundwater contamination, caused by the large number of farms in the area.

A preliminary numerical model has been developed for this zone, using the CODESA 3D finite element code, that enabled us to formulate various hypotheses concerning the causes and mechanisms of groundwater salination.

Continued monitoring, for collecting new water level measurements and chemical data, combined with vulnerability studies has improved groundwater characterization in the Arborea area, thus establishing a basis for updating and completing the numerical model.

I. Introduction

The Campidano plain, the largest plain in Sardinia, extends about 110 km between the gulf of Cagliari, in the south-est, and the gulf of Oristano, in the north-west, with variable width (25-40 km). The Campidano is the most depressed area of the great graben of Sardinia, which extends, from north to south, from Asinara Gulf to Cagliari Gulf. Since the Cenozoic, a great part of the graben has been filled, especially in the northern part, by thick volcanic rock formations, alternated with various types of sedimentary rocks (Carmignani et al., 2001). The western part of the Campidano ends with the gulf of Oristano, with many coastal ponds of great naturalistic and economic interest, bordered by reclaimed areas which were once marshlands. The hydrogeology of the coastal area is characterized by interface equilibriums between the sea, the river Tirso, groundwaters, and the Cabras, Mistras, Santa Giusta, s'Ena Arrubia and San Giovanni coastal ponds

(Figure 1). The aquifers are mainly located in the coarser formations (sand, gravel and pebble) of the present and recent incoherent alluviums, alternated with clayey and silty-clayey aquitards, with a very low hydraulic conductivity, which approaches zero.

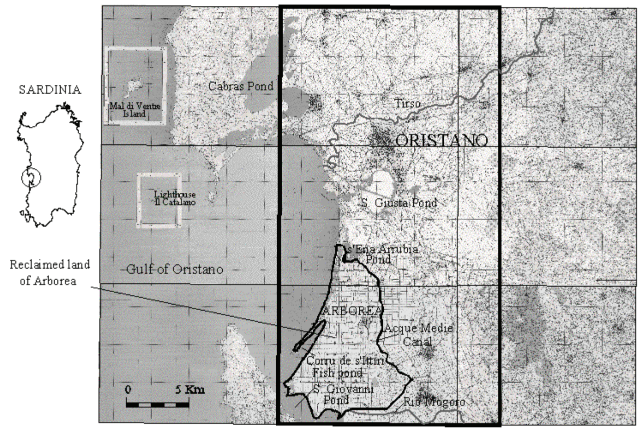

Figure 1. Location of the study area

They form a shallow phreatic aquifer and an underlaying multilayer artesian aquifer, separated by a clayey impermeable layer some meters thick.

The water demand for the economic activities of the Oristano Plain (first of all agriculture and animal raising, but also sheep farming, industry, and tourism) has always been satisfied first of all by superficial waters stored in artificial basins (mainly the river Tirso reservoir, located outside the study area) and widely distributed by a channel network and, second, by groundwater. In the most recent years, that, with few exceptions, have been very dry, the superficial water supply for irrigation purposes has been reduced in order to use the remaining resources for a drinkable water supply. To face the emergency, groundwater has been more and more exploited. Intensive pumping, together with other factors, has triggered various salination processes that have been studied (Barrocu et al., 1995; Staffa, 2003; Soddu, 2004; Barrocu et al., 2004) in order to define the overall quality of grounwater, identify the most contaminated areas and point out the causes and sources of contamination, also through a temporal analisys of the phenomena. In order to reach those

targets, geological, statigraphic, pedologic, hydrochemical, thermometric, pluviometric data were collected, organized into a GIS, and processed together with previous monitoring well data from 1990 to 2004, in an area that, had been extended from 142 km^2 to 470 km^2.

The total number of wells is estimated to be around 2000-2500, with pumping rates of 65-81 millions of cubic meters that, according to the water balance, are of the same order of

Manuscript received September, 2006
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magnitude of effective infiltration. Therefore, pumping produce in the costal aquifer an overexploitation phenomenon, expecially in the deep aquifer, which is exploited by a greater number of wells than the shallow aquifer.

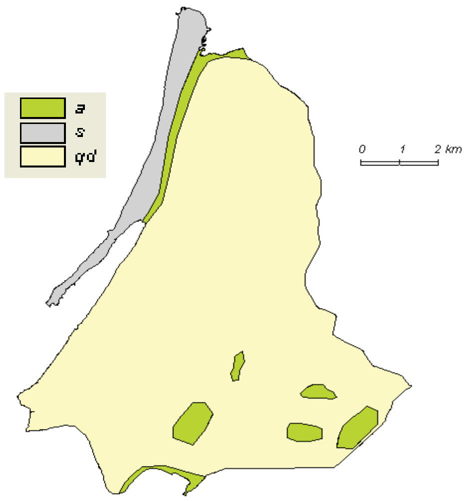


Figure 2. Geological map

II. RESULTS OF THE STUDIES

The analiysis of piezometric levels has indicated, for both the shallow and the deep aquifer, that groundwater flow is mainly directed coastwards. Anyway, in the deep aquifer there are some important inversions of flow, and this is mainly due to pumping wells.

Electrical conductivity values are much higher than 400 µS /cm, established by Italian standards for "class 1" groundwaters, and than 1000 µS /cm, recommended for waters to make drinkable, and in large areas are higher than 2500 µS/cm.

The problem is very serious, since the limit value for the most part of cultivations in the plain, is 2000 µS /cm.

Electrical conductivity values in the shallow aquifer are on average lower than those recorded in the deep aquifer, but the extension of areas in which electrical conductivity values are greater than 2000 µS /cm is larger in the shallow aquifer. The shallow aquifer is contaminated both near the coast because of seawater intrusion, and inland, because of the use of artificial fertilizers and other substances resulting from the presence of farms.

As to the deep aquifer, electrical conductivity is clearly related to seawater intrusion phenomena, with high values along the coast and in the lowest piezometric level zones (upconing).

Moreover, electrical conductivity values are influenced by the presence of coastal ponds and of some internal marshlands.

The temporal analysis of the phenomena has shown, in the shallow aquifer, that piezometric levels are unchanged or have risen locally. Electrical conductivity values are on the whole rates
unchanged and sometimes they have gotten worse.

Piezometric levels in the deep aquifer have slightly lowered, while electrical conductivity values have increased, especially along the coast.

In the light of the observed phenomena, it can be stated the the unchanged or increased piezometric levels in the shallow aquifer are due to the progressive abandonment of shallow wells, in favour of the more productive deep wells, that are used for irrigation purposes together with superficial waters. This intensive overexploitation has produced increasing contamination in the deep aquifer, without causing an improvement of salinity conditions in the shallow aquifer. The reasons are to be sought in a combination of the following factors, some of which were already mentioned:

1. overexploitation in the shallow aquifer can have led to an irreversible contamination;
2. salinity in the shallow aquifer is partially due to artificial fertilizers contamination;
3. shoddily constructed wells cause a mixing of groundwaters from the shallow and deep aquifers, thus increasing the electrical conductivity of the shallow aquifer;
4. the use for irrigation purposes of saline groundwaters of the deep aquifer, mainly during particular periods of the year, reduces the benefits of rainfalls and irrigation waters coming from the river Tirso reservoir.

III. THE RECLAIMED LAND OF ARBOREA

Since 2003, research has been focused in the southern part of the plain, in the reclaimed land of Arborea, not included in the previous studies. Up until 70 years ago, this area was a marshland in which no human activity could take place. When reclamation started, the situation completely changed and the area became the most productive of Sardinia in terms of agricolture and animal husbandry, but, in the meantime, very manifest over-exploitation processes were originated.

The studies made for the whole plain have been integrated in this area, with in-depth geochemical surveys and with the implementation of a preliminary numerical model. Recently, new stratigraphic data have been collected (Progemisa, 2002) which permitted a better definition of the spacial geometry of the aquifers and led to a reinterpretation of the previous results, and also to a more precise association between every well and the aquifer it pumps from. The study area, extending over roughly 70 km2 at 7 m of altitude above sea level (Figure 1), is bounded to the N by the "s'Ena Arrubia" pond, to the W by the sea, to the SW by the "San Giovanni" pond and to the E and SE by the "Acque Medie" canal and by the "Rio Mogoro" river. 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.

From a geological point of view, the outcropping formations are mainly variously cemented dune sands, largely

Wurmian (qd). Present and recent sands of the beaches can be found along the coast (s), while silty-clayey marshy or brackish deposits (a) are located near the coastal ponds and in some other marshy internal areas (Figure 2).

According to recent studies (Barrocu et al., 2005), the intrinsic vulnerability of the area, evaluated with the Sintacs R5 method, is classified as elevated.

IV. HYDROGEOLOGICAL FEATURES

As for the whole Oristano Plain, in the reclaimed land of Arborea a shallow phreatic aquifer and an underlaying multilayer confined aquifer can be found. The first studies made in 2003 and based upon 12 available boreholes, of which only 6 could be considered reliable, led to the hypothesis that the bottom of the shallow aquifer was on average 10 m deep from the ground level. This seemed to be confirmed by the fact that the main part of dug wells is no more than 10 m deep. On the basis of the limited stratigraphic knowledge, it was not possibile to formulate any hypothesis corcerning the morphology of the layers forming the deep aquifer.

The newly collected stratigraphic data made it possibile to go beyond the limits of he previous studies, especially concerning the shallow aquifer. At present 34 boreholes reaching the bottom of the first aquifer are available (Figure 3), 9 of which intercept the second aquifer top and 7 (yellow symbols in Figure 3) intercept its bottom.

These new data further clarified, with a certain reliability, the geometry of the first aquifer bottom and permitted us to

formulate a hypothesis about the top and the bottom of the second aquifer

The top of the first aquifer can be considered coincident with the ground level, the geometry of which is shown in Figure 4 (m a.s.l.), and has the maximum altitude in the NE and SE part of the plain and the minumum altitude along the coast. In detail, a depressed area, which extends landwards for about 3 km, can be observed in the central-western part of the study area

The first aquifer is separated from the second one by an aquiclude made of compact and dense clay, which is in practice impervious, whose thickness varies from 0,3 to 9 m. Sometimes that confining function is accomplished by a compact calcrete originated by previous circulation of carbonatic waters.

The second aquifer is located in eterometric sands with shell remains, whose thickness, though deduced by few punctual values, varies from 3 to 17 meters. Hydraulic conductivity, resulting from pumping tests on 2 wells, is 7.96x10-7 and 3.19x10-5 m/s (Progemisa, 2002).

Figure 7 shows a schematic cross section (whose planimetric track is shown in Figure 6) obtained through the interpolation of the stratigraphic data. Far from being accurate in an absolute sense, it is a reasonably probable model of the geometry of the aquifers, in which can be seen the thickness of the first aquifer, the thickness of the aquiclude and the location of the second aquifer bottom. Beyond the second aquifer bottom the stratigraphies do not allow the formulation of a reliable hypothesis on the geometry of the other aquifers.

V. EFFECTIVE INFILTRATION

As previously stated, rainfalls and irrigation waters play an essential role in the recharge of aquifers in the plain of Arborea. The calculation of effective infiltration has been based on the following procedure:

1. Rainfalls recorded in the pluviometric station of Arborea have been taken into account. The average values in Table 1 are calculated over a period of 30 years.

TABLE 1. AVERAGE YEARLY RAINFALL (MM)

J	F	M	A	M	J	J	A	S	O	N	D	year
67,7	62,8	53,6	65,1	35,0	18,8	4,6	9,5	40,6	86,7	106,6	79,9	630,8

Note the presence of two rainy periods at the beginning of winter and at the beginning of spring, with a very manifest maximum in November and a less manifest one in April. The pluviometric regime, typically coastal, is very irregular and it is characterized by heavy rainfalls alternated with completely dry periods.

2. Temperatures recorded in the thermometric station of Santa Giusta, the only station which has a significant thermometric series, have been taken into account. The average values in Table 2 are calculated over a period of 30 years.

TABLE 2. AVERAGE DAILY TEMPERATURES (C)

J	F	M	A	M	J	J	A	S	O	N	D	year
10,1	10,5	12,3	14,2	18,3	22,1	24,8	25,3	22,5	19,1	14,2	11,1	17,1

The thermal regime is tipically mediterranean, with mild winters and hot and dry summers. The colder months are December, January and February, while in March temperatures start to increase. Usually the warm season begins in May and lasts until late October, so that the average values in September and in October are higher than the ones recorded in June and May respectively.

The average yearly temperature is 17.1°C, while the minimum, recorded in January, is 10.1 °C and the maximum, recorded in August, is 25.3 °C. Winds have a great influence on temperatures, especially southern hot winds coming from northern Africa, but, above all, the mistral, which violently blows from the NW in every season, damages the vegetation and causes an intense evapotranspiration, reducing the benefits brought by rainfalls.

3. Irrigation waters (superficial waters supplied by the "Consorzio di Bonifica" and coming from the river Tirso reservoir) are shown, as average values calculated over 10 years, in Table 3.

Figure 5. First aquifer bottom elevation (m)

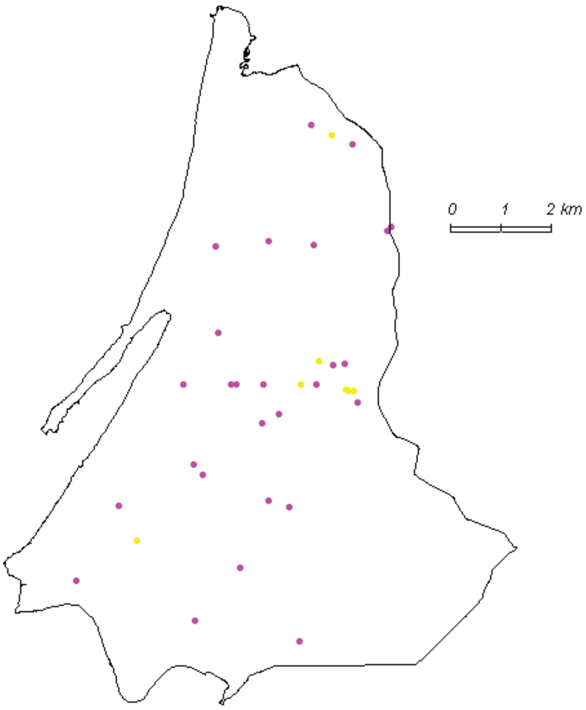


Figure 3. Borehole location

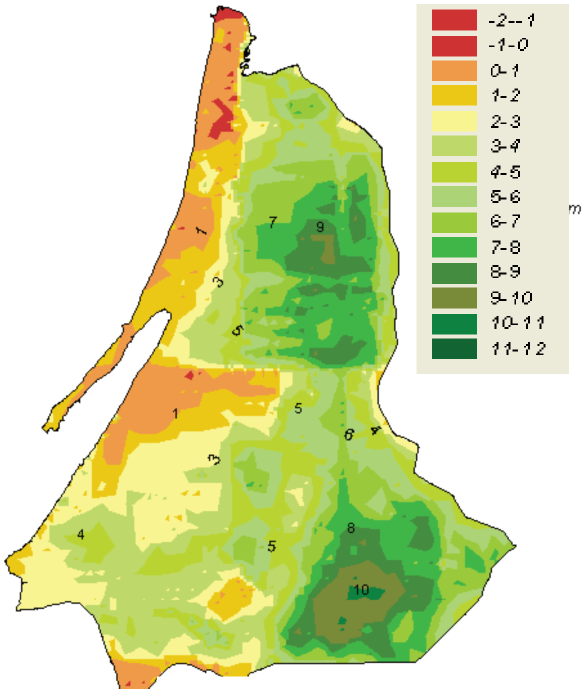
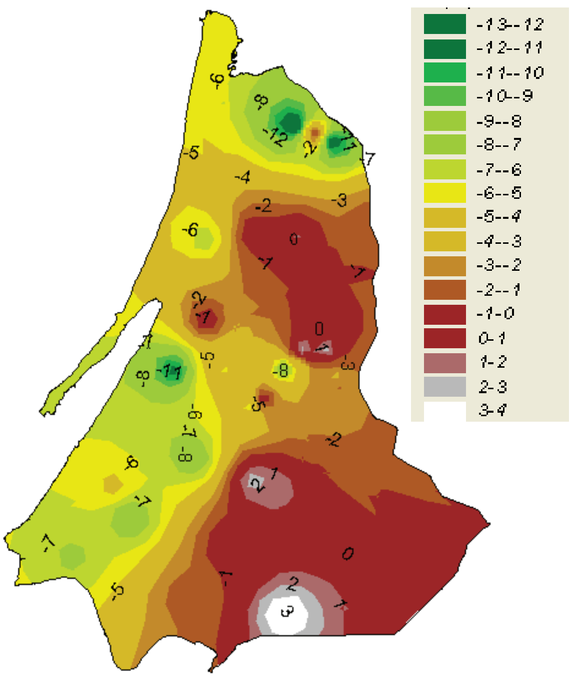


Figure 4. Terrain elevation (m)



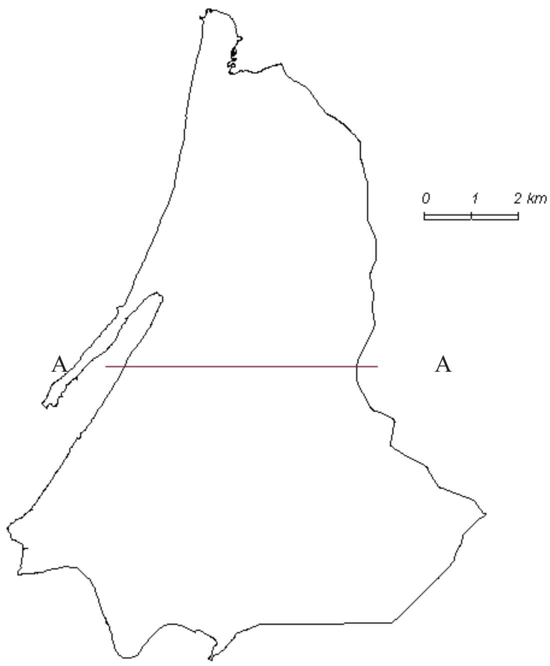


Figure 6. Cross section A-A

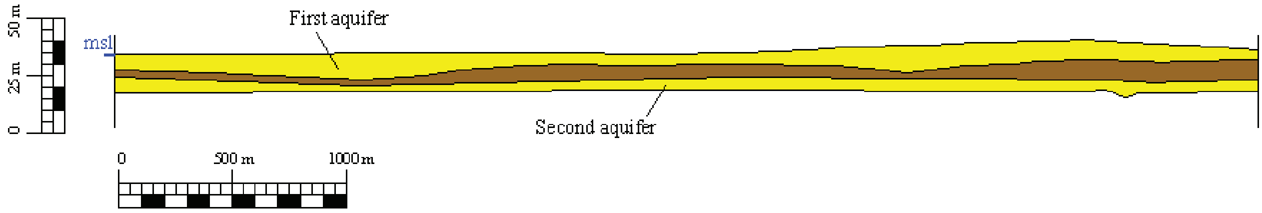


Figure 7. First and second aquifer (cross section A-A)

TABLE 3. INFLOW FROM THE RIVER TIRSO RESERVOIR (MM)

J	F	M	A	M	J	J	A	S	O	N	D	year
0,0	1,3	7,5	12,6	16,5	26,8	38,9	30,4	8,7	3,5	1,1	0,0	147,3

TABLE 4. TOTAL SUPPLIES (MM)

J	F	M	A	M	J	J	A	S	O	N	D	year
67,7	64,1	61,1	77,7	51,5	45,6	43,5	39,9	49,3	90,2	107,8	79,9	778,1

4. The calculation of real evapotranspiration has been made on the basis of values in Table 4, which represent the sum of precipitations and irrigation waters.

The Turc formula has been used, with a modification made by Santoro (1970):

$$E_r = \frac{P_a}{\sqrt{0.9 + \frac{P_a^2}{L^2}}} \quad (1)$$

With L = 586 - 10 T_c + 0.05 T_c^3 and where Pa is the yearly average in Table 4 and Tc is the average diurnal yearly temperature in Celsius degrees with a correction to keep into account rainfalls:

$$T_c = \frac{\sum_{i=1}^{12} P_i T_i}{P_a} \quad (2)$$

where T_i are the average diurnal monthly temperatures and Pi are the montly values in Table 4.

The Turc formula gives the real average yearly evapotranspiration in mm; Santoro modification permits us to fit the Turc formula to the Mediterranean areas.

The knowledge of evapotranspiration has made it possible to calculate the net supplies to be used as a basis to obtain effective infiltration. The results are shown in Table 5.

TABLE 5. REAL EVOPOTRANSPIRATION AND NET SUPPLIES (MM)

Supplies/ year	T_c	L	Evapotrnspiration	Net Supplies
778,1	16,06591	632,6822	501,0	277,2

5. Effective infiltration has been evaluated on the basis of the net supplies and of the hydrogeologic characteristics of the surface, which have been incorporated in infiltration indexes. Those indexes (Table 6), after evaluating in situ soils, have been chosen on the basis of the superficial lithology, keeping into account that the terrain is basically plain and there are no fissured rocks (Civita and De Maio, 2000).

TABLE 6. POTENTIAL INFILTRATION COEFFICIENTS

Formation	a	qd	s
Coefficient	0,25	0,75	0,80

In the whole, an effective infiltation of 200,6 mm/year has been calculated (14.050.363 m3/year)

The average yearly groundwater consuption of the wells located in the plain has been calculated on the basis of data provided by the "Genio Civile" of Oristano and its value is 34.35 m3/well. The total pumped groundwater, considering a number of wells (including the illegal ones) of 400-450, can vary from 14 to 15 million of cubic meters per year, a value that is larger or equal to effective infiltration. Also if lateral recharge, the estimation of which is very difficult and inaccurate, is taken into account, it must be considered that only a part of effective infiltration waters reaches the multilayer aquifer, from which groundwater is mainly pumped. Moreover, in a coastal aquifer, a significant part of recharge is dispersed in the saltwater-freshwater transition zone (Tulipano, 2003). For all the mentioned reasons, it can be stated that aquifers in the Arborea plain are in extremely critical condition.

VI. MONITORING RESULTS

The monitoring network, set up in 2003, is composed of

114 wells of variable depth (from 2.43 to 110 m). A first overview has shown that electrical conductivity values higher than 2000 µS/cm and piezometric levels lower than zero are mainly located in the central-southern part of the plain.

As already mentioned, the new aquired stratigraphic data have permitted us to identify with a certain reliability the aquifer from which each well pumps, leading to a new classification of wells and to a revision of previous monitoring results.

A. . Shallow aquifer

Shallow wells are very few in number, just 17, mostly abandoned. Actually, almost all farms have deeper wells that pump groundwater from the most productive multilayer aquifer. The depth of shallow wells ranges from 2.43 to 10.83 m.

Piezometric contours of the shallow aquifer, according to the limited pumpings, are rather regular and follow the geometry of the first aquifer bottom; they have a feeble and homogeneous gradient and show a flow directed coastowards and towards the coastal ponds (Figure 8). The range of variability is 0.85 – 4.83 m. Figure 9 shows a cross section, whose track is represented in Figure 6, in which the piezometric surface is displayed.

The electrical conductivity, as shown in Figure 10 contours, is higher everywhere than 1000 µS /cm, with a maximum of 3580 µS /cm. The maximum values have been found in the southern area.

No direct relationship between high electrical conductivity values and seawater intrusion seems to exist. First of all, there is no concentration of very high electrical conductivity values along the coast, which is also the lowest piezometric surface area. Secondly, chemical analysis performed in 2004 on some selected wells (Soddu, 2004) does not seem to indicate the presence of marine waters in the wells having the highest electrical conductivity values: for instance, as displayed in the diagram of Figure 11, there is no direct relationship between electrical conductivity and chloride contents. Moreover, a preliminary modelling study (Soddu, 2004; Barrocu et. al, 2004) has shown that in the shallow aquifer, seawater contamination can have an influence only in a coastal belt from 250 m (central area) to 1600 m (ponds area) width. This leads us to believe that contamination in the farthest from the coast areas is because of interactions, though limited (Progemisa, 2002), with the deep aquifer (high salinity waters pumped from the deep aquifer used for irrigation purposes and/or shoddily constructed wells) and/or to the use of artificial fertilizers.

B. Second aquifer

Given the limited number of boreholes intercepting the second aquifer bottom, the identification of the wells that pump water from the second aquifer is by now uncertain. On the basis of available data, the wells pumping from the second aquifer are likely to number 43, with a depth ranging from 7 to 23 m.

The geometry of contour lines (Figure 12), due to high exploitation levels, is complex if compared to the one recorded for the shallow aquifer.

In the northern part of the plain, from an inland recharge area with a piezometric level of 6-8 m, the flow is directed radially towards the reclaimed land limits, while in the central-southern part inversions of flow are manifest and piezometric values fall under zero. The range of variability is -1.80 – 8.70 m. Figure 13 shows a cross section whose planimetric track is dispayed in Figure 6, with indication of the piezometric line and of the depressed piezometric (< 0 m) area.

The electrical conductivity values of the second aquifer range from 553 to 9870 µS /cm, a bigger interval than in the first aquifer. The maximum values are, in this case, placed near the coast, near s'Ena Arrubia pond and in the central-southern area, in the same location where the mentioned inversion of flow has been recorded (Figure 14).

This can suggest that the second aquifer is directly affected by seawater intrusion, due to the recall of marine waters in the coastal zones where the piezometric surface is lower than zero and to upcoming phenomena. The hypothesis seems to be confirmed by chemical analysis wich show, in detail, a better match between electrical conductivity values and chloride contents of groundwater (Figure 15). It is important to remember that, because of shoddily constructed wells, there is a certain degree of communication between the first and the second aquifer, so that this can be contaminated by artificial fertilizers too.

C. . Underlaying aquifers

The available boreholes do not permit the formulation of any hypothesis on the geometry of aquifers underlayng the second one. Anyway, the few boreholes that go across the second aquifer bottom show an alternation of high permeability formations bearing groundwater with confining impervious o semipermeable layers. Therefore, the results of monitoring for wells that are deeper than the second aquifer bottom (46 with a depth range of 20-110 m) can not be correlated.

Punctual values maps of piezometric values, ranging from -3,97 and 6,44 m, and of electrical conductivity values, ranging from 785 to 4600 µS (Figures 16 e 17), have been set up.

The maps show that lower piezometric values are located in the central-southern part of the plain and match with higher electrical conductivity values. It is reasonable to expect that, as the depth increases, the infuence of artificial fertilizers decreases, and the causes of salination are likely to be identified with seawater intrusion, upconing and contact with non leached saline formations.

This seems to be confirmed by the relationship between electrical conductivity and chlorides (Figure 18), which for the aquifers below the second is closer than the one found for the second aquifer.

VII. CONCLUSIONS

Hydrologic calculations in the reclaimed land of Arborea show that the consumpion of groundwater, pumped through the numerous wells mainly for agricultural purposes, is too high with respect to the aquifers recharge. This has led in time to a series of over-exploitation phenomena that, in detail, have changed the equilibrium regime between salt and fresh water.

In the light of piezometric, electrical conductivity and chemical (chloride in particular) data, it can be stated that the first aquifer is contaminated by seawater intrusion near the coast, while in inland areas high salinity is more likely due to the use of artificial fertilizers and to interactions with the underlaying aquifer. The second aquifer, subject to a more intense pumping regime, shows manifest signs of saline contamination due to seawater intrusion and upconing, but, as a certain degree of communication between the first and the second aquifer seems to exist, the second aquifer can also be contaminated by artificial fertilizers coming from the first aquifer.

On the contrary, it is not likely that artificial fertilizer can reach the aquifers below the second one. In these aquifers the relationship between electrical conductivity and chlorides is very tight.

The highest electrical conductivity values have been recorded in the multilayer aquifer (particularly in the second aquifer) that is by now the most exploited, but the shallow aquifer is the one that shows a greater extension of high electrical conductivity areas.

AKNOWLEDGEMENTS

The authors, Giovanni Barrocu, coordinator of the research programme, and Samuela Soddu, who was responsible for the operating steps, wish to thank the "ESAF" for providing data about the project "Riconversione dell'impianto di depurazione di Arborea", performed by the "Progemisa S.p.A."

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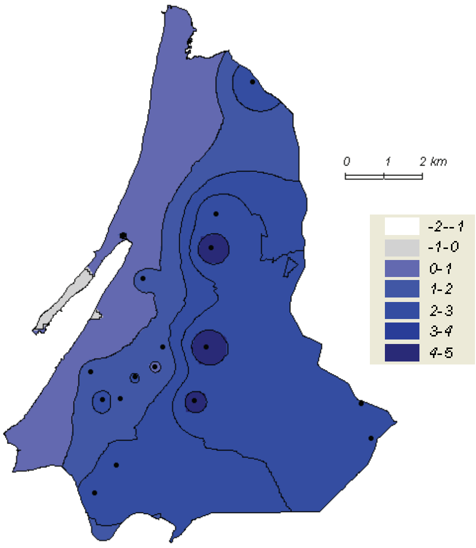


Figure 8. Piezometric contours (first aquifer, m)

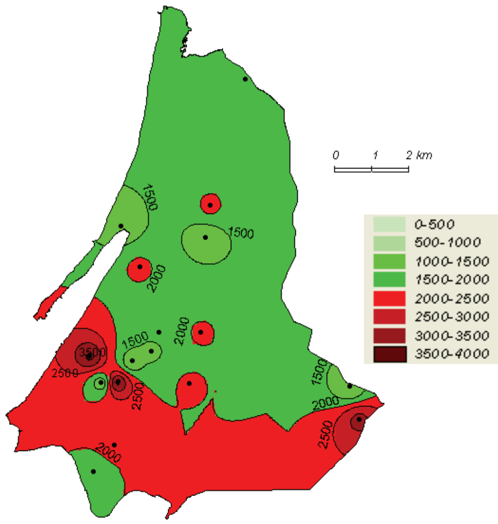


Figure 10. Electrical conductivity at 20 C (first aquifer, µS/cm)

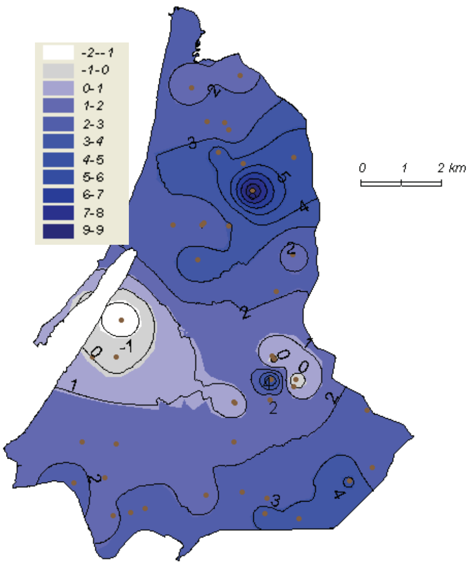


Figure 12. Piezometric contours (second aquifer, m)

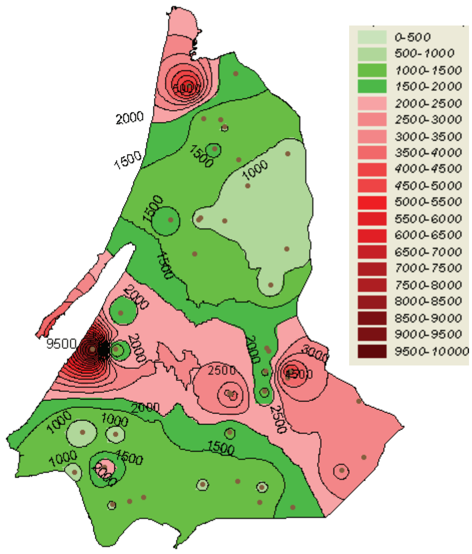
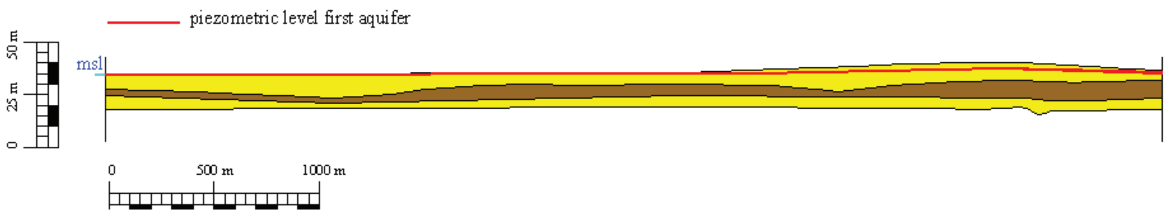


Figure 14. Electrical conductivity at 20 C (second aquifer, µS/cm)



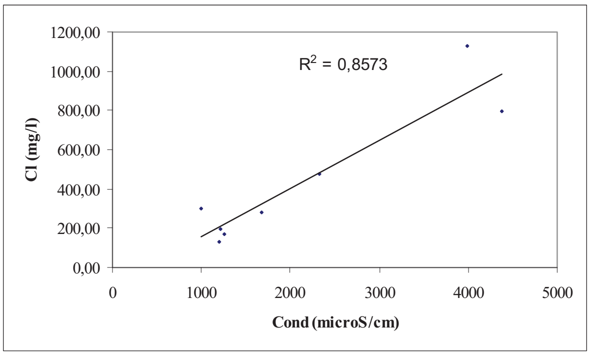


Figure 11. Chloride versus electical conductivity (first aquifer)

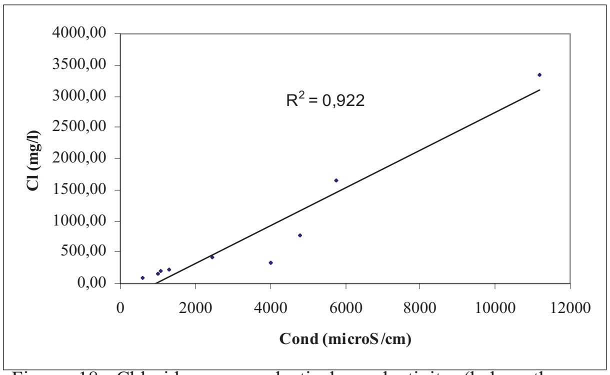


Figure 18. Chloride versus electical conductivity (below the second aquifer)

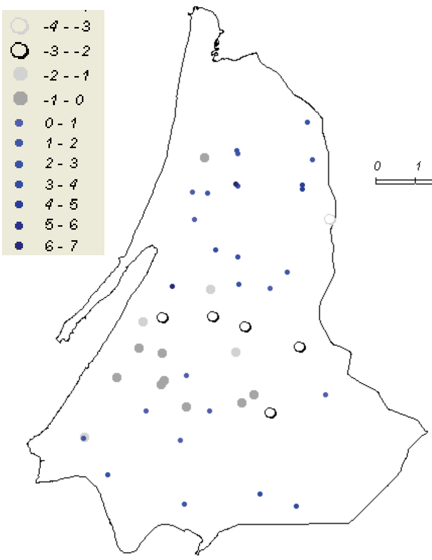


Figure 16. Piezometric levels (below the second aquifer, m)

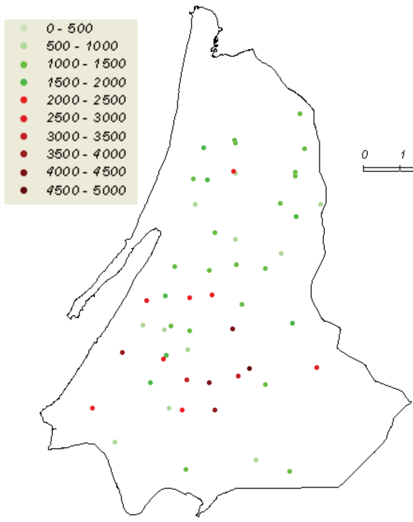


Figure 17. Electrical conductivity values at 20 C (below the second aquifer, μS/cm)

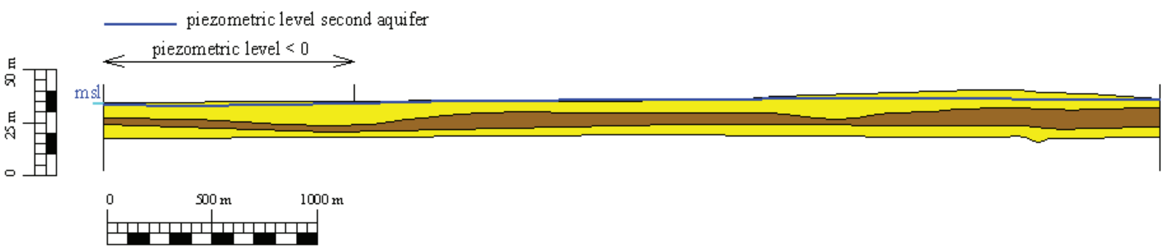


Figure 13. Piezometric level (second aquifer cross section A-A)