Coastal aquifer management in Europe

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Abstract

Europe has a long continental and island coastline along which many human activities are concentrated. Coastal aquifer development is often intensive and subject to salinity problems as a result of seawater intrusion, upconing of deep saline water, and residual salinity in aquitards. These coastal aquifers are important freshwater sources that risk being salinized by different processes. Often important coastal aquifers are of relatively small size but crucial to supply human needs, which vary from mostly urban and industrial supply in mid to high latitudes, to dominantly seasonal for irrigation and tourism in the Mediterranean area and many of the islands. To prevent quality loss through salinization, management is needed. This is a complex objective, full of difficulties and with scarce experience. Solutions are highly dependent on local circumstances. Some aquifers are carefully studied, monitored and managed. Examples can be found in different countries, such as The Netherlands, Belgium, and northeastern Spain.

Keywords: Europe, Coastal aquifers, Seawater intrusion, Groundwater management

I. Introduction

In comparison with other continents, the highly irregular shape of continental Europe and the numerous European islands yields a very long coastal zone per unit surface area. In the southern parts of Europe, especially along the Mediterranean shore, in the numerous small islands and in the Atlantic Ocean Macaronesian archipelagos (Canaries, Madeira and Azores), irrigated agricultural activities and tourist resorts, with their markedly seasonal patterns, have a large freshwater demand. In these areas, available surface water resources are often scarce or inexistent. However, there are numerous coastal aquifers, whose development to get freshwater is a key social and economic issue. This leads to a situation in which many of these coastal aquifers become intensively exploited, and the natural seawater–freshwater relationships may be greatly modified.

Consequently, the interest on the influence of seawater on freshwater resources, and especially on groundwater, has been traditionally high, including methods and management practices to fight the deleterious effect of seawater–induced high salinity. Salinity problems have been growing with more intensive groundwater abstraction and, in some areas, as a result of coastal lowland reclamation impact on groundwater flow. The construction and operation of civil works and transportation ways may include important drainage activities or, contrarily, introduce barriers to groundwater flow towards the shore, which may be the cause of important coastal aquifer flow pattern changes. Besides their natural values, coastal aquifers are key, valuable, and important natural infrastructures for water supply (Custodio 2005).
Salinity problems in many European coastal areas have been well known since the late nineteenth century. In fact, the Ghijben–Herzberg principle (Badon Ghijben 1899; Herzberg 1901) was developed from observations on the Dutch North Sea coast and the northern Baltic shore of Germany. For decades, these problems have attracted the attention of European professionals, specialists and scholars dealing with groundwater, willing to know more, share experiences, and bring forward new ideas. So, every other year, since 1968, meetings under the title of Salt Water Intrusion Meeting (SWIM) have been convened in Europe and recently alternating between Europe (the last one in Ponta Delgada, São Miguel Island, Azores, 2010)

and in America (the next one in Buzios, Rio de Janeiro, Brasil, 2012). SWIM publications contain a lot of relevant information on the progress of knowledge about basic concepts of seawater–groundwater relationships in key European areas. A recent compilation of cases, with emphasis in the Mediterranean area, has been published (López–Geta et al., 2008).

II. General geological and hydrogeological aspects

Coastal areas may be rugged and steep, but also recent gentle plains associated to the large depressions of major river basins, such as the Vistula (Poland), Thames (UK), Garonne (France), Po (Italy), Guadalquivir (Spain), Rhone (France), Danube (Ukraine/Romania), Ebre (Spain), and Rhine (The Netherlands). Large areas correspond to crystalline and metamorphic rocks, such as Scandinavia, Scotland, northwestern France, and the northwestern part of the Iberian Peninsula. There are notable carbonate rock series, from the Palaeozoic to the Cenozoic, in southwestern England, north France and all along the European Mediterranean area, including the major islands, and also coral–reef–associated Miocene sediments in the Mediterranean area. The Atlantic islands of the Macaronesia are fully volcanic, as well as the Eolian and many of the Aegean islands, in the central and eastern Mediterranean Sea. Also Iceland is partly a volcanic island. Many of the largest continental European aquifers have the sea as one of their boundaries (Custodio, 2010).

Different geological processes have had a large influence on many of the main European coastal aquifers. The great Messinian (Miocene) crisis of the Mediterranean Sea, during which it was isolated from the Atlantic Ocean, produced very deep sea levels. Deep valleys were excavated, now filled with sediments, which include large volumes of marls. During the last glaciation, the northern half of Europe was covered by ice caps, including parts of the British Isles. Deep glacial valleys were excavated and later on filled with glacial and fluvioglacial deposits, mostly gravels, sands and clays. These deposits dominate in Jutland (Denmark) and the coasts of northern Poland, northern Germany and The Netherlands.

During the last glaciation, which lasted until 10,000 years ago, with their maximum about 16,000 years ago, sea level was depressed down to about 120 below present sea level. All along the Atlantic and the Mediterranean areas, this favoured the excavation of encased valleys by rivers that cut into existing rocks and sediments, including those deposited during older low sealevel stands. These valleys have been lately filled up with fluvial, estuarine, marine and eolian sediments. They often contain permeable to very permeable layers, especially close to the old valley bottoms. The resulting coastal plains are currently densely populated and highly productive agricultural areas with intensive groundwater abstraction.

From the point of view of groundwater resources, deltaic areas are one of the most important coastal formations. They are found in the lower reaches of rivers when the rate of river–contributed solids exceeds their dispersion by sea tides and currents, as in the low–tide Mediterranean Sea. Typical deltaic areas are those of the Rhine–Meuse (The Netherlands), Aveiro (northern Portugal) and Guadalquivir (southwestern Spain), in the Atlantic coast, the Ebre and Llobregat (Catalonia, northeastern Spain), Rhone (southern France) and Po (northeastern Italy) in the Mediterranean Sea. In the Lower Tagus River, in Lisbon (Portugal) and the River Thames, around London (southeastern UK) there are wide encased estuaries but not deltas.

Deltaic sediments were partly or dominantly deposited under saline water, which may be still there (Post, 2004; Custodio and Bruggeman, 1997). Such are the cases in the lower Rhone River (southern France), the lower Guadalquivir–Doñana Area (southwestern Spain), and around Aveiro (northern Portugal). Deposits may also contain brines produced by intense surface water evaporation in the marshy, closed areas created by coastal dynamics.

Sandy sediments dominate in the southeastern North Atlantic coast, with more or less continuous clay–silt layers that separate an upper aquifer from a deeper one, in this case containing remnant seawater bodies (De Vries 1981; De Breuck and De Moor 1974). Inland icepushed hills and coastal dune chains have favoured the formation of elongated freshwater bodies in the coastal plains. Behind the coastal dunes, the land has very low elevation and there are shallow lakes, lagoons and marshes with clayish top sediments. In The Netherlands, especially around Amsterdam, many of these low areas *(polders)* have been drained to accommodate human activities (Fig. 1). Their elevation may be below current local mean sea level and even below the minimum local sea level. This situation is being aggravated by current seawater level elevation trend, land subsidence, and compaction of peat layers. These drainages for land reclamation have created conditions for extensive deep saltwater upconing.

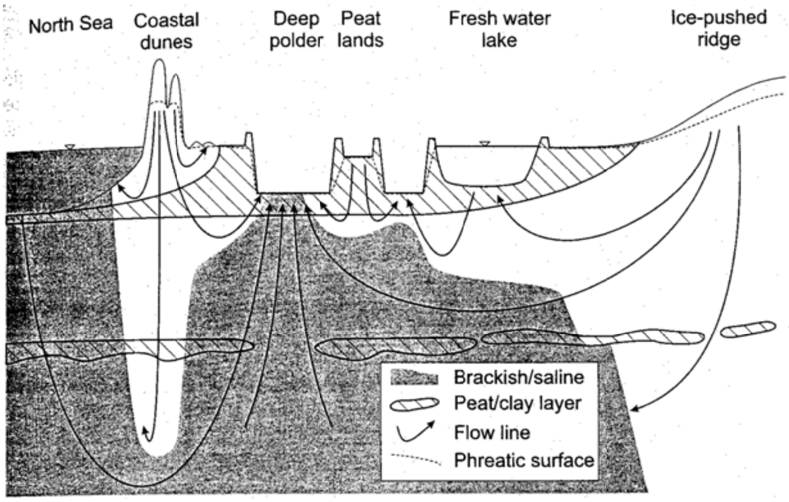

Fig. 1. Schematic flow systems in the western part of the Netherlands. The cross–section is about 60 km across.

Typical Mediterranean delta conditions are represented by the rather large Ebre and the small Llobregat deltas in Catalonia, northeastern Spain. The last supports an important groundwater development (Custodio 1981; Niñerola et al. 2009). Both of them have a well–developed typical sedimentary structure consisting in an upper aquifer and a deep one, separated by a clay–silt–fine sand wedge (Manzano et al. 1986; Gámez et al. 2009). The deep layers merge upstream with the low valley river terraces, where there are good recharge conditions. Figure 2 is a typical hydrogeological cross–section corresponding to the Ebre delta. For the Llobregat delta, the initial situation and the current intensively modified situation due to intensive groundwater abstraction is shown in figure 3.

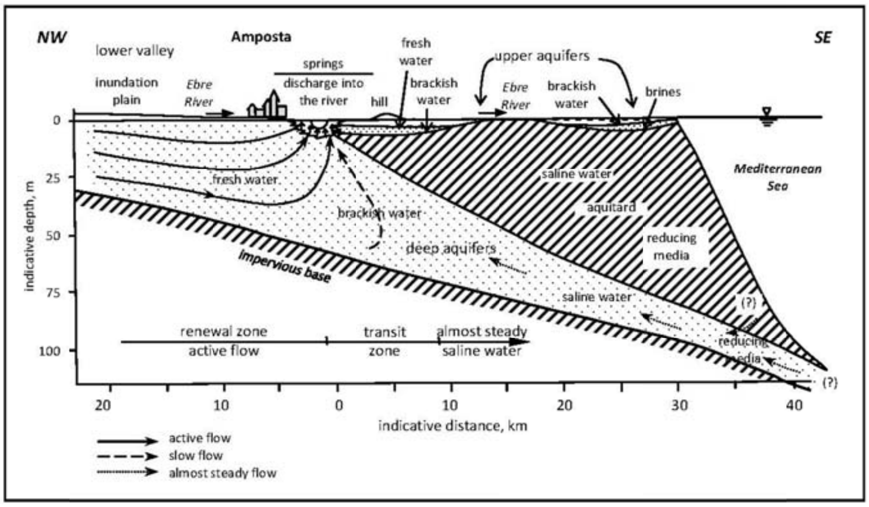

Fig 2. Idealized hydrogeological cross–section of the Ebre delta indicating groundwater flow, which is very slow where *arrows are discontinuous* (after Bayó et al. 1987).

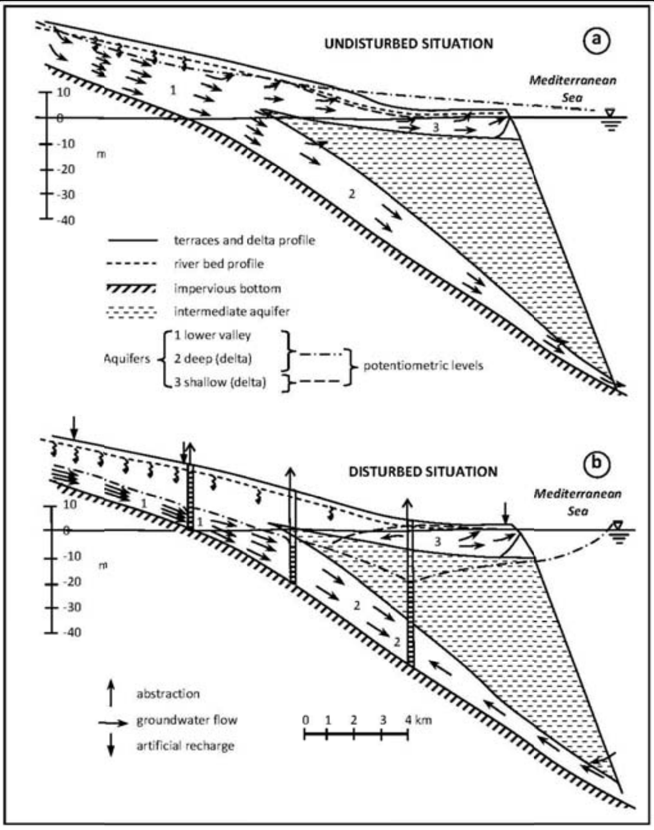

Fig 3. Idealized hydrogeological cross–section of the Llobregat delta (Barcelona). **a** The undisturbed situation prevailing until early the twentieth century; **b** the current highly disturbed situation (after Iribar and Custodio 1992).

In the Ebre delta land elevation at the upstream deep aquifer outcrop is very low, less than 0.5 m above mean sea level. This means that there is not enough freshwater head to flush out the original seawater from the deep coarse sediments, and the deep aquifer contains marine water (Bayó et al. 1987), with some sluggish inlandward saline flow towards the upstream outcrop. This is due to the higher equivalent freshwater head of seawater at the deep aquifer depth, and to saline water inflow from the slowly compacting top silt–clay wedge. The situation of the Rhone (southern France) and Po (northeastern Italy, see Antonelli et al., 2008) deltas are similar to that of the Ebre delta, although they are more complex, with several permeable layers and large areas prone to be flooded.

In the Llobregat delta, the inland outcrop of the deep aquifer is produced at a much higher elevation, about 11 m above mean sea level, due to the lower valley coarse filling deposits and the torrential nature of the river. This allows freshwater to flow toward the existing submarine outlet at about 4 km offshore, at about 120 m below sea level, or an equivalent freshwater head of 3 m above sea level. Old marine water has been already flushed out in large areas, with only a rather small salinization component due to the clay–silt wedge compaction and diffusion from remaining saline layers in it (Manzano and Custodio 1995), which was the natural situation. Intensive groundwater development since late nineteenth century and especially after the 1950s, has produced a dramatic flow pattern change. The result is a progressively advancing seawater intrusion from the submarine suboutcrop (Fig. 4) that was noticed early in the 1960s, after about 15 years of starting intensive development. Saline water penetration is limited by wells abstracting brackish and saline water (Custodio 1981; Abarca et al. 2006; Niñerola et al. 2009). This is also the situation in other small Catalan deltas in northeastern Spain and southern France.

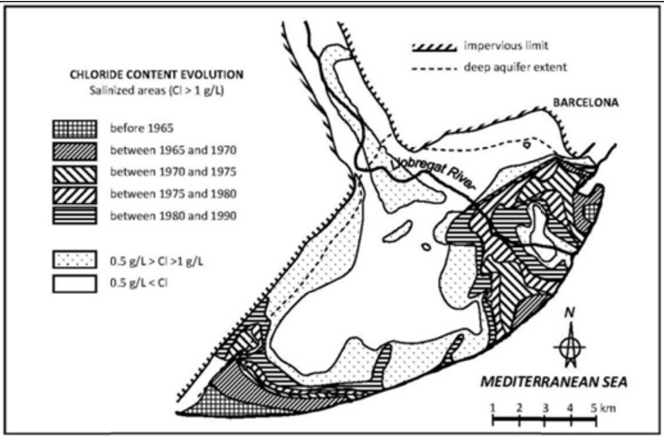

Fig 4. Advancement of seawater intrusion into the Llobregat's delta deep confined aquifer from 1965 to 1990. Penetration is faster where the aquifer is more permeable and the confined clay–silt layer pinches out or is breached by deep excavations, as in the new harbor docks to the east (after Iribar and Custodio 1992). Groundwater has been modeled by Iribar et al. (1997), and later on, including saline water transport, by Abarca et al. (2006) and Vázquez–Suñé et al. (2006).

Carbonate massifs are common in the European Mediterranean coast. They are mostly of Mesozoic and Cenozoic age. These formations may be karstified and the associated enlarged cavities may extend down to 100 m below present sea level, or more if they correspond to older sea–level stands or to the Messinian crisis (La Vaissière et al. 2007), or to tectonic vertical displacements.

Often water discharges at the shore or offshore at shallow depths. Deep, old submarine outlets offshore from the present coastline may be clogged, and then younger, vertical outflow shafts near the shoreline have often been developed by rock dissolution, forced by hydrodynamics. Large springs are found all along the continental coast. Well–known situations are found in eastern and northeastern Spain (Moraig; La Falconera), southern France (Port–Miou, Cassis), southeastern Italy (Basilicata and Taranto areas, in the Salentine Peninsula), Sicily, the western coast of the Adriatic Sea (Dinaric karst of Croatia, from where the name karst comes), and Greece. They are also found in the islands. Carbonate massif systems are often complex, and so is marine water intrusion in them.

There are some coastal shallow holes, continuously absorbing marine water, as in the Argostili peninsula of Cephalonia island, in the Ionian Sea, which were used in the past to power a watermill. There are submerged coastal caves continuously absorbing seawater –except in very wet periods– such as that of Toix (eastern Spain). Brackish to saline springs discharging a few metres above sea level are known in Greece (Almiros spring, Heraklion, Crete) and in eastern Mallorca Island (S'Almadrava). They are the result of continental groundwater recharge that mixes at depth with seawater, thus reducing its salinity and consequently increasing the equivalent freshwater head, in a network of perhaps a few hundred metres deep karst conduits connecting inland areas with the sea, and with vertical outflow paths near the coast (Fleury et al. 2007; Arfib et al. 2007; Sanz et al. 2002).

Salinity problems in carbonate massif areas, mostly in the Mediterranean area, are well known. Groundwater development concentrates in the permeable areas since the yield of other areas may be too low. In these cases, wells should be drilled or excavated just to penetrate the water table, and the pumpage rate has to be low to very low to try to avoid saline water upconing. Another possibility is drilling horizontal water galleries at around sea level to try to skim groundwater at the water table. Often karstic areas suffer from scarce freshwater resources, and salinity problems increase at times when freshwater is more in demand in regards to irrigation or seasonal tourism. This is common in Southern Europe. When karstic coastal formations have a clastic cover, freshwater resources may be developed from it, with relative success, but intensive exploitation may lead to progressive, often intensive, salinization problems from below and laterally. Such happens in the Augusta Plain (eastern Sicily) and in part of the Tarragona coastal area (Catalonia, northeastern Spain), where aquifers include detrital formations. Compilations of knowledge can be found in Calaforra (2004) and Tulipano (2005).

The large discharge of karstic coastal springs, although often from slightly to fairly brackish, has attracted the attention of water developers. Attempts are known of since the early twentieth century, but without significant success due to low exploitable flow, or fast increasing salinity after development, or being too complex to be operated. Perhaps the most sophisticated attempt has been carried out in the Port–Miou coastal spring (Cassis, Provence, southern France), in the 1980s. The attempt was not very successful since brackish water was obtained. Other attempts were carried out in La Falconera spring (Garraf, Catalonia) early in the twentieth century. In localized sea bottom outflows in Taranto Bay, Salentine Peninsula, southern Italy, submarine devices have been tested to avoid freshwater mixing with seawater, but freshwater yield was too low for practical use. A successful case in Greece involves groundwater discharging near the shore and surrounded by poorly pervious materials, which allows the isolation of the springs from the sea by an engineered barrier, but this is a special case under highly favorable conditions.

Islands often support large populations and intense agricultural, tourist and in some cases industrial activities, but they may be devoid of significant permanent springs and streams. In most cases they have intensively developed their fresh groundwater resources, especially near the shore. Currently, they are complementing available water resources by seawater and brackish water desalinization (The Canaries, Mallorca, Cyprus, Malta, Pantelleria) and reuse of treated waste water for compatible demands (Gran Canaria, Mallorca). Sustainability of groundwater development is a key issue, although groundwater abstraction is often excessive and is accompanied by seawater encroachment.

Many of these small islands are fully volcanic. Typically, but not always, volcanic islands present a low to fairly low–permeability volcanic "core" of old, highly altered volcanics with dense dike sets and buried volcanic chambers, which may or may not crop out, in which a more or less high freshwater body may exist, up to 1,500 m in some of the Canary and Madeira islands (Custodio 2004). These "core" materials may extend to the coast or have recent volcanics on and around them, forming a cover and an apron of permeable to highly permeable formations. Seawater intrusion may be not serious when "core" materials are found along the shore, but the saltwater wedge and dispersion zone may penetrate deeply into the highly heterogeneous apron of young volcanics and the associated coastal sediments (Figure 5). In this last case, depending on the recharge rate, extent of the contributing basin, and sea tide range, a thin freshwater layer may exist, or the top of the aquifer may be already brackish and even saline. Groundwater development near the coast is easily affected by saline–water upconing. However, in other cases salinity is of climatic origin, as in the southern areas of the western Canary Islands. In Fuerteventura old marine water remains in the deeper parts; it is partly above current sea level due to the slow island rising (Herrera and Custodio, 2002), and show old thermal effects.

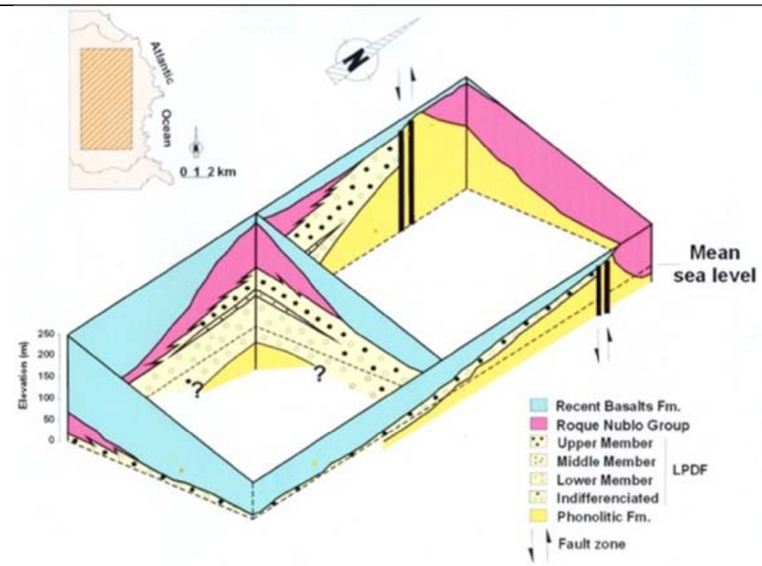

Fig. 5. Volcano–sedimentary conditions at Telde coastal area (eastern Gran Canaria) with coarse clastic layers that are currently seawater intruded.

Other European islands are not volcanic and consist of crystalline and metamorphic rocks in the northern Atlantic Ocean and around the British Isles. They behave similarly to the same circumstances in the continent, except for the isolation from continental or large island water sources. Carbonate–dominated inlands are found in the Mediterranean Sea, as characterized by Malta and Gozo (Figure 6). They have a karstified limestone basement and a thick cover of low–permeability chalk through which recharge is produced. Climate is semiarid and consequently the recharge rate is small. In Malta, groundwater is mostly obtained by means of excavated deep shaft wells that penetrate down to the karstified limestone –whose top is above sea level– where a thin freshwater lens floats on saline water. To reduce upconing, a drainage galleries network –constructed during the British rule– connects wells and radiates out from them. Variable height spillways limit groundwater drainage to the galleries in order to avoid excessive salinization by upconing, especially in dry periods.

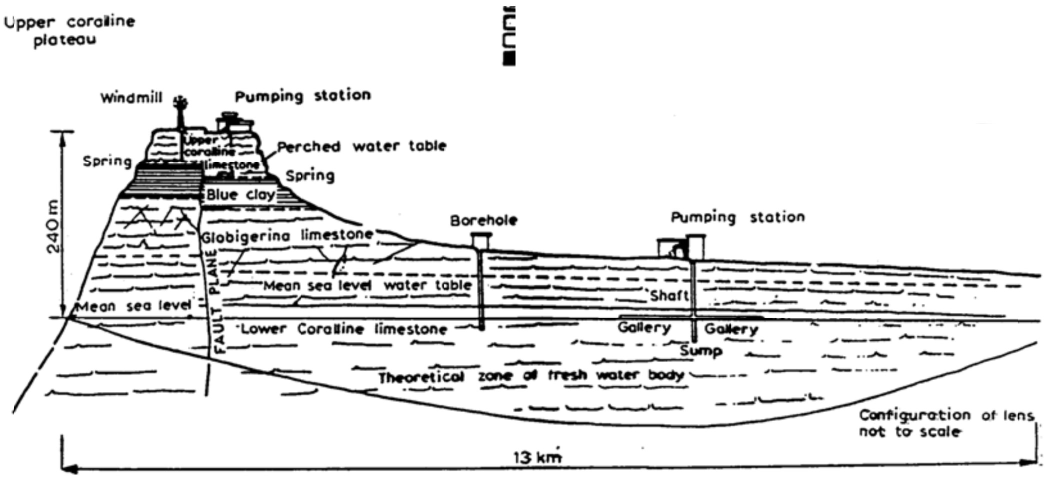

Fig. 6. Idealized NNW–SSE section of Malta island that show low permeability limestones (chalk) on karstified coralline limestones at about sea level. Exploitation by means of very low penetration galleries irradiating from a central shaft–well allow skinning freshwater.

The Balearic Islands are geologically complex and their behaviour is more similar to common carbonate coastal massifs, except in the smallest islands. Sardinia, Corsica, Crete and Cyprus, which are relatively large islands, behave as continental–like masses. In Cyprus, the noticeable and growing salinity of the eastern coastal aquifers is in part due to return irrigation flows, which is also a common circumstance in other islands. The effect is enhanced when poor–quality irrigation water is applied.

III. Aquifer management and sustainability considerations

The varied hydrogeological conditions, the intensive groundwater development stage in many areas, the deep social implications, and the legal framework affecting the European coastal areas have led to the development of local solutions to try to fight and control seawater intrusion into aquifers, and also to avoid old, deep saline water in large areas, which is a common circumstance in the northern areas of Germany and Poland.

Groundwater in coastal areas is not only a source to supply human needs, but also play an environmental role in continental and offshore areas, to be taken into account as wetland support, contribution of nutrients and local dilution with changing cation abundance and proportion.

When coastal groundwater is mostly for town supply, restrictions on well drilling and abstraction, and on emplacement, are relatively easy to enforce since they often depend on a few public or private organizations. However, in the southern European areas, including the archipelagos, irrigation is often an important and even dominant groundwater user. This is also true regarding the supply of water to tourist–resort areas. In these cases, the number of stakeholders may be very high, and they act mostly individually, with little regard to aquifer–use sustainability. Intensive groundwater development has been the result of a kind of bottom up "silent revolution" starting a few decades ago, with little governmental knowledge, involvement, monitoring and management. In many cases, according to the commonly applied Roman Code of Law, groundwater was a *res nullius* natural good, which became the property of the abstractor. Consequently, water regulatory organizations (public water agencies) have often disregarded groundwater, considering it alien to their water administration duties, have been unprepared and uninterested in coastal aquifer management, and have also lacked the adequate human and economic resources to take groundwater into account. This has been changing in recent times, but action is often rather late and poorly effective. Groundwater in these areas has suffered from serious salinization problems. However, this is not an unavoidable situation. Intensive–use consequences such as too much groundwater level drawdown and salinization can be redressed with management, which includes regulation together with participation and co–responsibility of stakeholders who must be aware that aquifers are a valuable common asset. Management needs adequate monitoring, which is not an easy task in coastal aquifers due to the three–dimensional characteristics of groundwater flow and salinity patterns. Data should be available for all interested parties and the public in general; it has been noted that some experience has begun to make itself available.

In the year 2000, the European Union enacted the Water Framework Directive, with further details on groundwater in 2006, in the "daughter" Groundwater Directive. These Directives are aimed at the protection, halt of further degradation, and restoration of the water dependent environment. The Directives are compulsory in the whole European Union, and have been incorporated into Member States' Water Acts and regulations, following the subsidiarity principle. Good quantitative and qualitative statuses of aquifers have to be attained by the year 2015. Where there is risk of not attaining them, extended terms may be negotiated through well–documented studies (including the salinization of coastal aquifers due to human activities), clarifying measures to be implemented in order to reach the objectives by no later than the year 2027. The effective application to coastal aquifer need further development and experience. Modeling is generally an useful tool to support management (Vázquez–Suñé et al., 2006; Abarca et al., 2006), as was done in the past for the Llobregat Delta aquifer (Iribar et al., 1997), and is currently a decision tool for the Water Agency and the Groundwater Users Community.

Member states are taking steps to accomplish goals, although some situations are very difficult to redress since they imply a high economic and social cost, if they can be redressed at all; this relates mostly to southern Europe, the Atlantic Ocean archipelagos and the Mediterranean islands, where supply to agricultural and tourist areas are the main, highly seasonal, groundwater demand. This may pose a serious challenge to those areas, for which there is not currently a clear way forward.

What has been done up to present are local efforts, variable from one area to another. In many cases, there are restrictions on well drilling, emplacement of wells, and groundwater abstraction, and even on carrying out civil works projects that need drainage. Preserving the more or less continuous clay layers that protect against or greatly delay and disperse, saline water upconing is an important issue. The dunes of Haarlem (Amsterdam) have received artificial recharge with imported Rhine water since the 1960s to maintain the freshwater balance. The management success depends on a careful consideration and protection of clayish layers, which limit and delay salt water upconing from below. More of less effective restrictions on distance to the shore and well depth have been established in The Canaries and some areas of Mediterranean Spain, although often without being supported by detailed studies. This affects currently the abstraction of brackish and saline water for desalination, which is becoming a coast normal issue on the effects and brine disposal.

In the Llobregat delta and low valley (Barcelona), aquifer recharge by river water has been enhanced by careful scraping of the river bed since the 1940s, and there has been artificial recharge through deep wells of excess potabilized river water since the 1960s. A line of coastal deep injection wells started operation in 2007 to decrease and reverse seawater intrusion by injecting tertiary treated waste water, which is further microfiltered and UV–ray disinfected, with salinity reduction through reverse osmosis (Niñerola et al. 2009). Recharge of treated waste water is also practiced in Belgium (Vandenbohede et al. 2009) and is under detailed studies near Amsterdam by the Water Supply Company.

In the Mediterranean coast of continental Spain, and the islands of Mallorca, The Canaries and Porto Santo (Madeira archipelago), the pressure on coastal aquifers is being reduced by producing desalinizated water from seawater or aquifer brackish water, mostly by reverse osmosis, and using treated waste water. The restoration of some coastal aquifers may be accompanied by water–table recovery. In urban areas this may produce the inundation of already constructed underground space (railway and subway tunnels, underground passages, underground stores and subterranean parking lots), constructed when the water table was depleted due to intensive pumpage. Current groundwater abstraction decrease in many coastal aquifers, especially in urban areas, is partly due to well abandonment as a consequence of seawater intrusion, and this has allowed the progress of saline water towards other wells. This is a further problem to be considered in coastal aquifer management. In the Barcelona Plain, the water–table recovery is partially solved by abstracting the poor–quality groundwater for urban use and watering of public gardens and spaces, and also for additional town supply after careful treatment. This has been modelled in order not to increase seawater intrusion in other areas.

As already noted, the involvement of stakeholders in coastal aquifer management and sustainable development is considered a necessary goal. Users' organizations have been created in southern France (L'Herault) and the Llobregat's delta and low valley (Barcelona) (Custodio et al., 2001). Since 1975, in the Llobregat area, groundwater stakeholders, mostly water–supply companies and industrial establishments, but also farmers' representatives, formed such an organization, which has increased activity and helped to improve a fast deteriorating situation (Niñerola et al. 2009). The need for these organizations was already specified in the Spanish Water Act of 1985, but their creation and effective functioning has been a complex affair, especially in coastal aquifers, with a lot of social and administrative handicaps. Progress is being made, with improved legal procedures and the thrust of a state–wide, private sector users' association, a civil organization. Bottom up initiatives are much more effective than top down ones. However, in any case, good public and private cooperation and understanding is needed, even if some objectives are not shared, but a win–win situation can be uphold.

IV. Conclusions

The long coastline of continental Europe and its islands presents a complex geology, with climate conditions varying from temperate to cold, relatively humid in the northern areas, to warm and dry in the Mediterranean area and Atlantic archipelagos. This produces a large variety of situations with respect to seawater–groundwater relations, in which intense groundwater development has to be taken into account.

Seawater intrusion, from natural to man–induced, from lateral seawater penetration to upconing from below, or the displacement of saline water from still unflushed aquifers and aquitards, are common circumstances. However, most of them reflect local situations and do not necessarily represent the behaviour of the whole aquifer. Management is needed and some approaches are under way, with some interesting examples of private and public collaboration through groundwater users' associations. The European Water Framework Directive is pushing knowledge, monitoring and management of coastal aquifers improvements.

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