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Seawater intrusion and coastal groundwater resources management. Examples from two Mediterranean regions: Catalonia and Sardinia

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Summary. Seawater intrusion is a natural phenomenon that allows the encroachment of saline water into aquifers. Nevertheless, many human actions along the coastline, in particular groundwater withdrawal, enhance this process and finally cause the salinization of groundwater resources. Here we review the hydrogeological basis of seawater intrusion and describe specific cases in Catalonia and Sardinia, as examples of environmental problems and water management actions. We emphasize the origin of salinization and the hydrogeological details of each case, as well as the solutions that have been implemented to prevent groundwater salinization. [**Contrib Sci** 10:171-184 (2014)]

Introduction

For centuries, groundwater resources have been strategic aspects of the socio-economic development of coastal areas. Agriculture, urban development, and industrial growth have benefited from the availability of both surface water and groundwater. Nevertheless, because of the scarcity of stream discharge and the easy availability of groundwater on most of the coastal plains subsurface resources have become crucial to satisfy human water needs. In arid areas, such as those along the Mediterranean coast line, the exploitation of groundwater has enhanced the water supply, especially during the last century, when the development of high efficiency pumps were able to provide enough water meet demand [43]. Moreover, access to groundwater resources boosted economic growth by increasing crop planting and extending

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urban areas. Touristic activities started in the decade of 1960 and were based on an arguable model that led to urban sprawl (mostly in previously small villages with limited infrastructure) and did not consider environmental issues such as water resources management in their planning requirements. Therefore, high water consumption was usually not a limiting factor: wells were drilled and surface water was diverted to fulfill these seasonal needs.

The impact of this rapid and severe exploitation of water resources is a loss of water availability and quality. Today, this is a major managing concern in attempts to guarantee a supply while preserving the hydrological and environmental status of surface water bodies and the quality of groundwater, as defined by European directives (e.g., Water Framework Directive, Directive 2000/60/EC; and Groundwater Directive, Directive 2006/118/CE). Among the distinct processes that contribute to the deterioration of coastal water resources, seawater intrusion into aquifers is probably the most common process affecting Mediterranean groundwater resources. This situation has challenged the sustainable development of coastal areas, as stated by the United Nations Environmental Programme, such as the Mediterranean Action Plans (http://www.unepmap.org/), which in its Protocol on Integrated Coastal Zone Management in the Mediterranean (2008) explicitly express concern regarding seawater intrusion.

In general terms, seawater intrusion is the occurrence of seawater in fresh groundwater. This wedge of saltwater inland from the coast line is a product of the distinct densities of saltwater and freshwater. In addition to the density ratio, aquifer properties, such as hydraulic conductivity, and the groundwater hydraulic gradient near the coastline, determine the geometry and extent of the intrusion wedge. However, this natural process can be made worse by human activities. Groundwater withdrawal in coastal aquifers lowers the water table (or the piezometric surface) in the vicinity of the shoreline below sea level, allowing the interface between seawater and freshwater to advance inland [14]. All coastal aquifers around the world suffer from seawater intrusion [1] to some degree. However, in many cases, after years or decades of exploitation their water resources have become useless to meet human needs. Other human pressures, such as gravel and sand mining from streambeds, and alluvial formations also contribute to the salinization of water resources [45].

Seawater intrusion obliges all coastal areas to search for alternative resources while aquifers recover, if possible, their quality. These alternatives usually involve long-distance water transfers between basins, finding deeper good-quality groundwater levels (which may also be vulnerable to future salinization), or building desalination plants. However, while the latter partially solve the problem of freshwater availability, they raise other issues regarding water prices, energy costs and environmental concerns.

Here we review the fundamentals of seawater intrusion into coastal aquifers, the effects of groundwater withdrawal on its development and inland progress, and the consequent deterioration of groundwater quality. Although salinization is, sadly, a widespread problem (Fig. 1), we limit our examples to two Mediterranean locations, the Catalan coastline and the island of Sardinia, to describe the extent and particularities of seawater intrusion, its present status in these locations, recent management actions, and future threats based on demographic growth, land-use changes (such as increasing urbanization), and seawater rises due to climate change.

Some fundamental aspects of seawater intrusion in aquifers

Geological controls. The occurrence of seawater intrusion in a particular coastal region depends on its geology. Aquifer lithology and structure will determine the region's hydrogeological behavior and therefore the balance between groundwater flow from the continent to the sea and the buoyancy effect of freshwater on seawater along the immediate coastline. Coasts with crystalline rocks, whether igneous or metamorphic (i.e., those whose porosity is basically due to fractures), will typically have lower hydraulic conductivity values, such that seawater intrusion will be restricted. Nevertheless, the effect of pumping will enhance seawater encroachment, especially if flow takes place along fractures as preferential flow lines. This may create deeply penetrating seawater wedges.

Furthermore, coasts on sedimentary consolidated rocks offer a large variety of potential seawater intrusion scenarios. From the occurrence of fine-grained layers (clay, silt) of low hydraulic conductivity to the outcropping of carbonate formations (with well-developed karst), the extent of the intrusion wedge may significantly vary as a function of the stratigraphic sequence, its structure, and its hydrogeological behavior. Carbonate formations are extremely common along the Mediterranean coast [24]. Their porosity is organized in cavities whose volume may extend over several orders of magnitude. Karstification may naturally allow a profound inland intrusion of seawater, which will become even worse if

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Fig. 1. Main seawater intrusion sites along the Mediterranean coast, according to the EEA (2006) report "The changing faces of Europe's coastal areas". The map clearly shows a common threat to groundwater resources. Despite it is not shown in the map, the density of seawater intrusion affected areas is similar all along the coast of the northern, eastern and southern rims of the Mediterranean basin.

pumping takes place near the shore. Conversely, carbonate coasts may also include submarine springs, in which freshwater flows through preferential paths via a series of well-connected cavities and/or fractures and then discharges into the sea.

The effects of seawater intrusions on human water needs are most obvious in deltaic areas. Deltas mainly consist of unconsolidated sediments and typically show a complex stratigraphic architecture defined by recent (Holocene) sea-level oscillations. Their stratigraphy determines both vertical and lateral heterogeneities that depend on the history of the combined balance between river dynamics, sea processes, and eustatic changes. Because of their flat topography, deltas have been ideal sites for human activities and development. This implies intensive water use and, therefore, enhanced seawater intrusion. Examples can be found in the delta regions of the major Mediterranean rivers, including the Nile, Po, Rhône, and Ebre, and on thousands of smaller drainage basins located in coastal massifs whose streams create seaside plains using the transported sediments. Furthermore, the equilibrium between inland and coastal processes gives rise to wetlands, as areas of great ecological and environmental value, that strongly depend on the local groundwater flow system. Seawater intrusions induced by the over-exploitation of groundwater may severely damage the balance between water resources and ecosystems.

Hydrological features of seawater intrusion.

The contact between freshwater and seawater has been usually represented as a sharp interface that, for the sake of simplicity, assumes that the two liquids are immiscible. This is certainly not the case, as they are indeed miscible and a transition zone between pure seawater and freshwater is accordingly established. Aquifer heterogeneity and hydrodynamic dispersion will determine the shape of this transition zone. Nevertheless, all common approximations that estimate the location and shape of the seawater-freshwater border are based on the Ghyben-Herzberg formula and its subsequent improvements by many authors [15,16,30].

The work by Badon Ghyben [5] and by Herzberg [38] is based on a conceptual model that assumes static equilibrium of freshwater with stationary seawater, a horizontal flow in the aquifer, and a sharp interface. Under these conditions, the weight of a column water of freshwater extending from the water table to the interface is balanced by a column of saltwater extending from sea level to the same depth on the interface (Fig. 2), expressed as:

$$\rho_s g z_s = \rho_f g \left(z_s + z_f \right)$$

where, ρ is the water density, g is the acceleration due to gravity, z_s is the depth of the interface from the sea level, z_f is the elevation of the water table above the sea level, and s and f stand for seawater and freshwater, respectively. Solving for the interface depth

$$z_s = \frac{\rho_f}{\left(\rho_s + \rho_f\right)} z_f = \beta z_f$$

where β is the density contrast parameter; which for ρ_s = 1.025 g/cm^3, and ρf = 1.0 g/cm^3, yields a linear relationship $z_s = 40\, z_f$. Therefore, the natural interface mimics the shape of

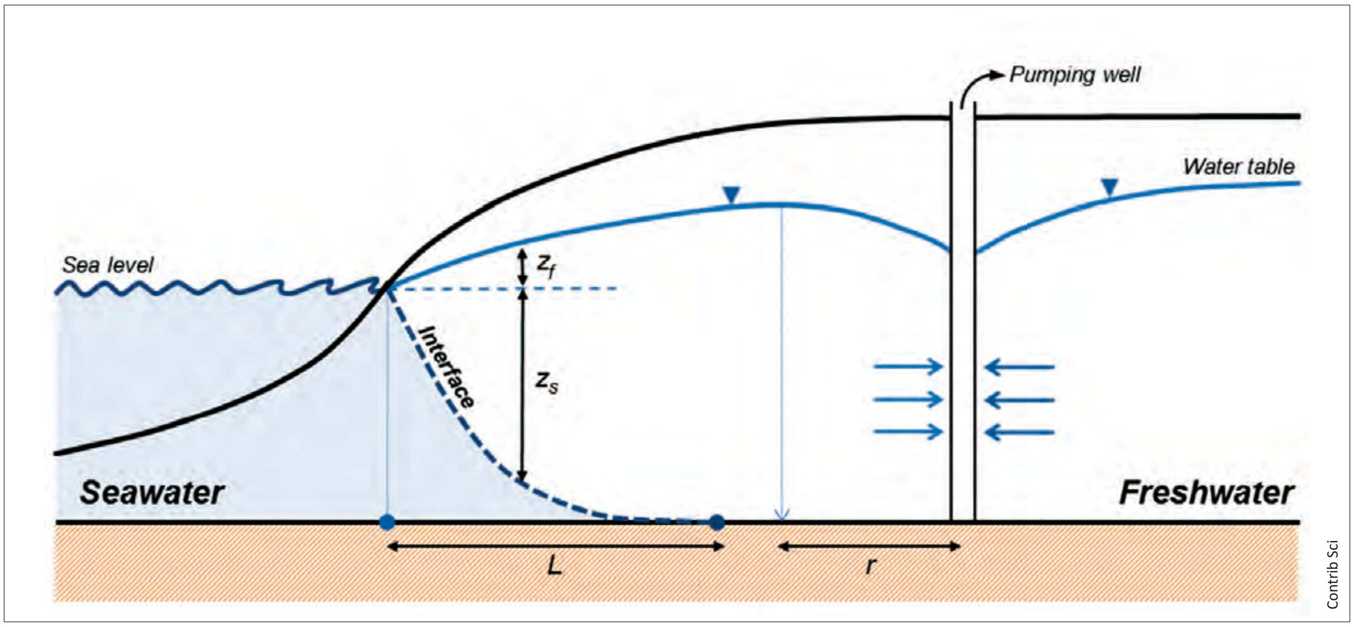

Fig. 2. Scheme showing seawater intrusion phenomena, with the location of the salinity wedge (interface) below the coastline indicating two distinct hydraulic conditions: left, a natural scenario, and right, the effects of a pumping well. Variables Z_f and Z_s correspond to the water table elevation and the interface depth, respectively. *L* indicates the location of the wedge toe (see text for explanation). On the right side, a pumping well produces a cone of depression that still does not generate seawater intrusion. If the cone radius (*r*) reaches the wedge toe, seawater will flow into the well and salinize both its discharge and the coastal side of the capture area.

the water table, and its location below sea level at a given distance from the coast line is 40 times below the height of the water table above it. Its maximum depth is limited by the lower boundary of the aquifer. However, this simple relationship ignores the vertical flow component near the interface and the seepage face above sea level that develops in phreatic aquifers [59]. Indeed, the distance from the coastline (*L*, in Fig. 2) that represents the extent of salter intrusion is a decisive factor in the management of a coastal aquifers, which under natural conditions are controlled by continental groundwater flow. The drawdown caused by wells and their intense use interferes with and reduces the natural flow, thus generating a saline up-coning below the wells. This vertical rising of the interface towards the pumping well screen [15] finally increases the volume of the aquifer affected by salinization.

The Ghyben-Herzberg formula is the basis for other estimations, including rainfall recharge and pumping near the shore. The effect of pumping wells on the regional flow field in a coastal aquifer and, more importantly, the shape and position of the interface in steady, essentially horizontal freshwater flow were taken into account in the work of Strack [60]. In this approach the critical pumping rate for a single well that retains the seawater wedge at a location far enough from the capture zone of the well can be estimated. An increase beyond the critical pumping rate will bring the wedge closer to the well and thus increase the risk of well salinization. Following Strack's approach, other authors have developed analytical solutions to solve for more complex hydrogeological scenarios in coastal areas [18,19,47,53,54].

However, if we consider the interface as a transition zone, the quality of the withdrawn water is likely to decline even before the point predicted by the analytical models. The effect of mixing under stationary conditions due to salt diffusion in a confined aquifer, also known as Henry's problem, reveals the importance of other, density-related phenomena—and the oversimplification of model based on a sharp interface—on the understanding of seawater intrusion. Pool and Carrera [57] showed that previous approaches based on a sharp-interface and static salt water underestimated the critical pumping rate and overestimated landward seawater penetration. Therefore, because of salt dispersion across the interface the actual seawater intrusion wedge shape will deviate from the predictions of simple, commonly used analytical solutions.

The effect of wells on the seawater interface necessitates external actions to influence groundwater balance and to modify the hydraulic head distribution near the shore such that the intrusion of seawater is contained. Enhancing water infiltration, whether by artificial recharge at the surface or injecting water, and restricting the pumping rates are among the common approaches used to control and restrict the landward advance of the interface [42]. However, these are not always feasible, as alternative water volumes, such as reclaimed wastewater, and land-use changes may be required, or water demand cannot be fulfilled from other areas or sources. In this case, the use of seawater barriers, based on a controlled management of the water levels using pumping wells, injection wells, or even both type of them, represent successful and viable ways to efficiently reduce seawater intrusion when other options are not possible [56].

Examples of seawater intrusion in western Mediterranean aquifers

Seawater intrusion at the Catalan coast: Extent, impacts and remediation actions. The Catalonian population is highly concentrated along the shore line. Whether due to urban development, especially in Barcelona and Tarragona, in the past, the more recent expansion of tourist activities all along the coastline, or to agricultural uses, groundwater exploitation has induced seawater intrusion for many decades. Most of it concentrates on fluvio-deltaic areas, as such of those of the Muga, Fluvià, Ter, Tordera, Besós, Llobregat, Gaià and Francolí Rivers and, finally, the Ebre Delta coastal system, (Fig. 3). Seawater intrusion in other hydrogeological formations, such as carbonatic rock aquifers, also occurs in Catalonia, for example, in the Montgrí, Garraf and Vandellós massifs [26,48]. Moreover, mobilization of connate or brackish water located in aquitards and low permeability formations may also be removed under the influence of pumping and cause the additional salinization of groundwater [13,44].

The most paradigmatic cases, however, mainly involve deltaic areas. They have the common initial scenario in which severe groundwater withdrawal for urban, industrial, or agricultural use induces high salinity in the groundwater. This forces managers to look for alternative water supplies but also to implement actions to satisfy human demand while protecting groundwater resources and restrain the advance of seawater encroachment.

The Muga and Fluvià fluvio-deltaic areas. Located in the northeastern part of Catalonia (Girona province), the intense groundwater exploitation in the common deltaic area of the Muga and Fluvià Rivers is linked to the touristic development of villages such as Roses and Cadaqués and to the urban sprawl of Empuriabrava, during the decade of 1970. As a result, seawater intrusion affected the unconfined and leaky aquifer that constitutes this deltaic formation [4]. Wells were placed in a leaky aquifer at an approximate distance of 3 km from the coastline. The withdrawal rates during the summer months increased from 0.31 Hm^3 in 1976 to 0.43 Hm^3 in 1986. By the time groundwater exploitation had stopped, in 1986, the chloride concentration in the water had increased to > 1,500 mg/l, making it unsuitable for urban supply [46].

To address this situation, while drilling more wells was rejected by the local administration, an existing irrigation channel was modified and used to divert water from the middle course of the Muga River, at a distance of 20 km from the coast. The Muga River discharge is regulated by the Boadella dam as the main supply for domestic demand and agriculture as well [33,55]. This solution is still in use, which highlights the need for detailed hydrological planning in the Muga basin to fulfill both agricultural and urban demand. Nevertheless, during the summer of 1999, demand could only be met by the additional use of groundwater [64]. After years of well rest, groundwater levels and quality had recovered in the leaky aquifer, and groundwater resources are now suitable for contributing to high demand peaks.

The Tordera Delta area and the first desalination plant in use. The history of this area is similar to that the Muga area: larger groundwater withdrawal associated with the growth of urban touristic areas whose water needs added to the already existing agricultural demand. Enduring groundwater levels below sea level in both the unconfined and deeper leaky aquifer layers, even several kilometers inland, were responsible for the drying out of the Tordera watercourse and the salinization of groundwater resources (Fig. 4). Furthermore, nitrate pollution from fertilization practices and several episodes of organic compound pollution from nearby industrial activity jeopardized the urban use of the Tordera Delta's groundwater resources [21].

Because of this generalized loss of groundwater quality, the Tordera area was the recipient of the first desalination plant in Catalonia. It was designed to supply an initial annual volume of 10 Hm^3 (2003) and able to reach up to 20 Hm^3 in subsequent phases, which have not yet been implemented. Ten capture wells drilled into the sedimentary materials of the Tordera Delta and with a depth of 130–180 m are located at a short distance from the beach. Mean electrical con-

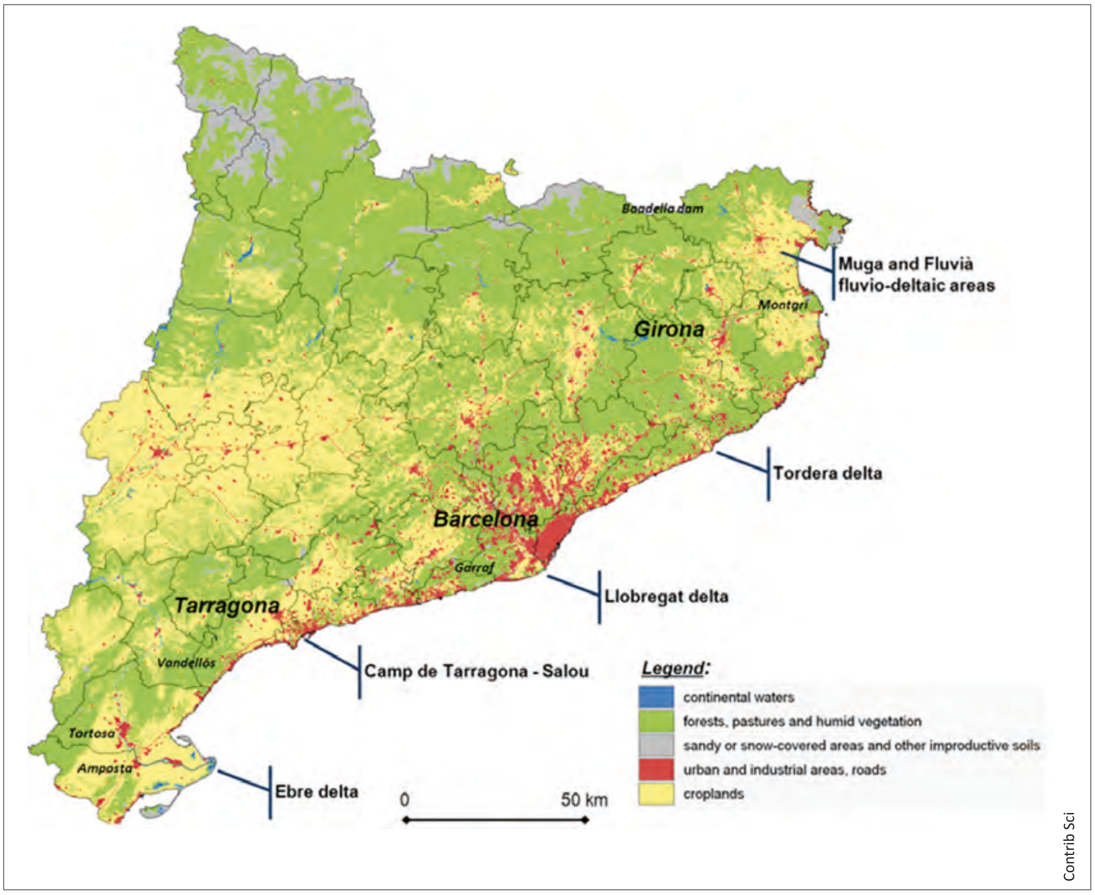

Fig. 3. Location of the described seawater intrusion case studies in Catalonia. A land-use map serves as a background reference to illustrate the intense urban and agricultural development along the coast line (*source*: Departament de Medi Ambient i Habitatge de la Generalitat de Catalunya, data from 2002).

ductivity (EC) is set at ~50 mS/cm (slightly higher than the usual seawater EC), although in some wells the EC was as low as 42 mS/cm during the first year of activity, raising concern about the hydrogeological origin of the captured groundwater [52].

The Llobregat Delta area and water supply to the Barcelona metropolitan area. The Llobregat Delta aquifer system is a well-known example of seawater intrusion. Groundwater exploitation in the delta area started in the 19th century to meet the needs of local agricultural activities, which are still economically important, and to supply residents of Barcelona. In the decade of 1960, the industrial development around Barcelona heightened the demand for Llobregat Delta groundwater resources. The result was significant seawater intrusion at all aquifer levels, driven by huge depression cones extending 25 m below sea level [62]. Seawater encroachment in the Llobregat Delta has been well investigated and described in many publications [23,25, 28,40]. Groundwater is still a major resource for agricultural and industrial activities, and it constitutes a major emergency reserve to supply the urban population.

Because of the strategic interest of groundwater and the importance of protecting it from exploitation, several actions have been undertaken to increase its recharge, improve its quality and reduce the extent of salinization within the aquifer, which covers about one third of the delta surface. These actions, led by local administrations as well as the user community (Comunitat d'Usuaris del Delta del Llobregat), include the following [49]:

(a) Enhance artificial recharge from the Llobregat River itself through periodic scarification and removal of the silty layers deposited in the riverbed. This action is being conducted at the upper part of the delta, upstream from the main exploitation wells (the annual infiltration is ~14.5 Hm^3).

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Fig. 4. Groundwater withdrawal near the coastline causes other impacts on the hydrological system in addition to seawater intrusion. The dry streambed of the Tordera River, near its mouth, is the result of the intense drawdown produced by pumping wells, which are also responsible for seawater intrusion in this area. This scene is common in many Catalan rivers (e.g. Muga, Ridaura, Foix, Gaià, Francolí) during the summer months and it persists until autumn rainfall events contribute to runoff and aquifer recharge.

(b) Injection of surplus treated surface water into the aquifer in order to increase water levels and improve groundwater quality. (Annual recharge oscillates between 5 and 15 Hm^3).

(c) Recharge from three ponds located in the upper part of the delta, with a total capacity of 6.3 Hm^3/year. These ponds are fed by surface water from the Llobregat River but they may also receive inputs from the Barcelona wastewater treatment plant, located in the delta area.

(d) The most important action is the creation of a hydraulic barrier to control seawater intrusion, which is expected to steadily increase in the near future [63]. The hydraulic barrier consists of a series of wells that will be able to inject 15,000 m^3 of treated wastewater/day. Before its injection, the reclaimed water is subjected to a tertiary treatment consisting of ballasted coagulation-flocculation, decantation, filtration and disinfection. Wells have been drilled at a depth of 70 m and they penetrate the complete thickness of the aquifer. Since the initiation of this action, in 2007, the chloride content has decreased progressively. The injected flow rate maintains head levels 1–3 m above sea level. Together, the high levels and the injection rates contain further seawater intrusion while also recharging water flows inland to the exploitation wells [50,51].

These efforts to reduce seawater intrusion in the Llobregat Delta are a valuable example of knowledge, investment and joint collaboration between administration agencies and users. The joint management of surface water and groundwater, the reuse of reclaimed water, and the implementation of engineering solutions are preserving groundwater resources, and improving their quality while also attaining several environmental goals, such as coastal wetland preservation, and securing traditional (agricultural) land-use within an intensely urbanized environment.

Tarragona area water resources and conflicts with industrial uses. The concentrated exploitation of water resources in the Camp de Tarragona due to urban and industrial uses created a huge salinity plume extending almost 10 km inland [13]. The geology of the area consists of the alluvial terraces of the Francolí River and the alluvial-fan-like deposits of Plio-Quaternary age, which constitute the main aquifer. At greater depth, Miocene conglomerates and Mesozoic carbonate formations constitute a fractured basement that shapes the geometry of the uppermost formations [31].

Salinity distribution in the area is highly variable. Salinity is highest in the Plio-Quaternary formations, where it depends on the exploitation intensity and on the sedimentary heterogeneity of this aquifer [22]. Water balances result in a deficit of about 14–18 Hm^3, which is compensated by seawater intrusion, especially in the area between Salou and Tarragona [41]. Groundwater chloride concentration in this area were as high as 9 g/l in the decade of 1970. However, after the major investments made in the decade of 1980, a surplus of surface water resulting from greater irrigation efficiency in the Ebre Delta region enable the transfer of water from the Ebre River (~80 km southward) to the Camp de Tarragona [27]. An annual average of 121.6 Hm^3, which covers 67% of the present demand, has highly reduced groundwater extraction and has lowered its salinity to < 1g/l. Salinity in the aquifer basement is mainly due to the overall low discharge of this system towards the Mediterranean, such that seawater intrusion develops naturally.

The Ebre Delta and its ecological, socio-economic and environmental fragility. Lowland coastal areas are especially vulnerable to water balances, which finally affect their quality. The hydrology of the Ebre Delta region is controlled by inputs from the Ebre River discharge, irrigation returns from the intense agricultural activity (rice) all along its surface and from the dense network of irrigation channels and the equilibrium with seawater, whether along the river channel or the subsurface.

The Ebre Delta is relatively recent. Most of its development took place during the last few centuries, related to climate change and deforestation. The delta constitutes a multi-layer aquifer system. The upper sand layer (6–8m thick) encloses rests of ancient lagoons and marshes as a result of delta progradation. It therefore encloses saline and hypersaline areas where groundwater salinities are usually >120 g/l. Groundwater withdrawal from this water-table aquifer is nil; yet a few wells at 50–80m depth, located in the main sedimentary body of the delta, provide water of appropriate salinity to allow aquaculture [13]. The shallowness of the carbonate basement in the inland areas of the delta permit an upward freshwater flux that appears as springs (locally named "*ullals*") that form small ponds whose salinity depends on the degree of mixing between this flux and the Quaternary aquifer resources [32].

Seawater intrusion in the Ebre Delta is thus limited to natural processes. However, the actual salinity balance in the delta groundwater resources reflects the weak equilibrium among geological features, the salinity of the river's surface water and irrigation practices. In fact, the Ebre River's salinity is due to inputs from the whole basin and, in the lower parts of the river, from the highly variable saltwater wedge, which under low flow conditions may penetrate the channel mouth upstream to Amposta (~25 km) or even to Tortosa (~35 km) [39,58]. This salinity allows lateral seawater encroachment into the alluvial aquifer [13]. Given these conditions, adequate management of the Ebre River discharge is essential to maintain the hydrological dynamics and water quality of the delta area and to preserve the socio-economic structure of its land but also its ecological value.

The salinization issue affecting Sardinia

Like most Italian coastal areas, saltwater intrusions along the coasts of Sardinia are generally attributed to the over-exploitation of aquifers [7]. The needs of a growing population, especially in summer, conflict with the reduced meteoric water resources available to fulfill the peak demands of residents and tourists. The use of groundwater depresses the hydraulic head and allow the movement of saltwater inland. The development of new urban areas and the expansion of traditional settlements have occurred in tandem with the loss of agricultural areas of primary interest such that conflicts regarding the allocation of water resources often arise between users [7,34]. The natural balance between the relationships of surface water and groundwater with the sea has been turned upside down. Because of poor management, the salinity of coastal waters has increased, which in turn has affected soils because of irrigation or the capillary rise of saltwater from water-table aquifers. This has forced farmers to forego the planting of valuable crops and to instead invest in those more resistant to salinity or, in the worst case, to abandon the land entirely [9].

As reported in the literature and based on a summary of research projects, groundwater salinization is ongoing in several areas (Fig. 5). Some of the most relevant locations affected by seawater intrusion are described in the following.

Asinara gulf. The Porto Torres and Turritana plains lie in the middle of the Asinara Gulf (NW Sardinia, Italy). The Porto Torres plain area covers 35 km^2 and includes the town of Porto Torres. In the decade of 1960, industrial development transformed Porto Torres from a fishing port into a manufacturing town. The size of the town's population increased rapidly. Together with the industrial demand for water this has increased the pressure on the supply of freshwater. Since the decade of 1970, ~25% of the town's drinking water supply has been provided from a system of wells, half of which are in continuous use in order to supply water at a rate of 40 l/s [37].

The most important coastal aquifer in terms of the local freshwater supply is located in the carbonate rocks of the Miocene succession. However, it is increasingly being degraded by salinization (2600–5000 μS/cm), mainly associated with intense groundwater over-exploitation [37]. Geochemical data strongly suggest that seawater encroachment is the major cause of the salinization. Over-exploitation of the aquifer is clearly evident near the coastline and has forced the water table to below sea level.

The Turritana plain area runs parallel to the coast for about 20 km, mainly in the Sorso municipality and with only a small part under the Sassari municipality. Overlooking the Gulf of Asinara is the natural seaside resort of Sassari. Until recently, the land was used chiefly for agricultural activities along the coast and main river valleys, but urbanization has been rapidly expanding. Several tourist resorts and the related infrastructure have been built along coastal roads, especially in the Gulf's eastern part, beyond the Silis River. Nonetheless, despite urban growth, the natural environment has not been compromised to any great extent, perhaps because of the more famous and better organized tourist centers located nearby.

The area consists of a long narrow strip of flat land that runs parallel to the coastline. It gently slopes to the northwest and along its eastern and southern edges are bordered by a series of a weakly terraced reliefs never exceeding 400 m above sea level. Isopotential contour lines seem to closely follow the local morphological features, with good local continuity between the phreatic aquifer within the Aeolian complex or the alluvial sediments along the main rivers and the aquifer occurring within the uppermost permeable layers of the Miocene sequence. This local continuity might explain the low salinity of the phreatic aquifers in the valley (about 1 g/l) and the fact that it does not seem to be caused by seawater encroachment. Progressively, nearer the coastline, salinity increases to ~1.5 g/l. In the central area of the inland plain, salinity reaches a peak of 4 g/l [20], which is likely attributable to water leaching from the fractured marl layers.

As for the confined aquifers, saline intrusion has been detected near the coast, but only in deeply drilled wells that have probably reached the freshwater-seawater interface [3].

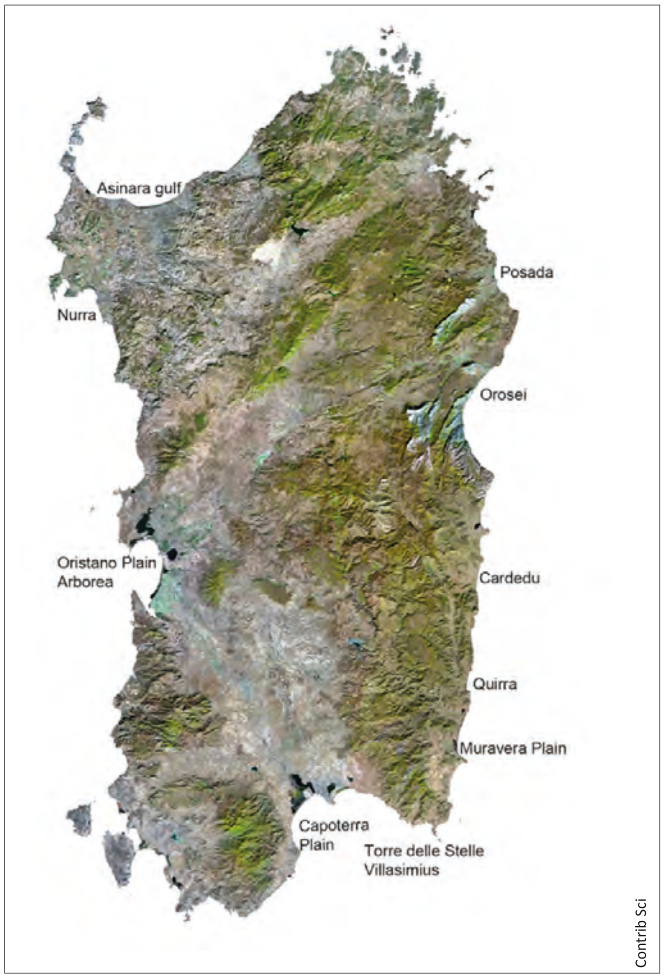

Fig. 5. Location of the Sardinian areas affected by saltwater intrusion.

Nurra District. The Nurra district is located in the northwestern part of Sardinia, in Sassari Province. It is part of the hydrogeological basin underlying the Calich coastal lagoon. The two major sectors that comprise the district are the flatlands of the Alghero plain, in the north, and the rolling landscape that extends from Alghero to Villanova Monteleone, in the south.

Due to intensive human activities and recent climatic changes, the Nurra district has become vulnerable to desertification [34,35]. Its aquifers have long been exploited, mainly for agricultural use but also for industrial and civil purposes. The high concentration of year-round residents, the seasonal population in the coastal zone and the intense agricultural activity on the territory have led to a relevant increase in water demand. While demand is generally satisfied by surface water collected in two reservoirs, during some yearly periods and/or in dry years, available freshwater resources are exceeded. During those critical periods, groundwater is the only alternative and thus constitutes a strategic water resource. Groundwater is exploited using deep boreholes in different aquifers, which can attain discharges as high as 145 l/s. The extensive exploitation of the Nurra aquifers and the consequent deterioration in water quality highlight the need for improved water management practices.

The main aquifer derives from the Mesozoic carbonate successions and has a yield that varies between 20–145 l/s. The direction of groundwater flow from this aquifer is strictly controlled by structural deformations and weathering processes [36].

Hydrochemical data indicate that salinization in the Nurra basin comes from various sources, even though most of the acquired salinity can be traced to sodium and chloride inputs that are mainly due to the interactions between water and rock. Nevertheless, seawater intrusion is not the culprit in the salinization of the area's groundwater [35,36].

Muravera Plain. The Muravera coastal plain is located in southeastern Sardinia and was formed by the Flumendosa River, the island's second largest river. The economy of the area, which is also of major environmental interest, relies heavily on agriculture and, along the coast, tourism as well as aquaculture [2,6]. The plain consists of Pleistocene and Holocene alluvium up to a few hundred meters thick and overlaying the metamorphic and granitic Paleozoic bedrock outcroppings at its edges. At least two aquifers have been identified in the plain: a shallow, highly productive phreatic aquifer and a deep confined aquifer. The former lies just beneath the surface (1–2 m) and has traditionally been exploited by farmers, who abstract groundwater from the wide-diameter wells, which are no more than 4–6 m deep. The thickness of this aquifer decreases progressively, from 15–20 m upstream to 4–5 m near the sea,. The two aquifers are separated by a clay layer ranging in thickness from a few meters to several tens of meters [2,6].

The natural hydrodynamic equilibrium between the groundwater and surface water flowing into the Flumendosa River and some of its channels, on the one hand, and seawater, on the other, has been deeply modified by humans [8]. 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, phreatic and deep aquifers are being increasingly exploited through wells that are being excavated and drilled to meet the ever-growing water demand for agriculture and domestic uses, mainly in summer. This situation has been exacerbated by the recurrent drought conditions on the island in recent years.

The shallow aquifer is contaminated by brackish waters, resulting in an EC as high as 3,000–6,000 µS/cm. EC peaks as high as 8,000 µS/cm have been measured in the area as a whole (extending from the sea up to the town of Muravera). Groundwater in the deep aquifer also has a high salinity but the extent of contamination has yet to be clearly defined. However, in the same area where the high salinity of the shallow aquifer has been recorded, conductivity logs also show contamination of the deep aquifer, but the chlorine content is much higher and conductivity increases sharply with depth, reaching 20,000–25,000 µS/cm [2,6].

Oristano Plain. The studied site is a large area of North Campidano, located in the province of Oristano. Its borders are the reclaimed Mar'e Foghe swamp to the north, the mountainous hills of Monte Arci and Monti Ferru to the east and the Sinis Peninsula to the west. The southern border is vague, running from the Cirras zone, between St. Giusta pond and the reclaimed land in Sassu (Arborea). The plain is nearly level, with an average height of 10 m above sea level but also depressed areas that in the past were completely reclaimed marshes. The topography is thus essentially flat, with the monotony broken only in the north and northeast by hill formations representing the last spurs of the volcanic mountains of Monti Ferru. The area's three ponds (Santa Giusta, Cabras and Mistras ponds) are of fundamental importance to the hydrological balance, together with the Tirso River, whose flow has been altered by the new Omodeo dam, located ~50 miles from the mouth; the regulatory action of the dam has caused a substantial decrease in surface and subsurface runoff, thus also greatly impacting the flow of groundwater.

The Oristano plain is next to a rift valley filled by Tertiary alluvial materials related to the evolution of the hydrographic network of the Tirso River and partly by materials transported via the rivers that descend from the slopes of Monte Arci. After intense volcanism of calc-alkaline character and the deposition of marine and continental sediments, the rift was completely filled. The last phase of sedimentation occurred during the Quaternary and was characterized by a succession of fluvial, lacustrine, marine and marsh deposits. The quaternary layer is therefore very thick, about a few hundred meters.

In the study area there are a shallow unconfined aquifer and an underlying multi-layered aquifer system, confined and semiconfined. The unconfined aquifer is set on the sandy-pebbly alluvial soils, which represent the last part of the filling due to the hydrographic network of the Tirso River. This aquifer is fed mainly by the recharge of losing streams, by the drainage of the numerous canals and by effective infiltration. The configuration of the area's complex hydrographic network is deceptive and hides the areal continuity of the aquifer. According to the available stratigraphic data, a silt-clay level 1–2 m thick occurs at an average depth of 10 m and forms the impervious aquifer bed [11].

The multi-layered aquifer system is also the product of floods and consists of gravelly-sandy Pleistocene alluvial soils intercalated with silty-clay horizons. Groundwater is found at variable depths and, due to the discontinuity of the confining layers, is characterized by varying degrees of artesian flow from area to area. Because of incorrect well development, the confined or semiconfined aquifers now essentially communicate with each other and with the shallow phreatic aquifer. An analysis of the equipotential lines [10,11,17] show an east-west average flow direction in both aquifers. In the shallow aquifer there are two drainage areas, south of the Santa Giusta pond and east of the Cabras pond. In the underlying confined aquifer, the drainage areas are east and west of the Cabras pond and in the urbanized area of Oristano.

EC maps show high values in the piezometric depressions of the phreatic aquifer, with values ranging between 5000–10,000 µS/cm and a peak of 24,000 µS/cm in the area surrounding Cabras pond, between 2000–3500 µS/cm in the area lying southeast to northwest of the Santa Giusta pond and in north-northwest of Oristano. The average EC values are lower in the underlying confined aquifer than in the one above, between 2000–4500 µS/cm in the area surrounding the Cabras pond, about 2500 µS/cm southeast of Santa Giusta pond, 2000–3000 µS/cm south of Simaxis and about 2000 µS/cm east of Massama [17].

Overall, in the Oristano plain, significant groundwater over-exploitation and the deficiency of active recharge have triggered seawater intrusion processes [10,11].

Capoterra Plain. The coastal aquifer system of the Santa Lucia River alluvial plain is situated in the southern part of the Campidano graben. The plain is bordered to the east by a natural lagoon of brackish water, a large area given over to saltpans that are divided into numerous evaporation ponds, and by the sea. The western edge of the plain is limited by granite hills. The area has undergone profound transformations due to the ever-increasing expansion of agricultural and industrial activities. Water demand has risen accordingly [61].

The coastal system consists essentially of two alluvial formations. The oldest one, dating back to the Plio-Pleistocene, forms an outcrop in the foothills and is composed of coarse, strongly weathered material that has undergone intensive soil genesis. The younger formations (Holocene) consist of a larger gently sloping fan that extends, down to the Santa Gilla Lagoon and the Gulf of Cagliari. The recent alluvium is underlain by a clay layer, below which lies a multilayer semi- or locally confined aquifer. Groundwater occurs in sand and gravel layers with interbedded clay lenses of recent alluvial deposits, while the ancient terraced alluvia are practically impermeable [12].

The aquifer system consists of a shallow, phreatic aquifer and a deeper, multilayer, semi- or locally confined aquifer. The equipotential contour lines show that both aquifers are recharged laterally from the western border by groundwater coming from granite bedrock. Supply probably occurs through preferential pathways due to widespread fracturing of the medium. In both aquifers there is a depression of the water table surface to below the mean sea level. This depression is located in the central part of the plain, where the over-exploitation of water resources is the result of the high density of agricultural and industrial activities. The numerous shoddily built wells have caused the intercommunication of the two aquifers at several points and therefore mixing of their groundwaters.

The plain is affected by sea-spray, which deposits considerable amounts of sodium and chlorine on the soils, thus altering the quality of the supply waters. Sodium and chlorine are also deposited through atmospheric precipitations. The vicinity of the sea has facilitated seawater intrusion, both in the phreatic and confined aquifers, thereby increasing the saline content of the plain's groundwater [12].

Other phenomena, both natural and anthropogenic, overlap with seawater encroachment to further modify the chemical composition of the waters supplying the aquifer system. This is especially the case for the phreatic aquifer. Of major significance in relation to the salinization of groundwater in the plain is the presence of the Contivecchi saltworks. Transport of the salts that deposit on the soil surface, whether from the saltworks or from the salt stocked on its grounds and near the evaporation ponds, has been included in the spray component that has been factored into the hydrogeological model.

The evaporation of rainfall and irrigation waters during the summer leads to the redissolving of the salts deposited on the soil. Of particular importance is the recirculation of irrigation waters abstracted through drilled wells from the confined aquifer. In summer, when irrigation demands increase significantly, the salt concentration of the phreatic aquifer diminishes. This has been attributed to the effects of dilution by irrigation waters abstracted through drilled wells from the deeper aquifer, which is of lower salinity than the shallow aquifer.

Final remarks

As described in this article, seawater intrusion exerts intense pressure on groundwater resources along Mediterranean coasts. Despite their specific hydrogeological settings, both Catalonia and Sardinia must cope with the over-exploitation of their groundwater because of the increased water demand to supply agricultural, industrial and domestic uses. Urban needs, which increase further during the summer months, when tourism peaks, increases groundwater withdrawal and enhances seawater intrusion. Decreasing water availability and the deteriorating water quality caused by excessive and irrational water consumption may restrain the future development of local agricultural, industrial and tourist activities, leading to adverse social and economic repercussions. The Ebre Delta is unique in the sense that the management of its surface water has limited the natural advance of the saline wedge in the river itself and within the aquifer.

These environmental degradation processes can be brought under control and reversed by means of targeted interventions and by the adoption of appropriate policies for effective water resources management. Water transfers and technological solutions, such as desalination plants and hydraulic barriers, have been applied to deliver freshwater to users and, directly or indirectly, to avoid further aquifer salinization. The decrease of groundwater pumping rates is only possible when alternative sources, for instance, surface water exist; yet this also alters water balance in the basins of origin. In environmental terms, technological solutions require a surplus of energy and desalination plants necessitate the subsequent treatment of the resulting brines and operational waste products. On the positive side, both recharge and the construction of hydraulic barriers allow the reclamation of water and can spare freshwater resources. Nonetheless, preserving freshwater resources from seawater intrusion while, at the same time, satisfying water demand comes with high economic costs that will increase the price of water.

Finally, by the end of the 21st century, water scarcity linked to climate (global) change processes will further challenge water managers in Mediterranean coastal areas. River and aquifer discharge to the ocean will certainly decrease, facilitating the advance of salinization under continuous pumping pressures. Lowlands will also suffer from the rise in sea level, thus affecting wetlands but also villages, tourist resorts, crops, etc. The needed solutions must foresee the effects of climate change and will inevitably lead to the extremely rigorous management of water resources in terms of efficiency and reuse.

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