Groundwater salinization in Southern Tuscany (Italy)

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Nearly all the coastal plains in Tuscany are plagued, to varying extents, by groundwater salinization. In southern Tuscany this creates serious problems for:

- municipal water supplies: during the summer, large numbers of vacationers added to the resident population make water rationing a necessity in some areas;
- farming, the main source of income in the region: the high salinity levels of groundwater used for irrigation has forced lucrative crops to be abandoned and replaced by others that can better withstand the salinity; in some areas, the high level of ground salinity may lead to the total abandonment of agriculture within a few decades;
- the coastal pine groves that are being damaged by groundwater salinity.

The authors of this paper presented a study on groundwater salinization in the Grosseto Plain (Bencini & Pranzini, 1992) at SWIM in Barcelona, 1992. The distribution of the water salinity and chemistry revealed that groundwater salinization was dependent upon various phenomena, not only marine water intrusion. The current study has extended the field of investigation to the nearby Albegna River plain and tackled the issue with several methods: hydrogeological reconstruction of the subsoil of the two plains, chemical and isotopic analyses, and geophysical surveys. The large amount of data findings definitely provided a more accurate picture of the situation and have made it possible to understand the factors involved in groundwater salinization.

Geology and hydrogeology

The coastal plain formed by the Ombrone and Bruna Rivers is a tectonic depression in which a considerable thickness of Quaternary sediments accumulated (at least 200 meters in the central part). The rocks surrounding the plain are primarily sandstone and siltstone with some Mesozoic carbonate outcroppings (Fig. 1).
On the plain there are alluvial sediments and fill deposits while the coastal strip consists of dunes and beaches. Near the Roselle limestones there are recent travertine formations linked to the rise of thermomineral waters.
In order to understand the mechanism of groundwater salinization it is important to take a look at the sedimentary evolution of the plain (Bravetti & Pranzini, 1988). A large amount of sediment (100 meters thick near the seacoast) was deposited during the Holocene transgression, these are both alluvial deposits and non consolidated lagoonal or marine sediments which, therefore, still contain connate salt water. During the past three thousand years the plain has advanced rapidly, especially due to the fact that the introduction of farming combined with deforestation markedly increased the volume of sand transported by the rivers. The Ombrone delta advanced quickly and the river sands formed two bay bars joined to the promontories of Castiglione della Pescaia and Uccellina. The bars enclosed two lagoons that were later reclaimed (the northern one is not completely dried) with sand transported by the Ombrone River.

The geological situation of the Albegna River plain is similar to the Ombrone plain (Fig. 3). The main difference lies in the marked development of the eolic sands attributed to the Wurm. The Orbetello lagoon has not been filled due to the lack of a tributary.
The small Talamone plain was constructed mainly by swamp reclamation.
The area covered by this study is the driest part of Tuscany: mean annual precipitation is approximately 600 mm; the mean temperature ranges from 16° to 15° C.

In both plains there are two main aquifer complexes in the Quaternary sequence (Figs. 2 and 4):

a) fluvial gravel and sand at various depths;
b) coastal sands.
The former are confined aquifers, except for the area where the Ombrone river enters the plain, where the gravel and sand practically reach the surface, and some areas along the edges of the plain where the aquifers are continuous with the hill-slope detritus.

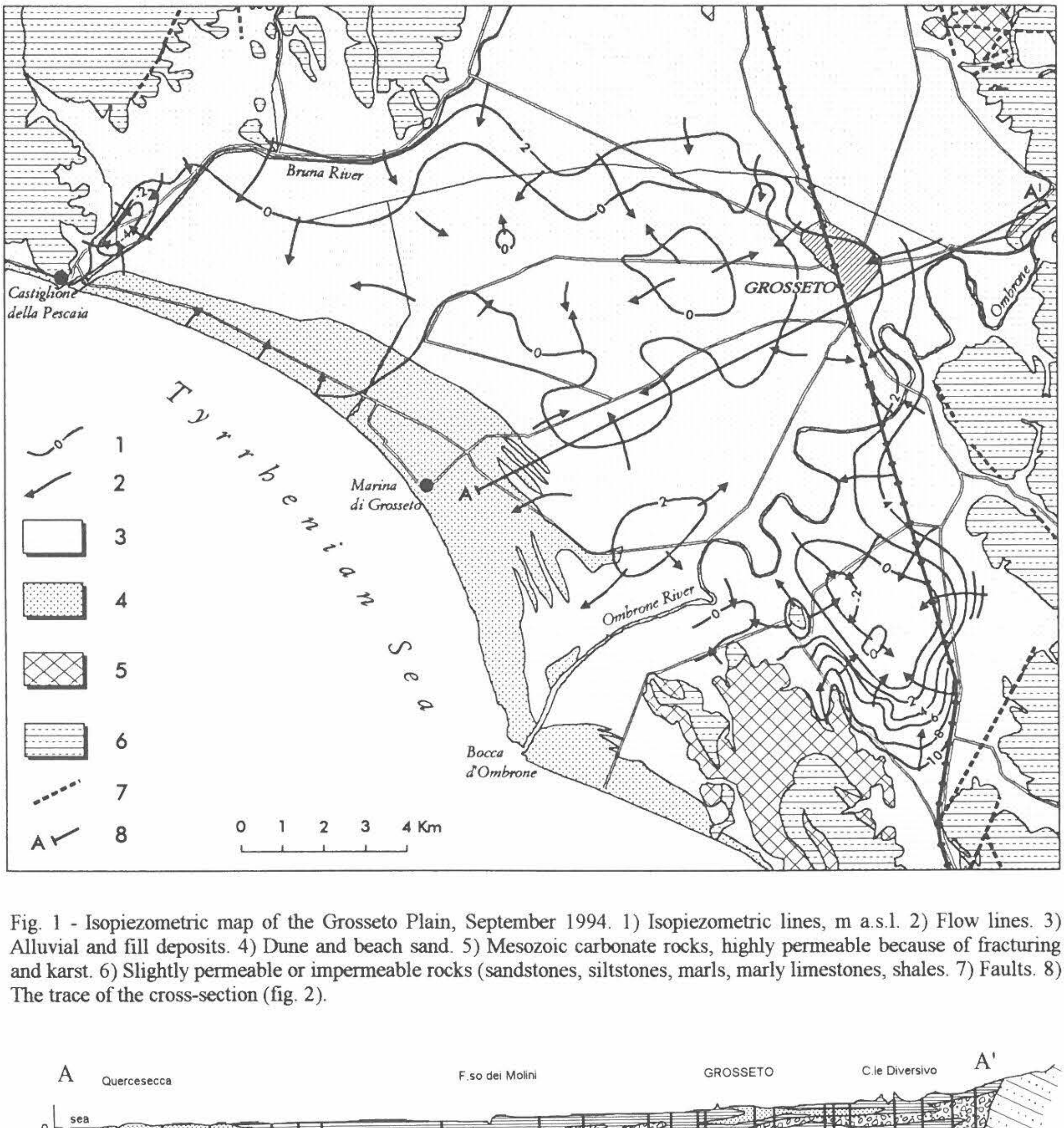


Fig. 1 - Isopiezometric map of the Grosseto Plain, September 1994. 1) Isopiezometric lines, m a.s.l. 2) Flow lines. 3) Alluvial and fill deposits. 4) Dune and beach sand. 5) Mesozoic carbonate rocks, highly permeable because of fracturing and karst. 6) Slightly permeable or impermeable rocks (sandstones, siltstones, marls, marly limestones, shales. 7) Faults. 8) The trace of the cross-section (fig. 2).

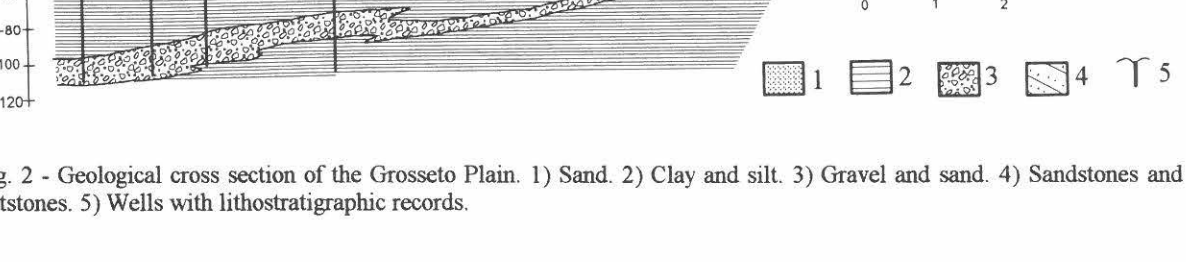


Fig. 2 - Geological cross section of the Grosseto Plain. 1) Sand. 2) Clay and silt. 3) Gravel and sand. 4) Sandstones and siltstones. 5) Wells with lithostratigraphic records.

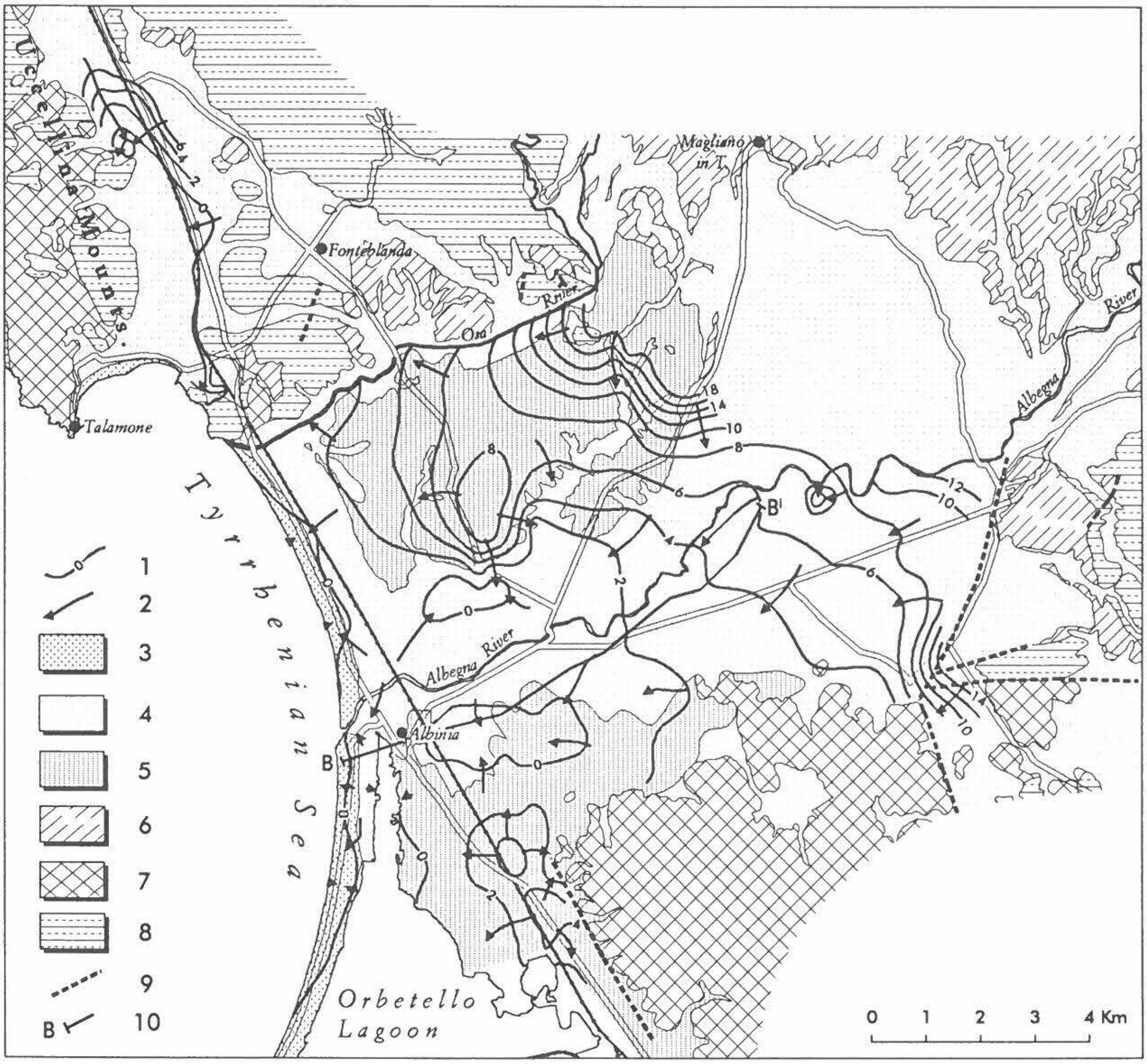


Fig. 3 - Isopiezometric map of the Albegna Plain, September 1994. 1) Isopiezometric lines, m a.s.l. 2) Flow lines. 3) Dune and beach sand. 4) Alluvial and fill deposits. 5) Eolic sand 6) Pliocene clay and sand. 7) Mesozoic carbonate rocks, highly permeable because of fracturing and karst. 8) Slightly permeable or impermeable rocks (sandstones, siltstones, shales). 9) Faults. 10) The trace of the cross-section (fig. 4).

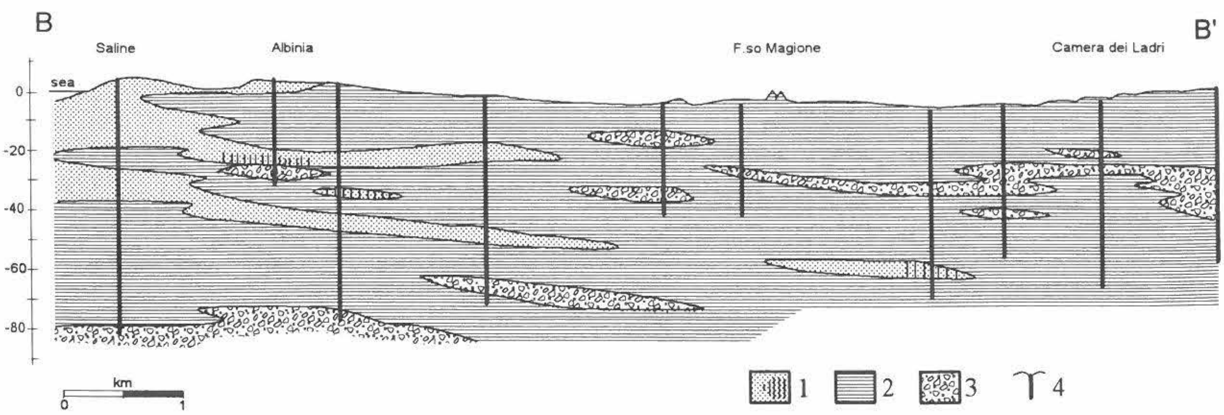


Fig.4 - Geological cross section of the Albegna Plain. 1) Sand. 2) Clay and silt. 3) Gravel and sand, locally cemented 4) Wells with lithostratigraphic records.

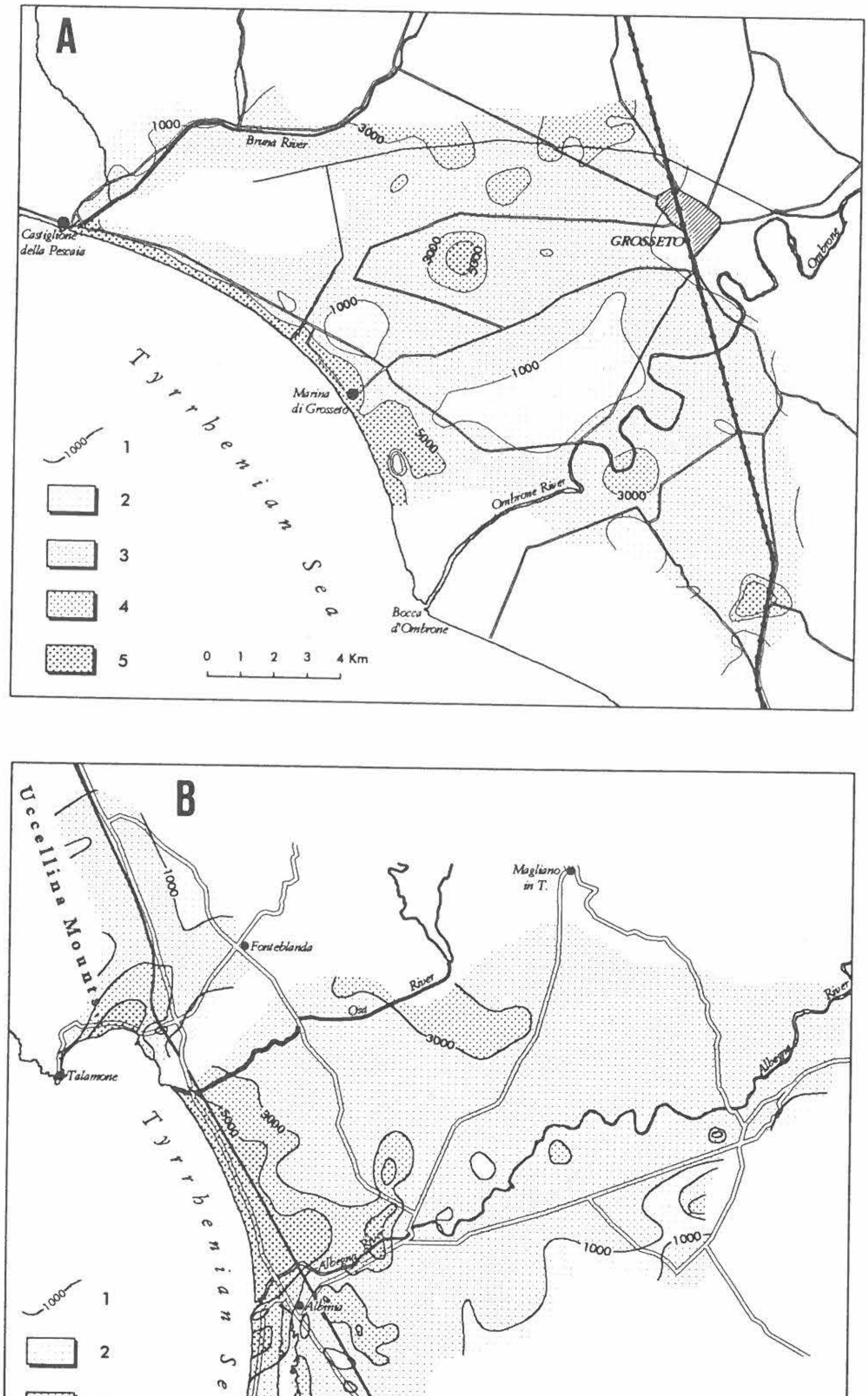


Fig. 5 - Groundwater electrical conductivity in the Grosseto Plain (A), and in the Albegna Plain (B), September 1994. 1) Isoconductive lines, mS/cm. 2) Electrical conductivity less than 1000 μS/cm. 3) E.C. between 1,000 and 3,000 μS/cm. 4) E. C. between 3,000 and 5,000 μS/cm. 5) E. C. over 3,000 μS/cm.

Pumping tests have revealed a transmissivity from 10^{-2} to 10^{-3} m²/s, while the storage coefficient ranges from 1.2 10^{-4} to 6.1 10^{-6}.
The groundwaters are fed by rivers and rain that infiltrate the surrounding hills. These groundwaters are used mainly for farming (over 4,000 wells) and also for municipal water supplies.

The coastal sands form an unconfined aquifer, which is not very productive, and is fed solely by direct rainfall. It is exploited mainly by shallow wells for campsites and summer homes.

The piezometric surface has been reconstructed over several years and seasons. Figs. 1 and 3 show the situation in autumn when areas with the piezometric surface below sea level expand considerably with respect to spring due to the increased summertime pumping. The seasonal variation in the water level is 1-2 meters, on the average, but in some areas, summer pumping cause depressions as deep as 10 meters.

Groundwater Chemistry

Figure 5 shows the distribution of groundwater electric conductivity on the basis of September 1994 measurements. Salinity generally increases between spring and autumn, especially in areas subject to intensive summer pumping.
In addition to the high salinity of the groundwater near the coast, there are also areas with high salinity farther inland which cannot be explained by the phenomenon of marine water intrusion. In this case, the chemistry of the water is the main element for an understanding of the salinization process.
We conducted basic chemical analyses of the water from 185 wells, 6 springs and 2 rivers. On 32 appropriately selected specimens we determined Br, Sr and Li levels. On 18 well water samples we also conducted isotopic analyses (Table 1). We also used 4 ^{3}H and 5 ^{18}O tests on well specimens taken from two small coastal plains north of the Ombrone plain.

A preliminary general evaluation, using the Langelier-Ludwig diagrams identified three main groupings (Fig. 6):
a) alkaline-earth sulfate waters
b) alkaline chloride waters
c) alkaline-earth chloride waters.

We can immediately see that the small quantity of alkaline-earth bicarbonate waters is a major anomaly. The alkaline chloride waters, those with the highest total salinity, are clearly related to marine water intrusion (Fig. 7). This is confirmed by the fact that the respective wells are located mainly along the coast, and that salinity gradually decreases going inland.

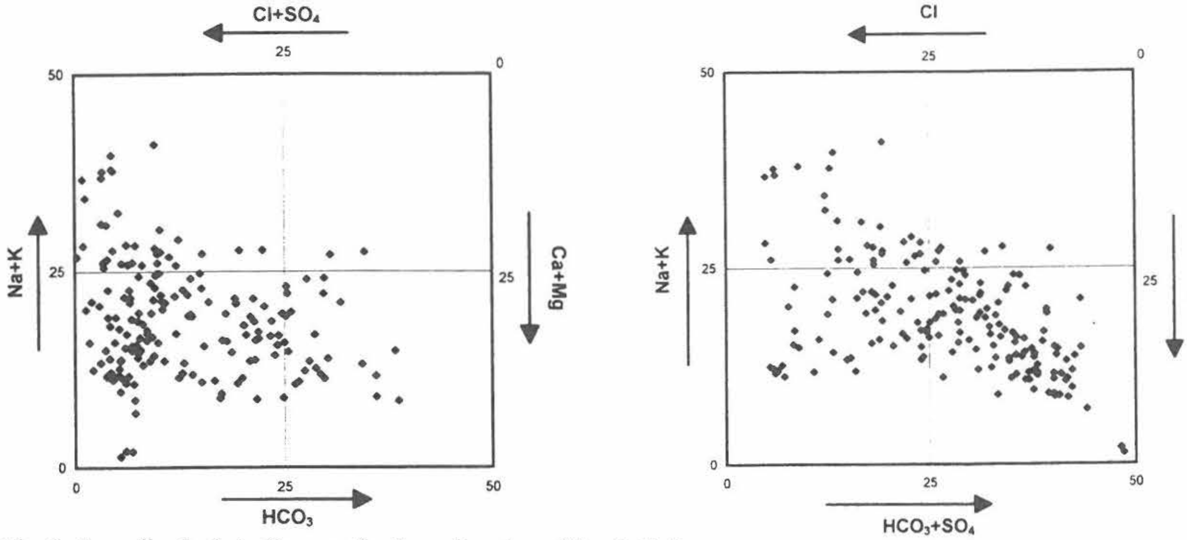
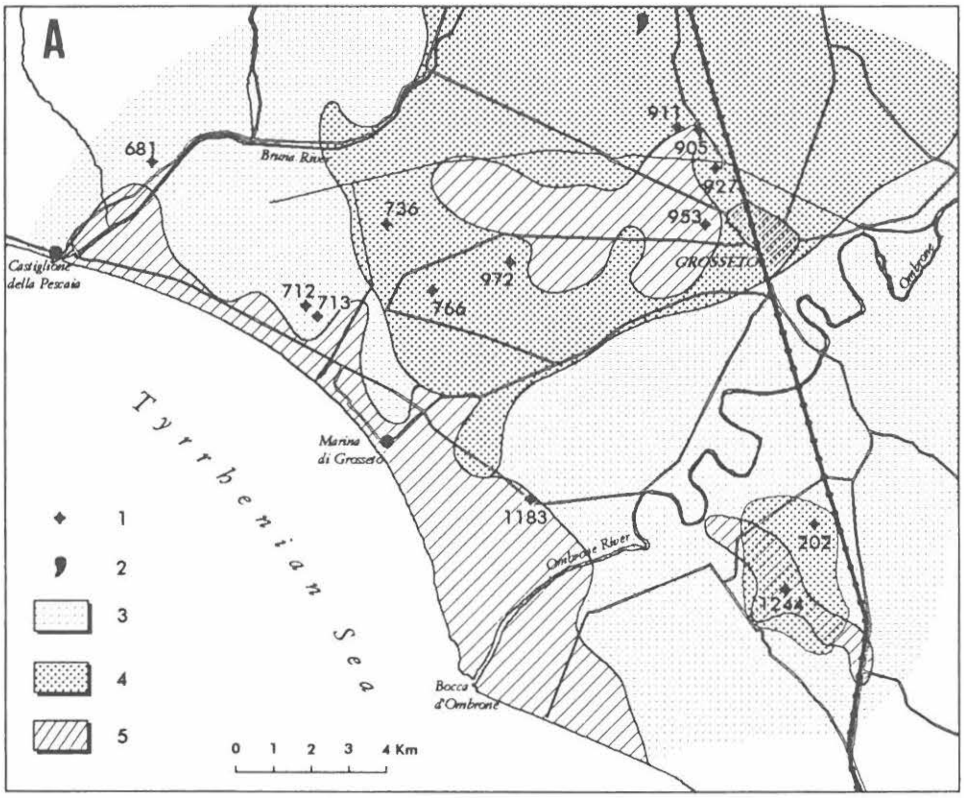


Fig. 6 - Langelier-Ludwig diagrams for the well waters of the studied area.



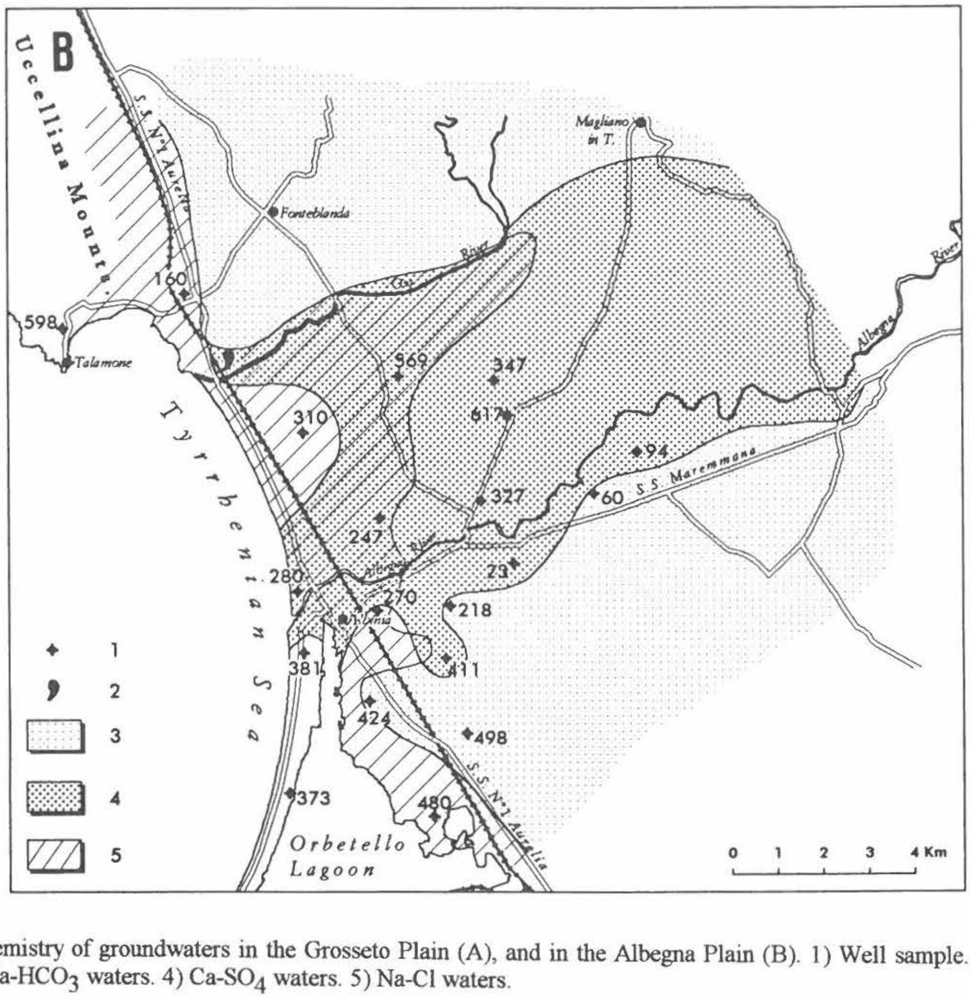


Fig. 7 - Chemistry of groundwaters in the Grosseto Plain (A), and in the Albegna Plain (B). 1) Well sample. 2) Thermal spring. 3) Ca-HCO_3 waters. 4) Ca-SO_4 waters. 5) Na-Cl waters.

The alkaline-earth sulfate waters are the most prevalent, and mainly in the north-central part of the Grosseto plain. The electrical conductivity and hence TDS values are also high. The chemistry of these waters can be attributed to the following mechanisms:

- washing away the gypsum formations in the upper part of both basins: this matches the definite sulfate calcium composition of the rivers, that have salinity levels that are totally abnormal for superficial waters;
- rise of thermal waters from the reservoir of Triassic evaporites (Bencini *et al.*, 1977). In the area there are springs with T>35°C; furthermore the mean temperature of the well waters is 19.5°C, approximately 3° higher than what we would calculate on the basis of the normal geothermal gradient.

The alkaline-earth chloride waters are more difficult to interpret especially since various percentages of other basic elements create a chemical family that is anything but homogenous.
In any event inverse exchange processes between sea and clayey waters (Na^++ Ca-X → Ca^{2+} + Na-X, Appelo & Geirnaert, 1983), and mixing mechanisms and/or aging processes of infiltration waters which evolve according to the well known sequence HCO_3^- → HCO_3^- + SO_4^{2-} → SO_4^{2-} + Cl^- → Cl^- have an evident impact on their composition.

Isotopic analyses performed mainly on the waters from inland wells, where the marine water intrusion does not seem to arrive also made an important contribution to interpreting the findings. For example, the Cl - $\delta\,^2H$ and Cl - $\delta\,^{18}O$ (Figs. 8 and 9) reveal a tetrapolar system with:
a) a local recharging pole: direct infiltration, even from irrigation, or losses from rivers (samples 60, 681, 905);
2) a pole of paleowaters that represent regional recharging and which are vehicled very slowly in the deep confined aquifers (766, 972);
3) a pole of deep thermal waters (911);
4) a "marine" pole, that of current or fossil sea water (1183).
The system seems to be further complicated by the fact that these terms may overlap and some specimens seem related to more than one pole.

Table 1 - Isotopic composition, δ.1000, Cl content, ppm, and Cl/Br of the well waters of the studied area.

samp.	Cl	^3H	^2H	^{18}O	^{13}C	^{14}C	$^{34}S(SO_4)$	$^{18}O(SO_4)$	Cl/Br
60	586.18	7.8±1.2	-35.7	-5.78					158
94		7.6±1.1	-38.3	-5.75					
247	1576		-33.6	-5.46					200
270	1279.95	3.2±1.1	-35.5	-5.57	-11.34	32.1±2.6	16.43	12.22	165
347	249.9	1.0±0.9	-34.9	-5.63	-11.05				223
411	570.15	1.1±1.0	-35.1	-5.8					210
617	145.08		-34.8	-5.45	-12.2	76.4±3.8	6.46	13.28	279
681	97.65	7.0±1.2	-37	-6.1	-12.46				192
738	181.65	<1.0	-39.2	-6.19	-6.91		16.27	16.93	249
766	225.4	<0.5	-40.9	-6.53	-4.97	<2	16.83	16.83	248
905	285.37	3.7±1.0	-31.6	-5.43					352
911	358.05	2.7±0.9	-32.7	-4.87	-12.15	34.4±3.8	15.09	15.85	385
927	272.97		-34.7	-5.51	-13.55	62.3±4.2			290
953	437.81	7.8±1.3	-36.6	-5.79					600
972	178.15	<0.8	-41	-6.47	-6.42				241
1183	1007.84	<1.2	-38.3	-6.45					271
1202	646.96	5.8±1.0	-35.4	-5.59	-10.89				
1244	148.05		-38.2	-5.96					290

An analysis of the Cl/Br ratio (Fig. 10) shows that only few waters exceed the sea water ratio. The high Cl/Br ratio of these waters could be explained by the dissolution of halite. Since there are no halite saturated fluids in Tuscany, the Cl enrichment may be explained by deep geothermal additions, since these are the same waters that in Figs. 8 and 9 appear to be related to the thermal pole.
Most of the samples, however, reveal Br enrichment with respect to sea water (Cl/Br ratio < 290). This

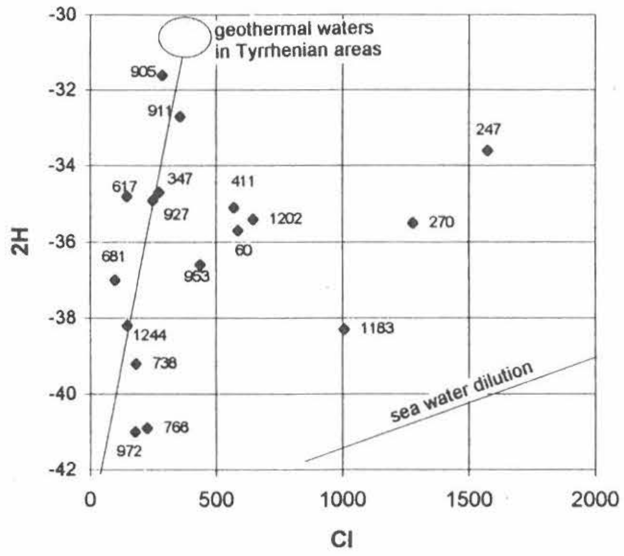


Fig. 8 - Correlation Cl - δ^2H for the groundwaters of the studied area.

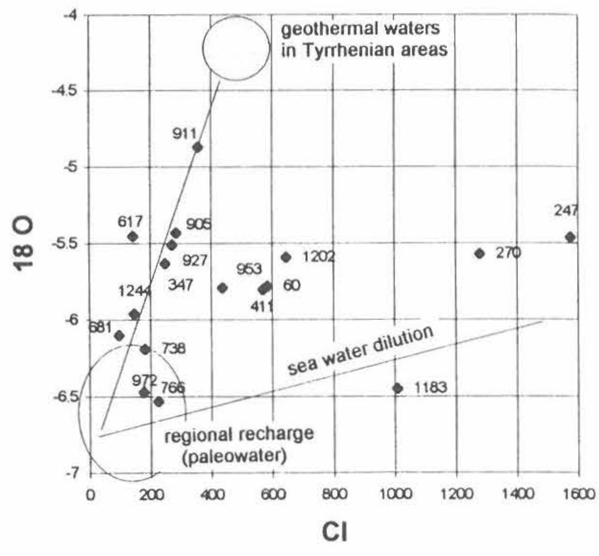


Fig. 9 - Correlation Cl - $\delta^{18}O$ for the groundwaters of the studied area.

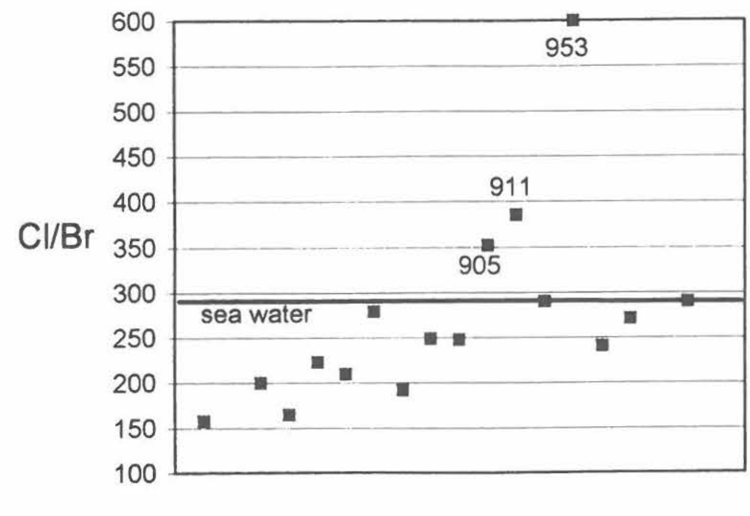
feature may be due to precipitation (with rainfall Cl/Br contents that can vary locally), and to two other reasons as well:

a) the effect of a secondary brine that follows halite precipitation (the ratio is approximately 175)

b) remobilization of a residual fluid subject to ultrafiltration phenomena.

Both of these hypotheses seem compatible with a mechanism that mobilizes marine water trapped in the sediments by underground flow. As we mentioned earlier, the sedimentary evolution of the two plains fits in with this hypothesis.

Fig. 10 - Cl/Br ratio for some waters of the studied area.



Groundwater salinization mechanisms and possible remedies

The salinization of groundwater is caused by:

1. marine water intrusion regarding a coastal belt 0.5 - 2.5 km wide. The width is greater in the areas where campsite and summer home wells are concentrated. The fresh water-salt water interface has been reconstructed through electrical conductivity measured with GEONICS electromagnetic equipment (2903 measurements) and through 177 vertical soundings (Fig. 11). The reconstruction

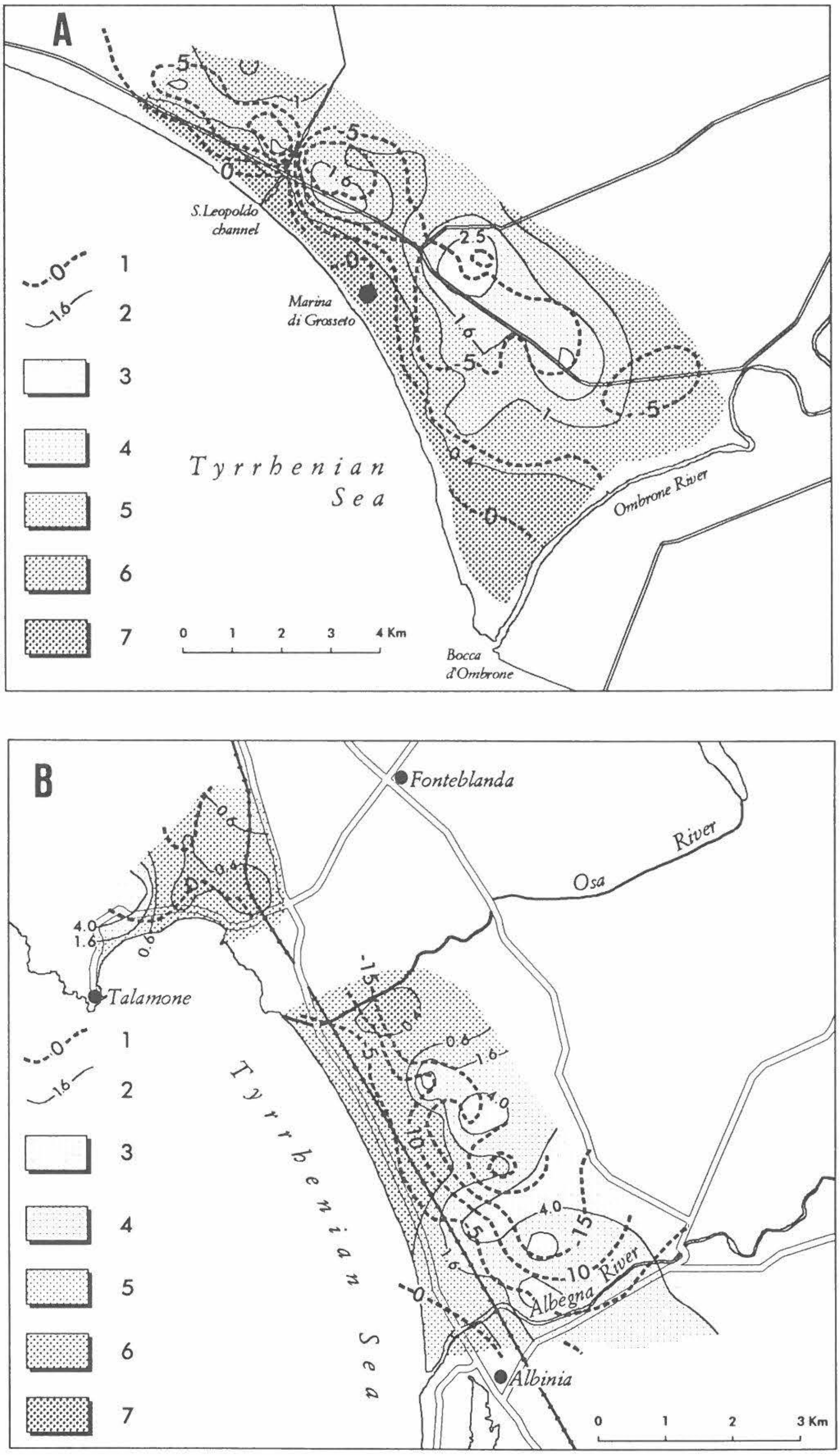


Fig. 11 - Reconstruction of the fresh water - salt water interface in the Grosseto Plain (A), and in the Albegna Plain (B). 1) Lines of equal depth of the interface, m. 2) Electrical resistivity of the layer under the interface, ohm.m. 3) E.R. over 4.0 ohm.m. 4) E.R. between 4.0 and 1.6 ohm.m. 5) E.R. between 1.6 and 0.6 ohm.m. 6) E.R. between 0.6 and 0.4 ohm.m. 7) E.R. less than 0.4 ohm.m.

was difficult due to the fact that going inland, the dune sand passes to lagoonal clay which has electrical conductivity levels similar to that of sand with saline water. The problem was solved by measuring induced polarization which changes from positive to negative values when going from sand with fresh water to sand with sea water, while the inversion does not occur passing to clay;

2. intrusion of marine water into rivers and artificial channels. In the Ombrone River delta marine water also reaches the interdunal depressions which are now pervious due to delta erosion;
3. chemical evolution of groundwater, characterized by cation exchange processes;
4. mixing with Ca-Mg-SO_4 thermal waters rising from the carbonatic reservoirs;
5. seepage of sulfate water from the rivers which flow in the gypsum outcrops of the upper part of the basins.

The following measures are suggested for stopping groundwater salinization:

- dramatic reduction of pumping in the coastal dunes affected by marine water intrusion;
- recharging of the coastal aquifer in the Ombrone River Plain through a channel dug parallel to the coast to which river water can be diverted during winter floods;
- reduction of pumping for agricultural purposes in the areas characterized by a groundwater TDS higher than 2g/l, and the use of superficial waters for irrigation.

Thanks

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