SEAWATER INTRUSION IN COASTAL AQUIFERS OF ITALY

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ABSTRACT
Seawater intrusion is affecting most coastal areas of Italy, mainly because of aquifer overexploitation to satisfy the demand of an increasing population in coastal plains. The problem is alarming especially in southern regions, where the proportion of the total resident population living in coastal areas attains 45%. The only immediate solution seems to be an integrated surface and ground water resources management. However, much remains to be done in terms of rational land and regional planning in the medium and long term so as to mitigate conflicts among different users.

INRODUCTION

The Italian peninsula juts southwards deep into the Mediterranean Sea in the shape of a boot more than 1300 km long and from 150 to 600 km wide. It has 7456 km of coastline, extremely long in proportion to the total land area (301,302 km^2). The coasts of Italy's two largest islands Sicily (25,707 km^2) and Sardinia (24,090 km^2) are 1500.1 km (20.1%) and 1849.2 km, (24.8%) long respectively.

The country's main topographical features are the Alpine arc, that forms the natural northern frontier with central Europe, and the Apennines chain forming the backbone of the peninsula. There is a sharp contrast between the unindented, lowlying lagoonal coasts, bordering the Po plain in the northern Adriatic, and the high jagged coasts to the east of the peninsula fringing the spurs of the Apennines or the short and narrow sandy strips at the foot of coastal hills. The only coastal plains on the west coast are those in Tuscany, Latium and Campania that stretch out into the Tyrrhenian Sea .

In Sicily high and rocky coasts prevail over sandy shores, and the coasts of Sardinia, apart from the small deltaic coastal plains with their numerous lagoons and ponds, are steep and jagged, especially in the NE of the island. The inland areas of the two islands are topographically similar to southern Italy, with rugged mountains in the interior. The other large islands off the west coast of mainland Italy are, proceeding southwards the Tuscan Archipelago, the Pontine Islands, Ischia, and Capri. The Lipari Islands, Ustica and the Egadi Islands lie off the coasts of Sicily; and Pantelleria and the Pelagie Islands between Sicily and Tunisia. There are a few islands dotted around Sardinia and off the Ionian and Adriatic coasts.

Italy's population, estimated in 2000 at nearly 57.8 million, is very unequally distributed, ranging from 37 inhabitants per km^2 in the Alpine region of Val d'Aosta to 425 persons per km^2 in the southern region of Campania. The metropolitan areas around of Naples and Milan have over 2640 and 1900 inhabitants per km^2 respectively, compared to an average population density for the whole country of 192 km^2. Italy's population density is one of the highest in Europe, but its distribution is highly uneven because of its physical features and differential urbanization. At present, more than the 67% of the population lives in towns with more than 10,000 inhabitants, and about 53% in towns with more than 20,000 inhabitants. The 20th century saw the beginning of a mass exodus towards coastal areas especially after the 2nd world war during the period 1951-91, reaching a peak between 1951-71.

On the one hand irrigated agriculture and stock farming expanded increasingly in the coastal plains, while on the other extensive areas underwent rapid and sometimes haphazard urbanization with infrastructures and residential housing as well as tourist resorts and the settlement of new industries. in proportion to total inhabitants. The proportion of the total population living in coastal areas attains 45% in southern Italy, 39.5% in central Italy and 11.5 in the North. The impact is dramatic if one considers the increasing number of tourists that swell the resident population, especially in the summer. The development of new and expansion of existing urban areas has led to the loss of prime agricultural land and often water resources allocation problems, leading to conflicts among land and water users. Generally, the natural balance between surface water, groundwater and seawater has been upset, and because of mismanagement of water resources coastal aquifers have become affected by saltwater encroachment resulting in soil salinization.

GEOLOGICAL CONTEXT

The main aquifer formations of Italy are shown in the hydrogelogical sketch-map of figure 1.

The northeastern part of the peninsula, at the borders with Slovenia and Croatia, consists of the karst limestone aquifer system, with sinkholes and underground rivers some tens of kilometers long, of which the best known is the

Figure 1. Hydrogeological sketch-map of Italy. Arrows indicate coastal aquifers endangered by saltwater intrusion.

Timavo. In the coastal areas of Friuli, Venetia and Romagna, rather complex multi-layered confined aquifer systems are hosted in the Recent alluvium deltaic plains of a number of rivers, the most important being the Tagliamento, Piave, Adige and Po.

The land bordering the Apennines to the east may be divided into two sectors, one extending along the coast from the Marche to the Molise, and then continuing southwards into the Bradano trench between Puglia and Basilicata down to the Gulf of Taranto, the other comprising the Apulian regions of the Gargano, Murge, Tavoliere plain, and Salento peninsula. In the first sector, small local aquifers are contained in sandy lenses interbedded in Pliocene deposits of clay and mud, many in contact with the Quaternary alluvium of the val1ey floors. The second sector consists of Cretaceous subhorizontal fissured and karstic limestones which form excellent aquifer systems. The Tavoliere plain is connected to a strip of the first sector and is then characterized by sandy deposits which form a major aquifer.

Farther south along the coasts of Calabria, the aquifers are hosted chiefly in a few small Recent alluvial deposits lying at the foot of hills and mountains along the valleys incised in the crystalline and metamorphic complexes of the Sila and Aspromonte. On the east coast, the Sibari alluvial plain represents the major aquifer region.

Proceeding northwards the coastal plains of Campania, Latium and Tuscany, bordering the Tyrrhenian Sea are composed chiefly of Quaternary deltaic alluvial deposits which form large, well-replenished aquifers. In Liguria up to the French border the major coastal aquifers are found in the Mesozoic karstic limestones of the marlstone, dolomite and calcarenite series of the Maritime and Ligurian Alps.

In Sicily, in the entire north-eastern portion of the Province of Messina, small local aquifers occur in the fracture zones of the Caenozoic flysch and Palaeozoic metamorphic rocks and in the alluvium of the valley floors. Along the north coast of the island across the Province of Palermo up to Trapani, the Mesozoic-Caenozoic series of karstic calcareous highlands (Madonie, Imerese, Panormidi, Trapanesi) host important aquifers. To the west, in the Marsala zone, there are major P1iocene-P1eistocene sandy-calcarenite aquifer complexes. The Cretaceous-Miocene limestone formation Hyblean plateau, rising in the south-eastern part of the island, contains major and well-replenished groundwater resources. To the east, the sandy-clayey Quaternary alluvial deposits of the Catania plain host a small aquifer, where in many places groundwater floats on top of saltwater. Between the Catania plain and the Nebrodi mountains, Etna, the highest vo1cano in Europe (3340 m) with its vast outcrops spread over 1300 square kilometres, hosts Sicily’s largest aquifers. Off the coasts of Sicily the volcanic rocks of the islands of Eo1ie, Pantel1eria and Ustica, and the calcareous rock of the Egadi and Lampedusa islands, constitute very poor aquifers, with insufficient yield to meet local demand (Aureli, 1991).

Sardinia's largest coastal aquifers are hosted in the Jurassic karstic limestone formations of the Bays of Orosei and Nurra, on the East and North-West coasts respectively, and in the karstic limestones of the Cambrian series of the Iglesiente region, in the south-west of the island. Most Sardinian coasts consist of imposing cliffs of Palaeozoic-Quaternary metamorphic, crystalline, volcanic and sedimentary rocks, where groundwater occurs locally in large bedrock fractures and in porous weathered zones of the overburden. Recent alluvial and sedimentary deposits with their numerous coastal ponds interrupt the cliffs at the mouth of the deep valleys incised by the most important rivers and at the margins of the graben stretching from the Bay of Oristano in the West to the Bay of Cagliari in the South.

COASTAL AQUIFERS

The Carso plateau, the region near Trieste in the far north-east of Italy which gave its name to the karst phenomenon, represents one of the most important aquifer systems in the Mediterranean. Surface waters disappear, infiltrating into sinkholes and grottoes, to reappear as groundwater drained by streams such as the Timavo, deeply carved out of the rough morphology, and flowing out from subaerial and submarine high-yield springs.

The unconfined, semiconfined and confined aquifers bordering the northern Adriatic sea are largely supplied by lateral inflow of groundwater formed in the Friuli, Venetia, and Po alluvial plains for direct recharge and upstream infiltration into the mountain and piedmont deposit areas at the foot of the Alps and Apennines. Stream discharge from the upper part of the plain is substantial and causes the piezometric surface to rise noticeably. In the Venetia part of the plain the average piezometric slope drops from 0.5-1.1% in the piedmont deposit zones to 0.01-0.04% in the coastal area (Zuppi, 2003).

That aquifer system, divided into distinct sectors, is certainly the most productive in Italy. Total stream-flow into the alluvial aquifer is estimated at about 100 m^3/s. In the intermediate hilly zone this water reappears at the surface and forms a continuous line of springs with an aggregate flow rate of over 150 m^3/s. Downstream groundwater is abstracted through thousands of dug and drilled wells to meet the increasing water demand for municipal, agricultural and industrial uses. Both the volume and outflow of the aquifer are considerable. In the Venice area there are more than 13,000 wells and groundwater overexploitation has been found responsible for the increasing subsidence of the area to the extent that many wells have had to be closed. In Romagna, and likewise upstream in Emilia and the lower Plain of Lombardy, flow lines tend towards the Po River with a piezometric gradient of 1-2% in the hilly zones and 0.1-0.2% in the lower zones. Aquifer recharge by the river system in the outer hilly zone is calculated at about 10 m^3/s, whereas average drainage from the same rivers in the valley zone is estimated to be 7 m^3/s. In this part of the plain, transmissivity varies between $5x10^{-2}$ and 10^{-3} m^2/s. The storage coefficient ranges from 10^{-2} for the surface strata to 10^{-4} for the deep zones, where the stratum is under pressure.

Along the Adriatic coast there are more than 20 valleys with major local alluvial deposits, all lying parallel in a SW-NE direction. As they are no more than 60 metres thick, only their large areal extent makes these aquifers valuable for satisfying local water needs. Analysis of the alluvium indicates a steady increase in grain size with depth. Further to the south, in Apulia, in the sandy deposits of the Tavoliere plateau, the piezometric surface indicates downward flow into the sea with a gradient of 0.5 per cent with several thousands of wells under exploitation (Cotecchia *et al.* 1981).

Calcareous outcrops appear in three distinct sectors of Apulia: on the Gargano promontory, the Murgia uplands and Salento Peninsula. The prominent elevation of the Gargano promontory hosts an aquifer supplying a number of peripheral springs flowing out into the sea. There are 27 known springs with a flow rate higher than 30 l/s, 14 with a rate of 100 to 300 l/s, and 5 with a rate of 300 to 1000 l/s. The aggregate yield is estimated at about 4 m^3/s. The Murgia karstic tableland contains significant groundwater resources, abundantly recharged at various levels, and supplying many springs flowing along the coast or spilling directly into the sea. The piezometric surface indicates a flow towards the Adriatic with a gradient of 0.1-0.3% and a less marked gradient towards the Gulf of Taranto. Springs are few, but some have significant capacity: the aggregate yield of the Murgia springs is 7 m^3/s. On the Salentina Peninsula, consisting of stratified and very faulted karstic calcareous rocks, there is a major groundwater reservoir with 80 logged springs yielding in total up to 10.4 m^3/s. The gradient of the piezometric surface 0.02%.

Along the Ionian sea, ten or so valleys originating in the Apennines of Lucania slope down into the Gulf of Taranto. Their alluvial deposits form the coastal plain of Metaponto, Scanzano and Policoro, with alluvial aquifers of considerable importance even though they are less than 100 metres thick and have poor permeability due to interbedded clay. Groundwater development there is quite limited.

In the multilayered confined aquifer of the Sibari plain, on the Calabrian side of the Gulf of Taranto the piezometric surface generally tends seaward, with a gradient of 2% at the upper level and 0.1 to 0.2% by the coast. This indicates that the aquifer is drained by the Crati River and fed by adjacent watercourses. Aquifer transmissivity is in the range $5x10^{-2}$-10^{-3} m^2/s (Aureli, 1991).

Along the Tyrrhenian coast, the aquifers of local importance in the alluvial plains of the Calabrian coast near the Straits of Messina, are overexploited by more than 6000 wells. Further north, the coastal aquifers of S. Eufemia and Gioia, 30 to 100 metres thick, are on the other hand of major importance to the local economy thanks to their large storage capacity, supplying more than 3500 springs .

Between the Gulf of Naples and the Gulf of Salerno, in the Sorrento Peninsula, composed of carbonate rocks that also crop out in the isle of Capri opposite, a number of springs (Castellammare di Sorrento, Cava dei Tirreni) yield more than 50 l/s, but part of their flow is directly discharged into the sea. The aquifers of the thick alluvial sediments, coastal sand dunes and vo1canic tuffs, the most common in the locally marshy coastal plains of Tuscany, Latium and Campania are abundantly recharged by lateral flow from the karstic aquifers and volcanic structures cropping out to the east, to the extent that large-scale land reclamation and drainage works had to be carried out. Spring outflow into the Pontine marshes, south of Rome, is estimated at about 20 m^3/s south. In the Campania plain estimated transmissivity ranges from 10^{-3} to $7x10^{-3}$ m^2/s. Actual outflow is significant and supplies more than 5000 dug wells and boreholes.

In Tuscany, in the rugged and fractured calcareous heights of the Apuane Alps, famous for their marble quarries, intensive fracturing has assured an abundant flow of water be it of little local utility. Other isolated carbonate rock occurrences, alternately rugged and smooth, cropping out in the semi-permeable fields of flysch are found in the marshlands between Grosseto and Orbetello,

The numerous more or less productive springs in the prevalently karstic limestone areas of the Maritime and Ligurian Alps yield an aggregate flow of 6 m^3/s, partly discharged into the sea.

In Sicily (Aureli, 1991) the complex aquifer system of Mount Etna (3340 m), the largest active volcano in Europe, supplies 289 springs, and 38 drainage gal1eries of which 18 have average yields of 110 to 1000 l/s. The lava flows on the east side of the volcano are in direct contact with the sea, where part of their groundwater is discharged. There are more than 1200 wide-diameter wells and 189 boreholes, giving a total yield estimated at 15 m^3/s. Total capacity of the aquifer is estimated to be about 20-25 m^3/s.

Estimated transmissivity of the sedimentary aquifer in the Catania Plain, largely supplied by lateral inflow from the Mount Etna volcanic rocks to the east, ranges from $2x10^{-3}$ to 10^{-4} m^2/s. A total yield of 6.8 m^3/s has been estimated for the carbonate aquifers of the Madonie mountains, whose springs partly supply the aqueduct of Palermo, and the Hyblean mountains, partly discharging into the Recent coastal aquifers of Priolo-Augusta, Lentini and Syracuse on their south-eastern borders.

On the coast of Syracuse, to the east of the Hyblean mountains, the springs of Ciane yield 600 l/s, Fons Aretusa, 250 l/s and S. Calogero, 200 l/s. Altogether 163 springs have been inventoried on the southern slope, with a tota1 yield of 3.3 m^3/s, and 168 on the eastern slope, with a total yield of 1.7 m^3/s. A feature of local, but considerable, interest is the presence of Quaternary sand and small ca1careous rocks spread over various area of the islands on the Pleistocene argi1laceous covers. They are found in the Marsala-Mazzara del Vallo area, where the piezometric gradient is 1-1.5 %, and in the zone of Piazza Armerina, on the Vittoria plateau, where 1286 logged wells are situated with an estimated transmissivity of $3x10^{-3}$ to 10^{-3} m^2/s.

Many of the small islands off the coasts of Sicily (Eolie, Ustica, Pantalleria, Linosa) are also of volcanic origin but the fresh-water lenses occurring on top of the saltwater are fairly shallow and only constitute a minor groundwater resource or are not exploitable at all.

The Campidano plain in the province of Cagliari, the most depressed part of the main Graben of Sardinia, filled with early Tertiary-Quaternary sediments and interbedded volcanites, hosts an important aquifer system, for the most part supplied laterally through the composite tectonic blocks delimiting the tectonic trough. The Pleistocene and Recent areas consist largely of shingle, sand and mud up to 200 metres thick. The resultant aquifer, extensively tapped by more than 1600 wells, is of considerable importance for local agriculture and municipal uses. The piezometric surface has gradients in the order of 0.2%. A major part of the groundwater flows towards the Bay of Oristano and the remainder towards the Bay of Cagliari. The total yield of the aquifer system of the area of Oristano and Arborea-Santa Giusta is estimated at 400-600 l/s, tapped through hundreds of wells. In the Capoterra aquifer system on the south-eastern edge of the Campidano plain, an average yield Q=0.360 m^3/s with a K= $1x10^{-2}$ to $4.5x10^{-1}$ cm/s and gradient of 0.3% have been calculated. An estimated yield of a few hundred l/s is tapped also from the aquifer system of the western edge of the plain. In the delta plain of the river Flumendosa, up to 200 m thick in its middle part, an average fresh groundwater flow of 3.3 Mm^3/year has been calculated, and a flow of 1.5 Mm^3/year was evaluated for the aquifer system of the contiguous delta plain of the River Picocca-Corr’e Pruna. Other aquifers of local importance, up to 50 metres thick, are hosted in small delta plains along the island’s coasts.

Sardinia's calcareous rocks constitute major aquifers. In the Portotorres area, near Sassari, Miocene calcareous rocks contain a significant aquifer, partly drained by the streams that discharge into the sea, in the Anglona region. There are more than 500 small springs with a collective average yield of 0.45 m^3/s, and a large number of wells situated at the margin of the hilly areas. The groundwater occurring in the Mesozoic calcareous rocks of the Nurra, in the north-western tip of the island, is extensively exploited due to the presence of numerous wells, the result being that many of the springs have dried up, and part of the groundwater discharges into the sea. There are 43 springs with an average overall yield of 200 l/s. In the East of Sardinia there are numerous outcrops of calcareous rocks, the largest being the karstic massif of Dorgali, facing the Bay of Orosei. These aquifers represent the only important ground-water resource in the area. Some springs have flow rates of 20-120 1/s. There are 155 springs with an overall average yield of 1100 l/s. Between 400 and 750 1/s of groundwater are discharged directly into the sea. A total yield of 25 Mm^3/year and reserves of 144 Mm^3 have been estimated. In the Iglesias region, to the west of Cagliari, there are about 100 logged springs with a total average discharge of about 500 l/s from the karstic aquifer in the Cambrian metalliferous limestones, representing the most important lead and zinc sulphide ore district in Europe. To enable to mining operations to be continued below sea level, the water table was lowered to –200 m by pumping salty groundwater up into a drainage tunnel at 15 m above sea level. Around 1600 1/s, mainly saltwater intruded from the sea, were discharged into the Mediterranean. Groundwater salinity was 11 g/l, while at the end of the 19^{th} century, prior to the water table drawdown to below sea level, a salinity of 0.113 g/l had been measured. Mining activities were eventually abandoned and in the mid 1990's the pumping station at –200 m below sea level was shut down. Subsequently a new piezometric surface of the freshwater floating on top of the seawater is now reaching a new equilibrium level. At present, a freshwater flow of 280 l/s is abstracted from the aquifer and conveyed by aqueduct to city of Cagliari.

SEAWATER INTRUSION IN ITALY

Saltwater intrusion has jeopardized to a greater or lesser extent most coastal aquifers in the Italian peninsula and its islands, as shown in figure 1.

All along the coasts of Italy, the post-glacial sea level rise brought about by the general climate change led to the formation of delta plains consisting chiefly of fluvial, lacustrine and evaporitic deposits in salty and brackish environment. Under the present hydrodynamic balance between fresh and salt surface and groundwater, those deposits, entrapping brine and connate salt waters, remain unleached, so that even fresh waters of lateral inflow from inland aquifers towards the sea become salty when seeping through them. Different permeability horizons corresponding to different karst drainage patterns depending on sea level variations over time have been recognized in Middle Cambrian to Recent limestone formations.

Overpumping is generally considered a major cause of saltwater intrusion, due to both freshwater table draw down and saltwater upconing. When evaluating the adverse effects of groundwater overabstraction, facts other than the amount of fresh groundwater withdrawal in relation to groundwater recharge should be considered. In fact salt water encroachment is controlled by aquifer attributes, namely its geometrical and hydraulic parameters, solid and liquid phase composition, mechanisms and times of natural and/or artificial recharge, and by well characteristics such as well diameter and depth in relation to interface level and the influence radius of resultant well draw down in relation to well distance from coast line. Furthermore, windborne saltwater spray depositing on the soil may be conveyed by infiltrating rainfall into surficial groundwater.

Overpumping in coastal areas has caused major problems in urban and industrial zones, like the metropolitan areas of Venice-Marghera and Ravenna, where, in order to satisfy industrial and municipal water demand, the local alluvial multilayered aquifer systems have been so seriously depleted that their piezometric surface has been lowered by hundreds of meters. This has resulted in the progressive intrusion of saltwater, which is now found at various depths depending on the zone, and also in land subsidence locally, to the extent that Venice and Ravenna are now threatened by sea flooding (Gatto & Carbognin, 1981; Carbognin & Tosi, 1995; Mar-tinelli et al. 1998). Efforts are now being made to halt groundwater exploitation.

The deltaic areas where aquifers are jeopardized to a varying extent by saltwater intrusion include the coastal plains of Tuscany (Maremma, Valle del Magra, Corna, Ombrone, and Albegna plains, Castiglione della Pescaia, and the Island of Elba), Latium (especially the river Tiber delta and the Pontina Plain), Campania, Calabria, Sicily (Augusta-Syracuse, Palermo, and Marsala), and Sardinia (the Flumendosa delta, and the bays of Cagliari and Oristano).

Saltwater has also invaded the karst aquifers of Apulia (Gargano, Murgia, Tavoliere, and Salento peninsula), Sicily (Hybleans and Palermo), and Sar-dinia (Alghero), and the volcanic rock aquifer of the island of Ischia, facing Naples (Corniello et al. 1994).

Over the last forty years, the increased population in coastal areas has exacerbated saltwater encroachment especially during the dry Mediterranean summers, when the tourist population, as well as agricultural water demand, reach a peak.

The deterioration of groundwater quality has also led to soil salinization locally, forcing farmers to switch from profitable to less remunerative but salt-resilient crops.

MANAGEMENT

In Italy, surface and groundwater are the property of the state and are distributed by state agencies upon specific authorization. A licence is required from local water authorities to abstract groundwater on privately owned land, but a great many wells are unauthorized.

A number of laws and regulations have been introduced to protect groundwater quality. The most important is the 319/1976 act, "Regulations to protect water from contamination", together with the "Criteria, methods and regulations for implementing art. 2 of the 319/1976 law", enacted in 1977. It was only in 1985 that legislation was enforced on drinking water quality (DPCM 08.02.1985), based on the 80/778/EC directive on drinking water standards. But the most forceful legislation in this regard is DPR 386/1988, which implements the EC directive 80/778. It concerns recommendations for national standards and permissible limits, and introduces water protection areas and related framework statements for control and policy.

The act also provides for full technical regulation. In late 1988 the Ministry of the Environment set up a commission of experts to undertake this task. The terms of reference cover general principles; Protection areas for wells, springs and surface water sources; hydrogeological surveys and reports; land-use regulation and human activity control; protection areas for drinking water sources; vulnerability maps; Analysis and central organisation; disaster plans.

The work is nearing completion and this technical regulation will soon be included in Italian legislation.

Artificial recharge experiments have been carried out in Sicily, aimed at replenishing the severely depleted aquifer of Syracuse, and in southern Sardinia, to explore the possibility of creating hydronamic recharge barriers to counteract salt water intrusion in the aquifer of Capoterra, in the Bay of Cagliari. In the delta aquifer of the river Flumendosa, south-eastern Sardinia, electric barriers have been successfully tested to stem saltwater intrusion. (Barbieri *et al.* 1990).

The conjunctive use of surface water and groundwater is common practice, but the principle that water should be managed in terms of integrated resources balance, considering water quantity and quality for the different uses, has not yet been adopted in all regions, and very much still remains to be done to inform and convince people to save and manage water resources in the proper way.

To date, systematic water quality monitoring is only carried out in the coastal aquifers of Venetia and Romagna, while saltwater intrusion in other regions is investigated mainly within the framework of research projects.

Seawater desalination plants have been installed for integrating water resources in many tourist areas, especially on the islands, chiefly to secure drinking water supplies.

In accordance with current legislation, all waste waters should be treated before being discharged, and filtered and disinfected depending on how they are to be reused. Industries in Italy have been using recycled water for several years in a number of coastal and inland areas, so as to increase groundwater availability for drinking water. The water treatment plant at Genoa recycles 5 Mm^3/year.

The severe droughts that southern Italy has been experiencing since the mid 1990’s, have prompted interest in wastewater reclamation and reuse for irrigation. Successful trials have been carried out in Sicily and in Sardinia, where experiments are currently under way on a variety of soil types cultivated with different crops. A comparative analysis of different irrigation techniques is in progress with a view to convincing and advising farmers to adopt the best practices. The results are encouraging and farmers are much less sceptical about wastewater reuse for irrigation. Long distance water transfer has long been practised in southern Italy for securing both drinking and irrigation water supplies; suffice it to mention the Roman aqueducts, which are still in operation today. To alleviate the effects of drought, a number of reservoir systems have recently been interconnected in southern Italy and particularly in Sardinia, despite its rugged topography.

So far, water rationing is the most common measure for mitigating water scarcity problems. Wastage and losses from leaking aqueducts are significant, especially in southern Italy, and the cost of water is partially subsidized.

CASE STUDIES

Venetia

Sand layers bounded by silt and clay strata constitute the Venice multi-aquifer system, with depth down to 1000 m (Quaternary basement). Moving northwest, towards the foothills of the Alps, the sedimentary structure tends to change. Materials become increasingly coarser, while the aquitards become shallower, eventually petering out. The unconsolidated deposits in the foothills belt form a homogeneous system of sand and gravel. For the hydrologist, the system constitutes the reservoir supplying the aquifer-aquitard system extending beneath Venice and even further below the Adriatic Sea (Conti *et al.* 2000; Zuppi & Sacchi, 2003).

The Venetian aquifer system consists of six aquifers, four of which are extensively exploited (2nd, 4th, 5th and 6th). Hydrogeological maps of the phreatic and confined aquifers show a general southward flow direction. Water heads at sea level or below are found in the southern sector of the Schio-Vicenza tectonic line extension. Saltwater wedges have also been studied by combining geophysical investigations with groundwater physical-chemical parameters, namely electrical conductivity and temperature.

The extent of seawater encroachment is only known to the south of Chioggia, where the ground elevation of the littoral sector is up to three m above sea level. Dune belt and palaeo-littoral strip sand formations constitute a well-developed phreatic aquifer with a fresh water body, up to 10 m deep, floating on salt water. Seawater contamination af-fects aquifers and aquitards below the fresh water body down to a depth of 70 m. Inland there is an area of reclaimed land at an elevation of -2 to -3 m below sea level, thus groundwater has to be pumped away to keep the water table below land surface. The critical ground elevation, drawdown and seawater inflow into the rivers during high tides all contribute to seriously diminishing the fresh water body and salination of agricultural land. Conversely, several piezometric depressions caused by groundwater overexploitation in the past (1950's, 60's and 70's) are evident in the northern portion of the above-mentioned tectonic line, like for instance around Marghera, Venice. Though close to the Venice lagoon, these depressions do not cause inland saltwater encroachment because of the high hydraulic head of the groundwater flowing from the Alps and the significant lateral recharge from the streams in the Venetian plain. In this case, saline intrusion is related to the different geomorphology of the littoral and inland sectors.

Apulia

In Apulia groundwater exploitation has resulted in extensive water quality degradation due to salt-water intrusion and contamination caused by major industries and the widespread use of chemicals in agriculture. The territory has been divided up into four hydrogeological units: Gargano, Tavoliere, Murgia and Salento, as shown in figure 2 along with their water balance parameters referred to a climatic time serie up to 1980.

Figure 2. Water balance of the hydrogeological units of Apulia. P= average yearly rainfall (mm); E_T =average yearly evapotranspiration (mm); average yearly recharge inflow (m^3/s); possible average yearly withdrawal(m^3/s) After Tulipano, 2001).

Owing to the heterogeneity of the carbonate sequence and also to the discontinuities generated by intense fracturing and karstification, the hydrogeological characteristics are very complex and diversified (Grassi et al. 1977).

Gargano behaves almost as an island, because of the length of its coast in relation to total land area. The majority of the terrains near the water table are highly permeable, hence thickness of the fresh water lens is limited because of its low hydraulic head. The well developed karst system favours the mixing of waters with different salt content. The cretaceous karstic limestones between Foggia and the Gargano are almost all invaded by seawater, which at low depth is present throughout the area owing to low groundwater head.

In Murgia, seawater has encroached to a depth of several hundred metres below sea level and in Salento the lens-shaped aquifer tapers towards the Adriatic and Ionian coasts of the peninsula. Preferential flow lines are at different levels, depending on the karst (Tulipano, 1976). Actually, from the lithological point of view Murgia and Salento form one substantially similar system consisting of Mesozoic carbonate rocks, but permeability is lower in Murgia, so that two distinct aquifer units have been distinguished (Alaimo *et al.* 1988). The "Soglia Messapica" represents the morphological, structural and hydrogeological boundary between Murgia and Salento within the same carbonate platform (Grassi & Tulipano, 1983). In fact throughout Apulia fresh groundwater floats on top of seawater and discharges into the sea through subaerial and subaqueous springs (Brondi et al. 1983).

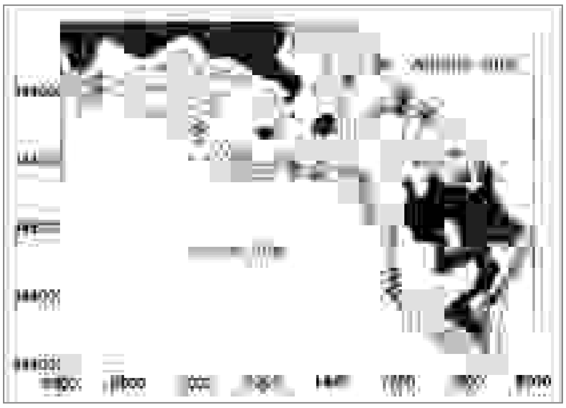

Figure 3. Contour lines representing saltwater content (g/l) in Apulian aquifers (After Tulipano, 2001).

Since the early seventies, the equilibrium conditions between fresh and saltwater have been changing as groundwater abstraction increases, to the extent that vertical flow has been detected in wells piercing groundwater levels with different salinity at various depths. Water head, temperature and salinity variations over time versus depth have been measured over a long period in a number of observation wells drilled for research purposes and in many other irrigation wells. These measurements have enabled to identify the main sources of saline contamination. Contamination is also related with the high degree of vertical anisotropy. Temperature proved to be an excellent tracer in recognising the main hydrogeological pathways and their interconnections, as well as in the identification of those factors strongly influencing the evolutionary processes of saltwater contamination of fresh groundwater. (Cotecchia et al., 1981; Tulipano & Fidelibus, 1986). Salt water intrusion in Apulian coastal aquifers is evident in figure 3.

The saturation attained by groundwater as a consequence of karst processes and fresh/saltwater mixing processes has been evaluated by hydrochemical determinations. Significant values of the characteristic ratios rCa/rMg, rMg/rNa, and rCa/rNa have been found considered to mark the limits for the change from over- to undersaturation also determined by a given value of Sr^{2+} concentration, at least for the groundwater in the zone under consideration (Tadolini et al., 1982). The chemical and isotopic features of waters drained from coastal springs, through which groundwater of the Apulia karst carbonate and coastal aquifer flow into the sea, are mostly affected by mixing phenomena between fresh and intruding seawater. By analysing certain chemical parameters intruding seawater could be differentiated, as a function, above all, of the different residence time of sea water in the aquifer. By comparing the isotopic characteristics of mixed water with the isotopic composition of groundwater of marine origin, it was possible to trace the original isotopic composition of the supply waters (Fidelibus & Tulipano, 1986).

Tuscany

In all Recent coastal plains of Tuscany ground-water is affected to a greater or lesser extent by saltwater intrusion, as shown in figure 4 (Bencini & Pranzini, 1992). The situation is still acceptable in the Versilia and Pisa plain, but this phenomenon is a major cause for concern in the Corna, Ombrone, and Albegna plains, Castiglione della Pescaia, and in the Isle of Elba. Saltwater intrusion is threatening water supply, mainly in the summer when the influx of tourists swells the resident population. Groundwater supply has to be rationed locally, and for agricultural use with the result that profitable strawberry production has had to be abandoned in favour of tomatoes because of water and soil salinization. In some places agricultural activities may well have to be abandoned altogether within the next ten years. Coastal pinewoods are also suffering because of high salinity levels. In the delta plains of the rivers Ombrone and Albegna, where more than 4000 irrigation wells are known to exist, values of $T=10^{-2}$ -10^{-3} m^2/s and a storage capacity (coefficient) $S= 1.22 \times 10^{-4} \div 6.1 \times 10^{-6}$ have been evaluated. The aquifer is recharged by direct rainfall infiltration and lateral inflow from the piedmont deposits. Groundwater table was above sea level in 1985 in undisturbed conditions, while there a significant drawdown to below sea level was observed in 1984 during irrigation. In autumn 1994 the drawdown appeared to have diminished considerably as the result of the less intensive aquifer exploitation for irrigation and an increase in withdrawals to secure domestic water supplies

Figure 4. Saltwater intrusion in Tuscany. 1:coastalplains; 2: areas affected by groundwater salinization (After Bencini & Pranzini, 1992).

for camp sites and private housing (Pranzini & Bencini, 1996). Salinity generally increases between spring and autumn in those areas where groundwater exploitation is intensified in summer, even at some distance from the sea.

Groundwater has been classified as follows:

- Sulphate-alkaline-earthy waters are the most common, owing to 1) leaching of gypsum formations, 2) uplift of thermal waters from an underlying Triassic evaporitic aquifer
- Chloride-alkaline waters, clearly associated with seawater intrusion
- Chloride-alkaline-earthy waters.

Bicarbonate alkaline-earthy waters, usually the most common, are poorly represented.

Isotope analysis inland (correlation Cl^-– ^2H e Cl^- – ^{18}O) shows a tetrapolar system consisting of:

1. local recharge pole with direct infiltration, also from irrigation or stream losses
2. palaeowater pole, with regional recharge, slowly infiltrated into deep aquifers
3. pole of deep thermal waters
4. sea pole, with present or fossil waters

Regulating exploitation of groundwater resources and recharging with river water have been suggested as the main actions for controlling saltwater encroachment and soil salinization (Pranzini & Bencini, 1996).

Latium

The entire coastal plain is affected to a greater or lesser extent by saltwater intrusion, from Maremma southwards to the Pontina plain. An intensive field campaign has recently been launched and an observation network has been set up comprising a number of wells for logging temperature, conductivity and salinity (Sappa, 2003, in prep.).

Sicily

Chronic scarcity of water has always posed insurmountable limitations to the intensive development of Sicily's vast land areas. Overexploitation of the island's groundwater resources has resulted in saltwater intrusion in numerous areas forcing farmers along the coastal strips to irrigate with brackish water.

The coastal karst aquifer of Siracusa –Avola suplied by lateral inflow from the Hyblaean mountains, on the west coast, is representative of this situation (Aureli, 1991).

Groundwater development in the lower-level zones of the mountains has led to the disappearance of many subaerial and submarine springs emanating from the karst aquifer, and has greatly diminished the outflow of others. The aquifer has lost its artesian characteristics almost everywhere and shows evidence of significant seawater intrusion. Where submarine springs have been identified. In the space of 20 years, the groundwater water table has dropped by as much as 100 m and more, especially in the Priolo-Augusta area, north of Siracusa, where the present water table lies at between 50 and 100 m below sea level. Artificial recharge experiments have been conducted in an attempt to stem sea-water intrusion.

Along the 37 km long coast, a block of Hyblaean Oligocene-Miocene limestone, displaced by faulting is overlain by a formation of Pliocene and Pleistocene marine and continental sediments with interbedded volcanic rocks.

Average rainfall varies between 413 and 949 mm, depending on elevation, which ranges from 15 to 390 m above sea level. Groundwater flows as springs scattered along the coast from the Mio-Pliocene formation, that hosts a secondary aquifer laterally supplied by the major underlying karstic aquifer, hence groundwater flow exhibits artesian conditions locally. Total average yield of the 108 subaerial springs of the area was 906.8 l/s, but a recent survey has shown their yield to have decreased significantly owing to the drawdown in 339 wells exploited for drinking and irrigation water, with the result that a number of springs have disappeared. When the karstic aquifer water table is drawn down by well pumping, submarine springs disappear and seawater intrudes along their conduits. The yearly recharge of the aquifer was assessed at 143 Mm with average annual losses into the sea estimated at 34 Mm^3, equal to a runoff of 1080 l/s.

Sardinia

There is increasing evidence of seawater encroachment in the coastal aquifers of Sardinia, especially in areas developed for tourism and/or intensive agriculture. The examples given below concern areas where systematic investigations are in progress.

The Muravera coastal plain, formed in south-eastern Sardinia, Italy, by the river Flumendosa, the island's second largest river, consists of Pleistocene and Holocene alluvium up to a few hundred meters thick, overlaying a complex metamorphic and granitic Palaeozoic bedrock cropping out at the edges of the plain (Barbieri et al. 1983).

At least two aquifers have been identified: the shallow phreatic aquifer, down to a few tens of meters deep, and a deep confined aquifer, whose structure is still not completely known. The two aquifers are separated by a clay layer, from a few to several tens of meters thick. Minor aquifers are represented by series of fractures draining the bedrock (Barbieri *et al.* 1986).

The natural hydrodynamic equilibrium between the ground- and surface waters flowing into the river and some of its old channels, now partly silted up and disconnected from the main one, and the sea has been deeply modified by man since the early fifties. The river and some of its main tributaries were dammed upstream, so that the natural recharge of the coastal aquifers has now decreased significantly, and the mouth channels, which once drained groundwater, now contain salt water coming directly from the sea. Furthermore, the phreatic and deep groundwaters are increasingly exploited through excavated and drilled wells to meet the ever growing water demand for agriculture and domestic uses, mainly in the summer. This situation is exacerbated by the recurrent drought that has afflicted Sardinia in latter years. The area is of major environmental interest and its economy, that relies heavily on agriculture as well as tourism and aquaculture along the coast, is jeopardized by salt water intrusion.

The trend of saltwater intrusion has been studied for more than twenty years through repeated campaigns of systematic hydrogeological, geochemical and geophysical investigation.

The study involving hydrogeological, geognostic and geophysical investigations and chemical analysis, conductivity and temperature logging, enabled to characterize the aquifers in the plain in geometrical and hydrodynamic terms. Preliminary geophysical investigations consisted of resistivity and induced polarization (I.P.) vertical soundings. Aclose relationship was established between salinity, resistivity and chargeability and as a result the extension and depth of the fresh, brackish and saltwater bodies have been defined in detail (Barbieri et al. 1988; Ranieri *et al.* 1988).

Piezometric and groundwater quality monitoring carried out periodically over the last two decades has indicated widespread and progressive saltwater encroachment, interpreted as due mainly to lateral intrusion, interface upconing, and spray. As a result, extensive tracts of farmland in the coastal plain have become unusable because of increasing groundwater and soil salinization.

In the late 1980's, experiments were carried out in order to counteract soil salination hazards and protect groundwater resource quality. This barrier, previously tested in a physical laboratory model, was placed in the field by setting energized electrodes parallel to an old salted distributary of a delta system. The electric barrier in alternating current, designed to check seawater encroachment and successfully experimented in the laboratory, proved to be quite efficient also in the field. In fact all experimental tests, performed under conditions of steady state continuous pumping, showed an appreciable TDS decrease throughout the whole study area up to a maximum of 22.2% downstream from the barrier in the nearest observation well (Barbieri et al. 1990).

A comprehensive programme of geophysical surveys, drilling campaigns and monitoring has recently been planned in order to define in detail the hydrogeological and conceptual model of the plain's complex aquifer system. Some important aspects such as depth of bedrock and the valley's main structural features have recently been determined by means of geophysical investigations, consisting of gravity and seismic reflection surveying, carried out in the plain by the Department of Land Engineering of Cagliari University. Furthermore, shallow seismic reflection surveys, combined with electrical methods, proved to be effective tools for determining the heterogeneous characteristics of the confined aquifer and the complex stratigraphy of the plain (Ardau et al. 2000). The entire data set has been reexamined in the light of the findings of recent geological and geophysical investigations, consisting of a gravity profile, a few drillings and laboratory measurements on rock samples, with a view to deriving more reli-able geological and hydrogeological interpretations (Ardau *et al* . 2002).

The flood plain of Capoterra is located in the south-western portion of the Campidano graben, bounded on the western edge by granite hills and on the south-eastern edge by the Mediterranean Sea, and the Santa Gilla lagoon and saltworks. The geological formations are, from top to bottom, piedmont deposits, fluvial and lacustrine sediments, recent and ancient terraced Quaternary alluvium, and fractured granites and metamorphic schists of the Palaeozoic. The recent alluvial deposits are very permeable and contain a phreatic aquifer, overlaying another multilayer aquifer system, semi or locally confined (Barrocu *et al.* 1994).

The hydrogeological model of the area is highly complex due to natural factors such as geology, the nearby sea, the presence of the lagoon and saltworks of Santa Gilla, as well as human activities such as increasing industrial expansion. Hydrogeological and hydrogeochemical measurements were taken at the observation wells of the control and monitoring network present in the plain. The results demonstrated that the two aquifers are laterally recharged from the west through the major fractures of the bedrock, striking ENE-WSW and WNW-ESE, and the fresh waters of the two aquifers are similar to each other and closely related to the groundwater of the crystalline bedrock.

Saltwater intrusion is caused by natural processes, such as long periods of drought, or is human induced for example by aquifer overexploitation. The results of chemical analyses have shown a greater increase in salinity in the phreatic aquifer than in the confined one. The salinity of the confined aquifer is due to seawater intrusion in the area where groundwater is overexploited to meet agricultural and industrial demands. In the phreatic aquifer salination is also due to brackish water encroachment from the lagoon and saltworks, and the direct infiltration of salt deposited on the soil by wind borne spray from the saltworks

Pumping tests and artificial recharge experiments have been carried out in the plain aimed at verifying the efficiency of a hydrodynamic barrier in checking saltwater encroachment and its spatial evolution. An artificial recharge test has been carried out in the coastal aquifer system, by means of a drainage trench on the surface phreatic aquifer, and through wells drilled into the underlying confined aquifer. Piezometric levels were controlled in both aquifers by observation boreholes. As no other water source is available, the artificial recharge was carried out using treated wastewaters from the treatment plant of the Consortium for Cagliari Industrial Development Area (CASIC). The effects of artificial recharge on groundwater quality have been evaluated and the model developed for flow and transport processes in artificial recharge validated.

The mathematical model of saltwater intrusion in aquifers was 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 (transport equation). Flow and transport equations are coupled by means of a constitutive equation relating density of the fresh water-saltwater mixture to its salt concentration. The numerical solution of these nonlinear equations involves spatial discretization with the finite elements method following Galerkin's approach, and time discretization using finite differences. (Barrocu et al. 1997) (figure 5).

The information acquired during hydrogeological studies in the Capoterra alluvial plain were organized into a G.I.S. for the purpose of modelling saltwater intrusion, as in the procedure shown in Figure 5 (Barrocu, et al. 2001).

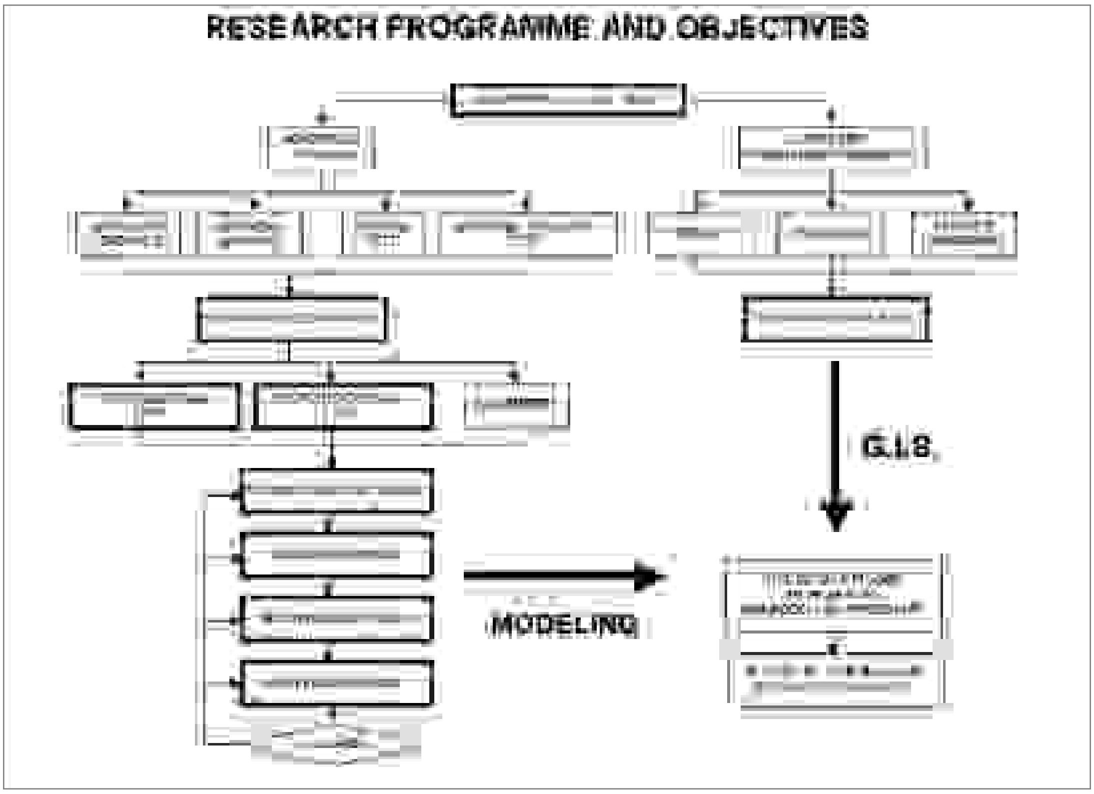

Figure 5. Research programme carried out in the coastal area of Capoterra, southern Sardinia (After Barrocu et al. *2001).*

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