INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS SELECTED PAPERS

6

Groundwater and Human Development

Editors: Emilia Bocanegra
Mario Hernández
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Groundwater and Human Development

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CHAPTER 3

Coastal aquifers as important natural hydrogeological structures

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ABSTRACT: Coastal aquifers share many hydrogeological characteristics with continental aquifers. The main difference is the risk of water quality deterioration by salinity increase. This is due not only to natural or induced mixing with present sea water but also to the possible existence of old marine water in deep aquifers and aquitards, and to the generation of saline waters and brines in flat areas at an elevation close to that of current sea level. The mixing of freshwater with 3–4 per cent of sea water is enough to make the freshwater unfit for most uses and may seriously reduce its environmental role. The principles governing the distribution of fresh and saline water bodies in the ground and the mixing mechanisms are reasonably well known, although their evaluation and monitoring require networks and methods of study that are often more complex and costly than those commonly used in continental aquifers. Currently it is possible to devise coastal aquifer exploitation plans to limit and correct salinization problems by applying technological methods as well as institutional management with the effective participation of stakeholders. Coastal aquifers are highly valuable as a freshwater resource and as a regulating, emergency and strategic water reserve, since they occur in the lower reaches of river basins. These areas are often flat, with little opportunity to store surface water, and often where population, economic activity and tourism concentrate. The widely diffused 'hydromyth' that developing a coastal aquifer necessarily means salinization problems is false in most cases. Improved knowledge, case studies and social communication are needed to counter this fallacy and to beneficially use opportunities that are technically, economically and socially of high value.

INTRODUCTION

Coastal areas of continents and islands, including small islands, sustain important human activity. They provide flat land to settle and cultivate crops and are key points for maritime communication; they also tap into an ancestral preference for mild maritime climates and environments, now compounded with tourism and third-age residential areas. Their occurrence at the lower reaches of major river basins with long coastal spans without significant streams or around islands with little permanent surface water makes groundwater in coastal aquifers an important freshwater resource for economic activity (e.g. irrigation, tourism, urban services, industry) and especially for drinking purposes.

A series of circumstances generate the risk of groundwater quality degradation in coastal aquifers by introducing an excess of dissolved salts. Sea water is the most important but not the only source of salinity. Mixing groundwater with only 2 per cent sea water produces a noticeable deterioration. If the proportion is 4 per cent there is a serious impairment for many uses. If it is 6 per cent, the water is almost unusable except for cooling and flushing purposes.

When there is poor management or overuse, some serious salinization problems appear, even if they are localized. This means that quality of life is impaired, economic activity is jeopardized and irrigated agriculture may be seriously damaged.

Salinity is caused not only by present sea water intrusion. These other causes have to be identified for the correct management of the situation, otherwise serious errors will arise. The possible sources of salinity in coastal aquifers are:

- encroachment of modern sea water
- mixing with unflushed old marine water in very slow flowing aquifers or in aquitards
- sea water spray on windy coastal strips
- intense evapo-concentration of surface and phreatic water in dry climates
- intense evaporation of outflowing groundwater in discharge areas and wetlands
- dissolution of evaporite salts from geological formations
- displacement of saline groundwater contained in some deep formations
- infiltration of saline return irrigation flows
- pollution by saline water derived from:
  - mine drainage and tip leaching, especially in salt and potash mines
  - leakage from industrial processes and cooling facilities using brackish or saline water
  - effluents from softening, de-ionization and desalination plants
  - dissolution of road de-icing salt
  - intense evaporation of water from factories
- saline water imported from other areas.

Coastal aquifers can be developed to yield fresh water if groundwater flow characteristics are well known, wells are correctly constructed and positioned, a capable management organization exists, adequate policies have been established and there is the will to protect, conserve and restore the aquifer. Popular support and participation, as well as public education, are important for governance and management.

It has been possible to quantify freshwater–saltwater relationships in coastal aquifers since Badon Ghijben (1889) in the Netherlands and Hertzberg (1901) in northern Germany formulated the pressure equilibrium balance of the freshwater–saltwater interface known as the Ghijben-Hertzberg (G-H) principle. Real situations may differ greatly from the very simplified conditions for which the principle was developed, but even in such cases it is useful to describe and quantify the actual behaviour, if the information is correctly applied. This means that the head of salt water in the ground has to be considered, according to Hubbert's principle (1940) of pressure equilibrium of both fluids at each side of an interface, especially during transient situations or when saline water is being pumped out directly or mixed with freshwater.

The basics and some relevant examples can be found in Van Dam (1997), Reilly & Goodman (1985), Custodio & Llamas (1983), Custodio & Bruggeman (1987) and Falkland & Custodio (1992), as well as in texts such as Todd (1959), De Wiest (1965), Bear (1979) and Strack (1989). Although saline water intrusion is an important hydrogeological issue, comprehensive books dealing with the topic in depth are relatively rare.

Specific contributions can be found in the SWIM's (Salt Water Intrusion Meeting) proceedings. A selection of the best papers from the first ten meetings was prepared by De Breuck (1989). Afterwards biennial meetings have followed in Gdansk, Barcelona, Cagliari, Malmö, Miedzyzdroje (Poland) and Delft, from which proceedings are available, and a new meeting is scheduled in Cartagena, Spain in 2004.

COASTAL AQUIFER CHARACTERISTICS

The behaviour of coastal aquifers, besides the geological characteristics that may derive from sedimentation processes in an interfacial environment, is conditioned by the fixed hydraulic head imposed by the sea and the greater density of sea water.

In most coastal aquifer systems groundwater flows naturally towards the sea driven by the head potential created by inland recharge. Since mean sea water level is practically constant there is no induced flow in it, except for short-range, periodical tidal fluctuations. The equilibrium conditions can be described by the G-H principle when a sharp interface separates freshwater and sea water. The interface depth is α times the freshwater head, both referred to the local mean sea water elevation. α measures the specific weight (γ) difference between salt- (s) and fresh- (f) water: $\alpha = \gamma_f/(\gamma_s - \gamma_f)$, and its value is approximately 40 under normal circumstances (see Custodio & Bruggeman,1987 for more detailed considerations).

Freshwater flow influences salinity stratification. The resulting isocones (isoconcentration surfaces) start near the coastline and plunge into the ground down to the lower boundary of the aquifer. This produces the classic saltwater wedge or the floating freshwater lens in small, thick permeable islands.

The actual situation is more complex and has to be described in terms of three-dimensional heads (Hubbert, 1940; Luszczynsky, 1961) as indicated in Figure 1. Diffusion, and especially groundwater flow-induced dispersion, tends to mix fresh- and saltwater, and this is enhanced by aquifer heterogeneities. But freshwater flow, especially in the zone around the expected position of the interface, drags the mixed water along with it towards the coast (Figure 2). Thus, this mechanism helps in limiting the thickness of the freshwater–saltwater mixing (transition) zone and also induces some saltwater flow towards it to keep the salinity balance. The result is that there is a mixing zone, the thickness of which depends on aquifer circumstances, and which can vary from a close-to-sharp interface to a very wide zone. The resulting mean sea water head in the ground is slightly lower than mean sea water level. At a given moment the sea tide induces oscillations and the consequent fluctuation of head and instantaneous groundwater flow velocities (Cooper et al., 1964). The same happens for the seasonal cycle of groundwater recharge (see details in Custodio & Bruggeman, 1987). All this means that in real aquifers circumstances may be complex and their quantitative description needs an elaborate and costly monitoring network that considers the three-dimensional flow and salinity pattern.

In confined aquifers groundwater discharges into the deep sea bed directly or through permeable cover materials if the freshwater head is enough to compensate for the denser sea water column above, as shown in Figure 3. Otherwise there is no discharge.

Near the coast or at the sub-marine outflow of a confined aquifer, regional vertical groundwater flow components are important. When considering aquifer layering and

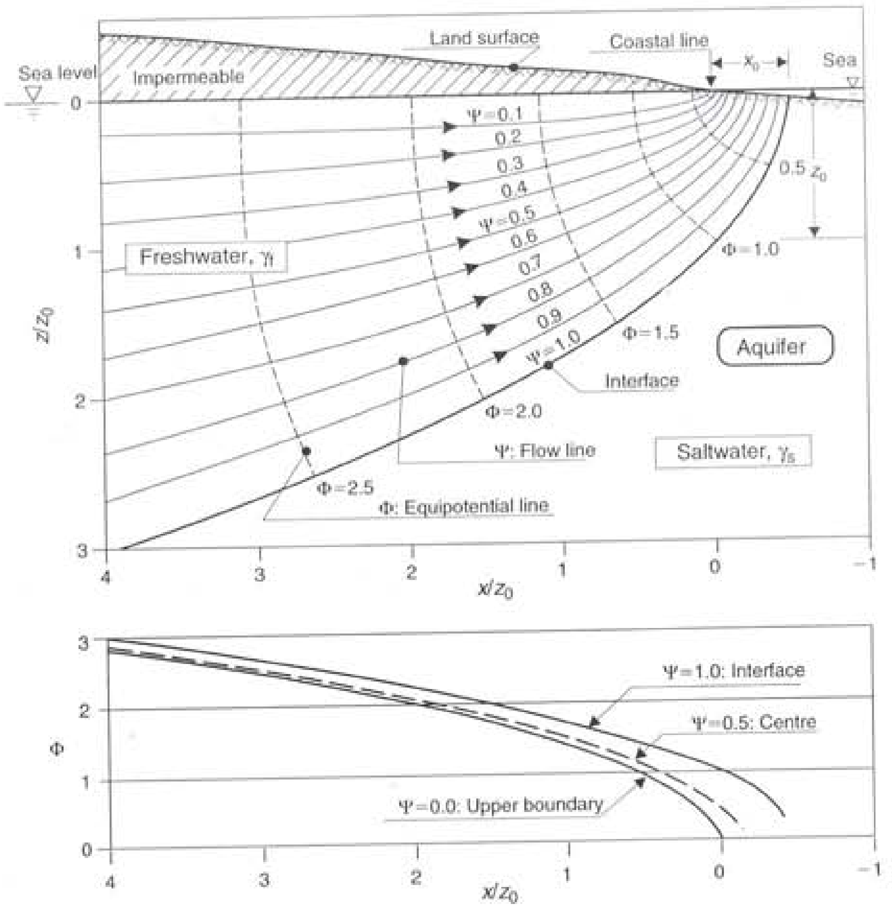

Figure 1. Glover's (Cooper et al., 1964) 2-D exact solution for a thick, homogeneous coastal aquifer with freshwater flowing on a sharp interface with stationary seawater. It is a homogeneous, isotropic aquifer of infinite thickness, confined at sea level. The outflow face is horizontal at sea level. Total freshwater flow is q_0, divided into 10 flow tubes. Freshwater potential is $h = \phi z_0/a = \phi q_0/k$; $\alpha = \gamma_f/(\gamma_s - \gamma_f)$; γ = specific weight of f = freshwater, s = saltwater, ϕ = equipotential number, z_0 = depth below sea level of the interface at the coast line, $x_0 = z_0/2$ = width of the freshwater outflow face in the sea, x distance to the coast line, z = depth below sea level. The lower part shows freshwater head profiles along the interface, the top of the aquifer and at an intermediate position. The interface depth corresponds to the G-H principle applied to heads along $\Psi = 1.0$, but it is deeper if heads are measured along $\Psi = 0.5$ or 0.0.

heterogeneities, these vertical flows translate into different heads in the various aquifers and sub-aquifers. This implies different freshwater–saltwater relationships. In some layers there is no flow when the freshwater head is not enough to balance the heavier marine water column at the outflow face (Figure 4). Upstream freshwater head control may have a decisive influence. Figure 5 shows the same confined aquifer structure under two different circumstances, one with high upstream freshwater head (freshwater flows

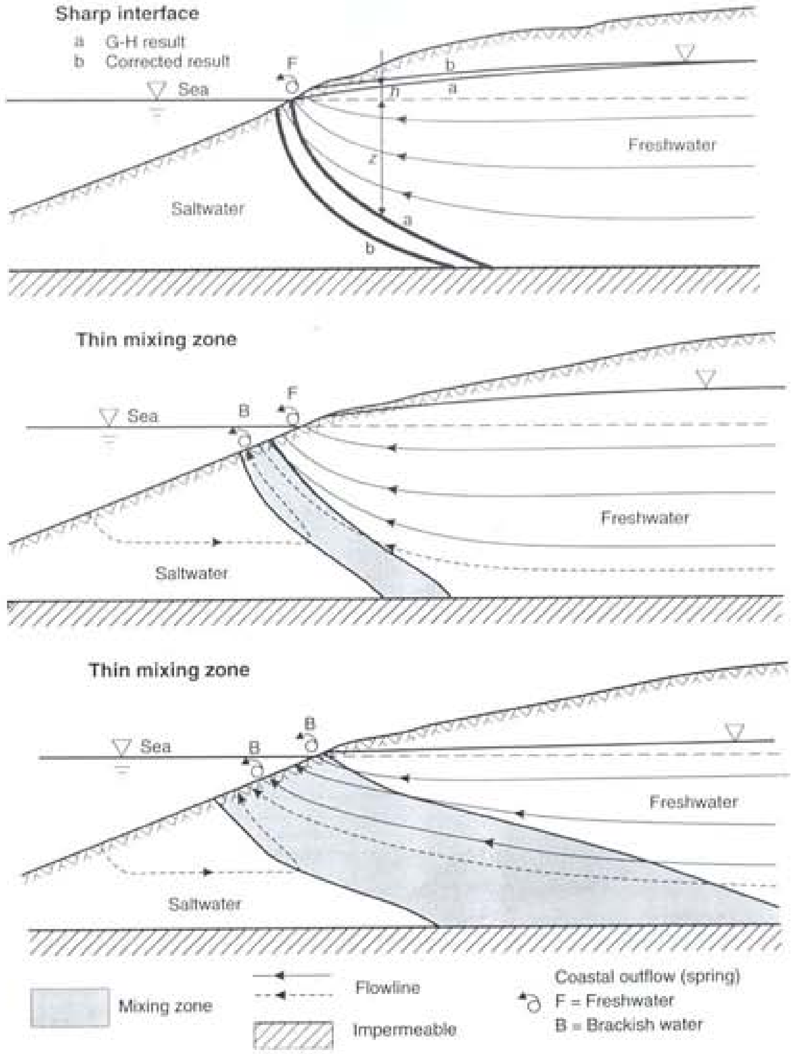

Figure 2. Freshwater–saltwater relationships in an idealized, homogeneous coastal water table aquifer in which main recharge comes from other areas to the right hand side. The vertical scale is exaggerated respect the horizontal one; the part above sea level is exaggerated respect the part below sea level, which explains the smallest apparent slope of continental surface. Actually $z = \alpha h$ in the upper figure, with $\alpha = 40$. The upper figure shows the sharp interface case: no mixing zone and steady saltwater. 'a' is for $z = \alpha h$, being h the water table elevation and z the depth of the interface; 'b' is for true heads along the interface (see Figure 1). The two other figures show the development of a steady state mixing zone. Inside the mixing zone the isoconcentration lines are more or less parallel to the zone boundaries and the flow lines tend to be also parallel to them. Brackish water is discharged along the coast, even above sea level for very flat water tables, which means that a small fraction of seawater must flow landwards.

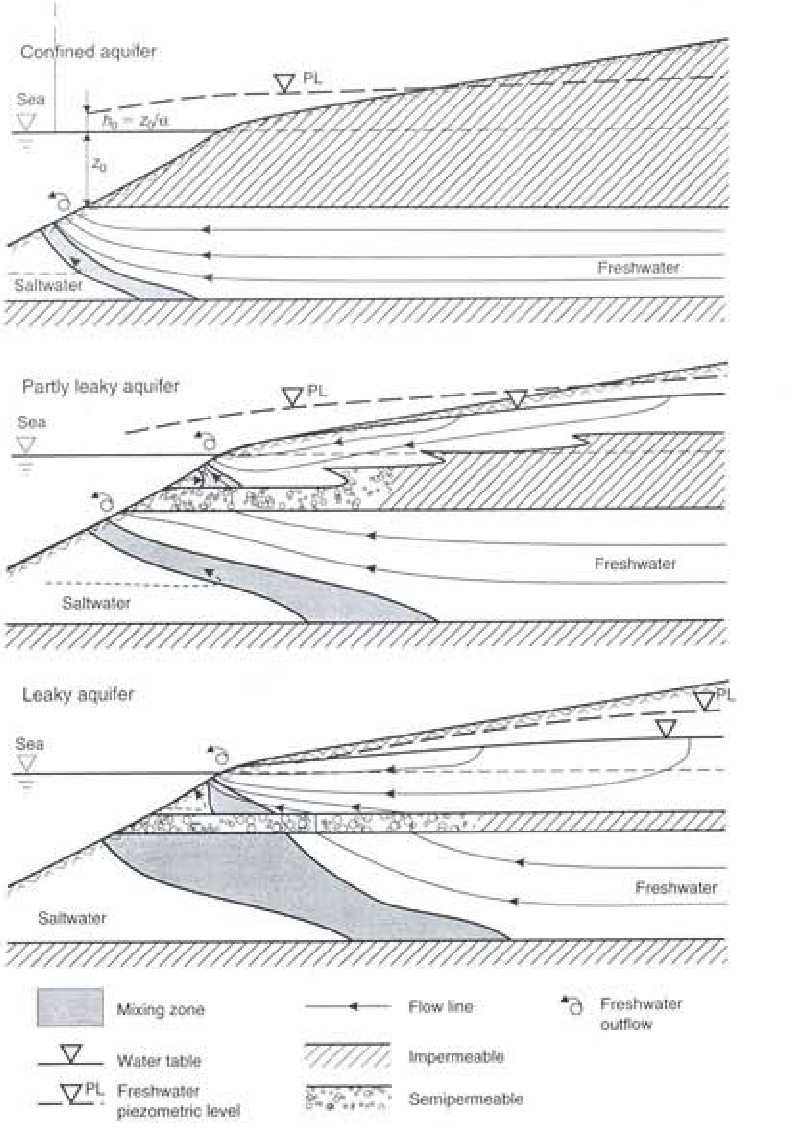

Figure 3. Freshwater–saltwater relationships in coastal confined aquifers. In the submarine outflow face the piezometric head of freshwater must overcome the denser seawater column; otherwise the discharge is not possible and the sea invades partly or wholly the confined aquifer. The upper figure corresponds to a fully confined aquifer discharging into the sea. The central figure shows the effect of a low permeability top layer that becomes thin near the coast, allowing upward discharge of freshwater to a locally recharged water table aquifer. In the lower figure the low permeability layer is thin, allowing confined flow to discharge to the water table aquifer, and there is no discharge to the sea. See caption of Figure 2 for comments on vertical scales.

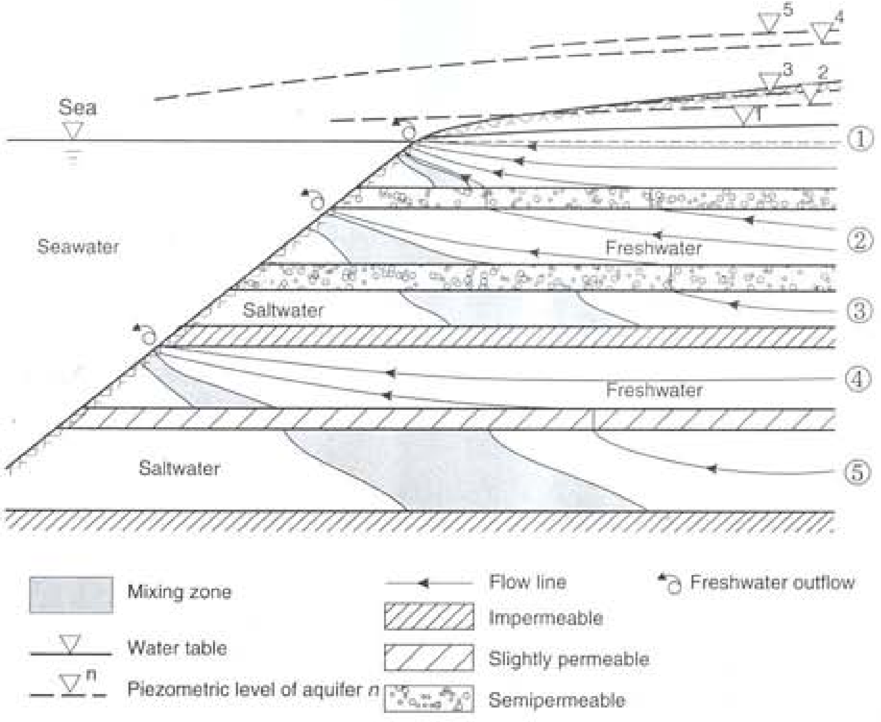

Figure 4. Freshwater–saltwater relationships in a thick multilayered coastal aquifer system. Aquifers alternate with variable low permeability layers. Each aquifer show a different saltwater and mixed water penetration, that partly depends on landward freshwater potential. A borehole will penetrate water bodies of different salinities, that vary accordingly to distance to the shore. See caption of Figure 2 for comments on vertical scales.

through the aquifer) and the other with a low upstream freshwater head (almost stagnant sea water in the aquifer, but with a small flow towards the mixing zone).

The assumption that there is steady sea water level and salinity distribution inside the aquifer system is true for short residence time formations. Otherwise the system may not be under steady conditions of water potential and especially of salinity distribution. It is well known that about 10–11,000 years ago the sea level was about 100 m lower than at present and has remained more or less stable at around the present level for only the last 6,000 years. This means driving forces and salinity changes in the ground that may still be ongoing in large and thick aquifers or in low permeability formations. Coastal changes due to sedimentation-erosion have a similar influence, as happens in quickly growing deltaic or subsiding coastal zones, or to the long-term changes in aquifer recharge due to climatic evolution and natural or man-induced land cover modification, (Lambrakis & Kalergis, 2001). The current trend for mean sea level is to go up, with forecasts of about 30–50 cm in the coming half-century. Problems of changing conditions of land elevation, both natural and man-induced, are well studied in the Netherlands (Kooi & de Vries, 1998; Kooi & Groen, 2000) where complex groundwater salinity problems exist.

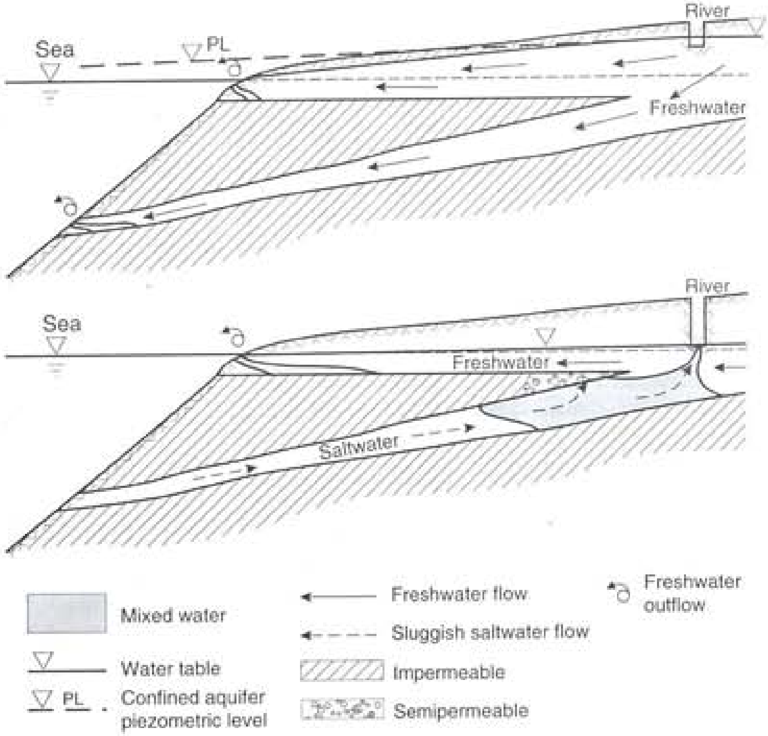

Figure 5. Schematic representation of a deltaic aquifer system with two aquifers, one phreatic and the other confined, which merge landwards, where the main river channel sets up the freshwater head. The discussion refers to the confined aquifer, considered here the most important hydraulic structure. In the case of the upper figure, inspired in the Lower Llobregat river valley and delta (Barcelona, Spain), the river channel altitude at the confined aquifer head is high and allows the flow of freshwater towards the sea outcrop and its discharge. The deep aquifer was seawater intruded early in the Holocene, when seawater rose to present position and invaded the estuary without the impermeable formation covering it. It is now flushed out with freshwater. The lower figure is inspired in the Lower Ebre river valley and delta (Southern Catalonia, Spain), in which the river channel is deeply incised by an important stream at the unconfined aquifer upper part. This means that there is no freshwater head for freshwater circulation, the aquifer contains early Holocene seawater. Besides seawater slowly flows upstream to mix with freshwater at the upstream part, where brackish water is discharged and flushed out by the main river and tributaries.

In any case the flow of freshwater exercises the important role of keeping the salinity distribution in the ground and of transporting advected and diffused salinity to the sea. From this viewpoint freshwater flowing out to the sea is not wasted if the goal is to maintain the current salinity pattern, to maintain water-dependent coastal wetlands and their salinity, and also to preserve some coastal sub-marine habitats that depend on the mixing with outflowing freshwater.

Coastal aquifers on relatively large islands do not differ essentially from continental ones except in the limitations imposed by the lack of large river basins and extensive recharge hinterlands. It can been considered that a small island has a surface area of less than 2,000 km, although the shape plays also an important role in the distribution of saline water bodies. The main characteristics have been considered in detail in Falkland & Custodio (1991) and in the numerous references given in this book. There is a wide range of situations from cases in which the effect of direct sea water can be considered small in most of an island's aquifers, as in the volcanic Canaries Archipelago, to others in which salinity seriously affects a large part of the aquifers, as in Mallorca (Manzano et al., 2000), which is somewhat larger than a small island, or to the extreme case in which

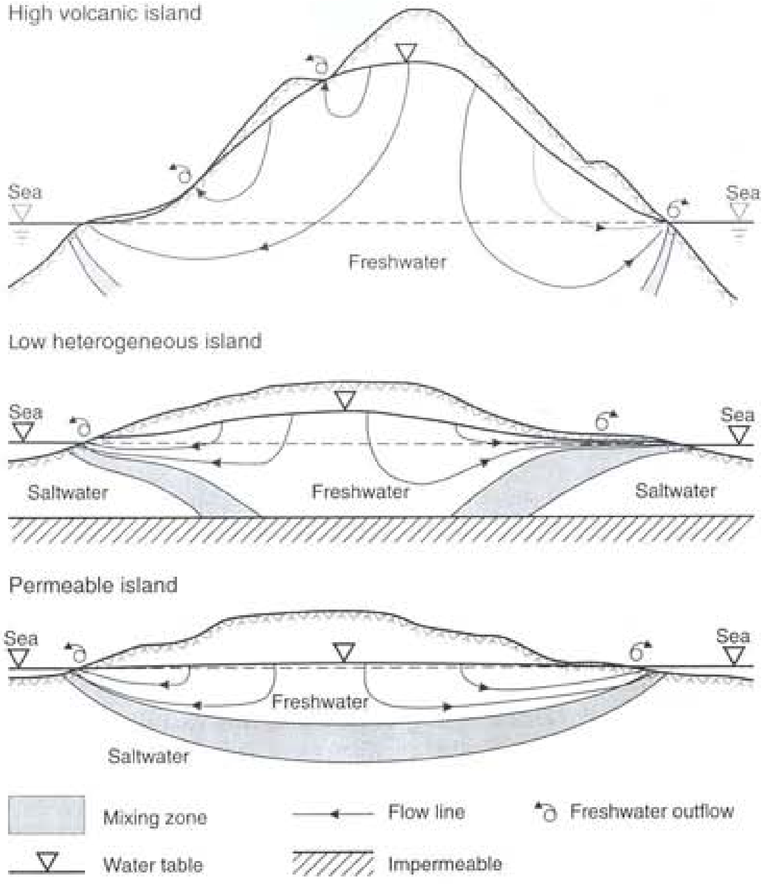

Figure 6. Small islands and capes, rounded or elongated, recharged by local rainfall. The upper figure, inspired in Gran Canaria volcanic island, shows a low permeability high island (internal structure may be quite complex) in which seawater intrusion is limited to a narrow coastal strip or coastal plains in recent volcanics, alluvium or slope deposits. The central figure, inspired in Mallorca island central corridor, corresponds to heterogeneous carbonate and marl formations, in blocks, in which there is a central body of freswater and deeply penetrating saline and brackish water wedges in the more permeable deposits. The lower figure, inspired in Malta island, show a floating freshwater lens situation in the lower highly permeable carbonates; the cover are low permeability chalky (globigerina) limestones.

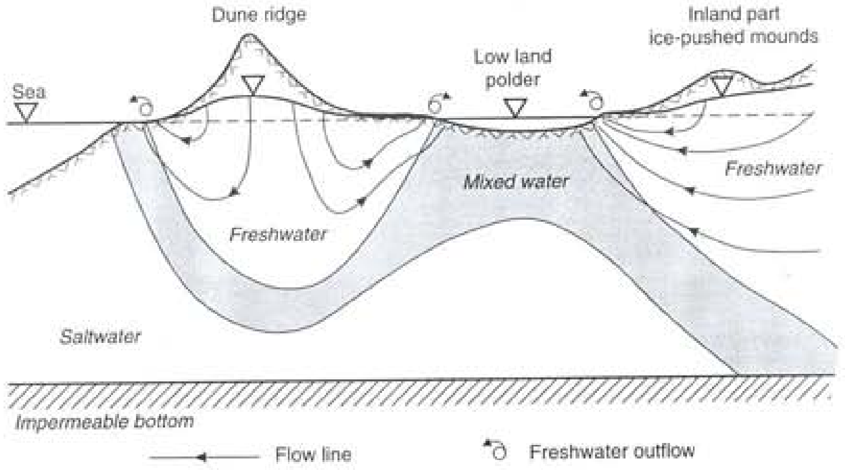

Figure 7. Situation in a coastal plain with a near-shore dune belt and intermediate low lands, as in the case of The Netherlands and Belgium, and also a series of coastal aquifers north and south of Mar del Plata. The existence of low permeability interlayers often play a key role in salinity distribution and the flow of brackish water to the low lands. The low lands may be evaporation ponds, or externally fed freshwater lakes, or in the case of The Netherlands artificially drained areas from which brackish water is discharged at low sea tide or pumped out; in recently 'reclaimed' areas current situation is unsteady and aggravated by peat layer subsidence.

there is a partly or wholly continuous body of sea water below the island. In this last case the body of freshwater is a lens floating on saline water, as in Malta and also in oceanic atolls (see Oberdorfer et al., 1970; Underwood, 1992 for additional information), key islands ('cayos') in the Caribbean sea and elongated sand bars along many coasts (as in eastern United States) and deltaic formations (see Figure 6). A floating body of freshwater may also be found in areas of continents and large islands, such as capes formed by very permeable formations, as in some areas of Florida.

The comments and discussions that follow refer to situations in which present sea level and marine water play the dominant role. But there are coastal and island aquifers in which salinity problems are mostly related to pre-Holocene marine water, as in many areas of Belgium and the Netherlands, or to present sea water, which may penetrate through top aquitards to slowly replace freshwater established in late Pleistocene times, when the sea level was about 100 m lower than at the present time and the sea coast was far away seawards, as is the case of Surinam (Groen et al., 2000) and other parts of Western Europe or the north-east corner of South America (Edmunds & Milne, 2001). Figure 7 refers to a coastal aquifer with a dune belt and lowlands behind. Figure 8 depicts the case of confined coastal aquifers that have no downflow discharge face directly into the sea bottom.

Ancient marine water, often concentrated by evaporation and suffering partial precipitation of salts, and later salt dissolution and dilution by continental freshwater, may be one of the sources of salinity of some coastal areas. This happens in Israel (Sharit & Furman, 2001; Vengosh & Ben-Zvi, 1994), where the formation of saline waters and brines are attributed to the Messinian (Miocene) crisis of the Mediterranean. In other cases diluted ancient marine water is trapped in highly heterogeneous formations that are

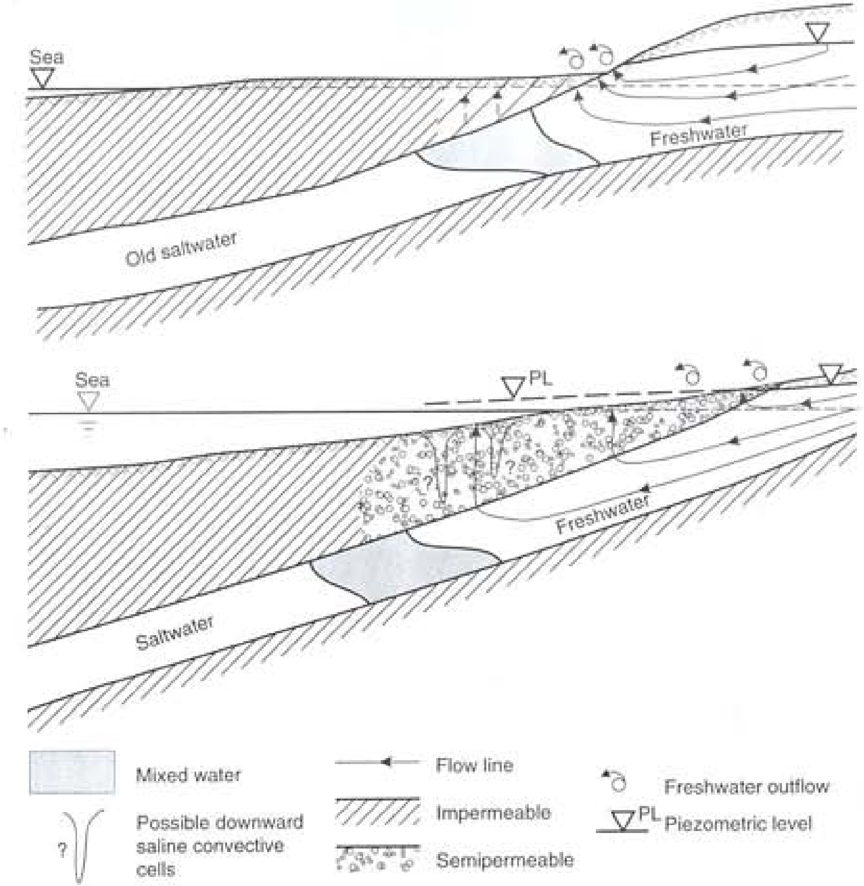

Figure 8. Two coastal confined aquifer situations. The upper figure is the case of a closed one in which recharge in the unconfined upstream part discharges inland; the rest of the aquifer may contain palaeowater, that may be fresh (as in the case of Aveiro, Portugal) or saline (as in the case of southeastern England) depending on past circumstances and the possible existence of permeable features in the impermeable confining layer. The lower figure shows a similar situation but with a semipermeable confining unit (inspired in northeastern Sudamerican situations) which in the late Pleistocene allowed freshwater penetration to displace preexisting water far offshore; with present sea level elevation this freshwater is a slowly renovating palaeowater or is being penetrated by convective vertical plumes of seawater in the offshore part if freshwater head in the aquifer is not enough to compensate for the unstable vertical salinity distribution.

regionally almost impermeable but with local permeable features that allow temporal discharges from wells, as in Fuerteventura Island, in the Canaries (Herrera & Custodio, 2002), or the high salinity is of climatic origin, as in many southern areas of the Canary Islands (Manzano et al., 2001).

Return irrigation water from crop cultivation plots in coastal areas may be quite saline if water use is highly efficient and may attain a total dissolved salt content of 2–5 g/l and even higher, as in south-east Spain and the Canaries; they may salinize groundwater resources that exist below the irrigated fields.

FRESHWATER DEVELOPMENT IN COASTAL AQUIFERS

Abstraction of groundwater from a coastal aquifer produces a groundwater head draw-down, both in the freshwater and the saltwater body. The immediate result is the creation of head depressions and the consequent reduction of freshwater discharge into coastal wetlands and riparian areas, and especially to the sea. This means an increased inflow of sea water and the modification of isocone (isoconcentration) contour surfaces. Saline water tends to approach the abstraction sites and there is a trend to slowly increase the thickness of the mixing zone at the time it moves (Figure 9). A new steady mean salinity distribution can be attained after some time. This period may be months to centuries long, depending on the aquifer characteristics and the location of abstractions. In any case an enlarged volume of the aquifer system will be occupied by saline and brackish water. Abstracted water will continue to be fresh or may become brackish and saline; the rate depends on the general behaviour of the aquifer and local circumstances. Lateral (mostly horizontal) displacement of saline water is a slow process while upward vertical movement (upconing) may be very fast (hours to days) in the absence of low-permeability horizontal layers. The presence of low-permeability layers may play a key role in delaying and reducing saline water upconing (Motz, 1992).

A three-dimensional description is often needed to correctly describe what happens, taking into account the vertical distribution of heads and salinity. An adequate monitoring network is needed, and this will be more complex and expensive than in common continental aquifers.

It is possible to abstract freshwater from a coastal aquifer that has saline water below if well discharge and penetration are small. Otherwise there may be brackish and saline water upconing (Figure 10) that may degrade pumped water or it render unusable.

Actual situations can be found in which there is intensive exploitation of a coastal aquifer with wells abstracting brackish water alongside those pumping freshwater. The situation may be quite complex and depend on local circumstances (Figure 11). Sea water encroachment is not homogeneous but follows permeability features and the spatial exploitation pattern (Figure 12), and varies with sea water inflow rates (Figure 13).

COASTAL AQUIFER MANAGEMENT

The purpose of coastal aquifer management is the same as for other aquifer systems – to achieve a sustainable use of groundwater, coordinated with the use of other water resources, to meet part of the demand for water by supplying water of adequate quality, in the place at the right time, respecting environmental and habitat restrictions. The main additional items to be considered are the risk of salinization and water quality degradation in relation with the possible accumulation of manmade contaminants in areas of low hydraulic gradient and flow pattern forming a closed area due to groundwater abstraction conditions. Often these risks do not result in immediate threats, but the results may be delayed for a long time. This means that coastal aquifer management should rely on conservation and protection measures. This is not new for aquifer management, but for

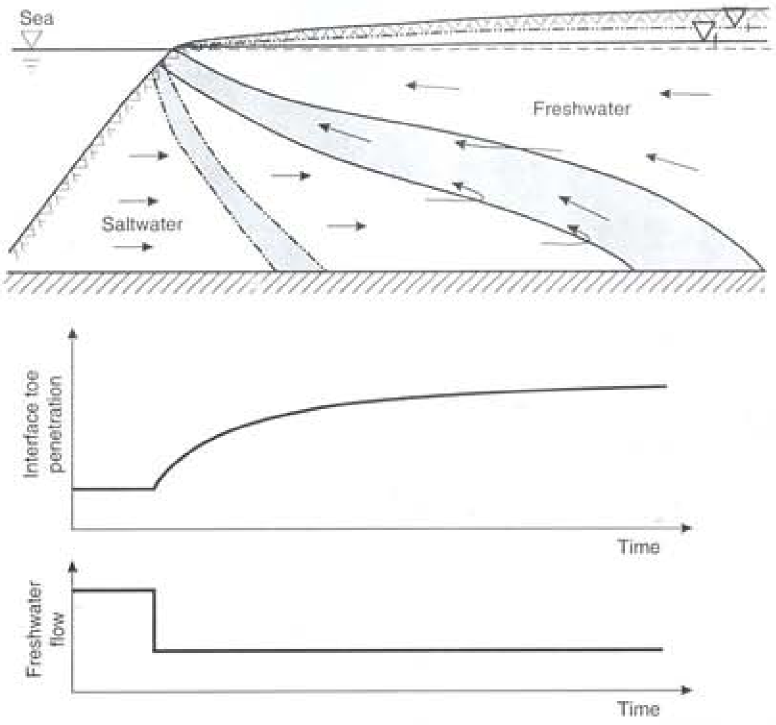

Figure 9. Effect of a reduction of freshwater flow at the coastal area. This means that the seawater wedge moves landwards to a new position at the time the mixing zone grows. The coastal freshwater storage decreases as well as the risk that near-the-shore wells may be affected by saline or brackish water. During the transient period the former freshwater part of the aquifer is invaded by saline water. This means cation exchange processes that for a given mixing degree makes harder the resulting water (especially in Ca) and depleted in alkaline ions (for Na the effect may be relatively small due to its high concentration, but it is more clear for K, so the ratio Na/K increases). The Ca increase may induce calcite precipitation and if the increase is very high (in high salinity waters in high cation exchange formations) it may happen that some gypsum precipitates, reducing the ratio SO_4/Cl. This gypsum may dissolve afterwards. The behaviour of calcite is more complex since activity coefficients behave non-linearly in the mixing. At medium to high salinities calcite, and especially aragonite, may dissolve.

coastal aquifers monitoring and protection measures should be more strictly and carefully planned. Management means a compromise between meeting the water demand and limiting the demand without serious damage to the local economy and social needs.

The main requirements for sound coastal aquifer management are:

- good understanding of aquifer behaviour
- adequate monitoring systems, with early warning signals and public information
- the authority and popular will to attain sustainable use
- a water management institution with adequate tools and resources
- the effective participation of stakeholders in management
- education, training and dissemination of knowledge and data.

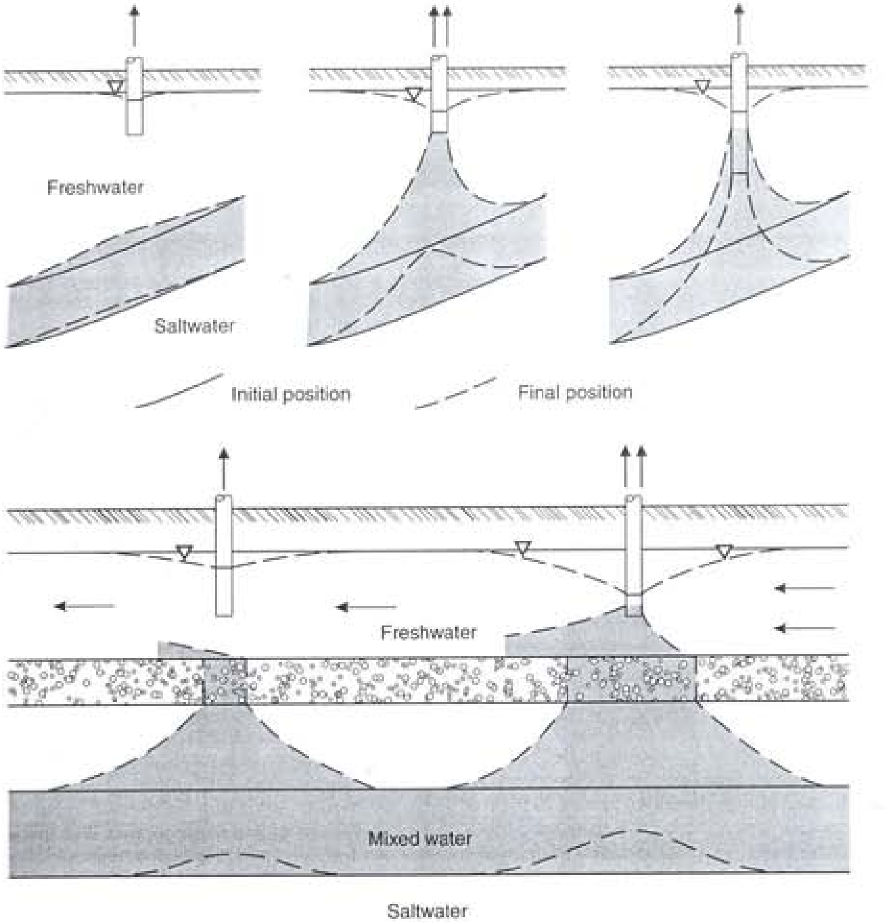

Figure 10. Abstraction of freshwater with brackish and saline water below. There is upconing of high salinity water toward the well or drain (or lake, reclaimed land, polder or drained excavation). This may be a relatively fast process. The well penetration and discharge rate control the result. The presence of low permeability interlayers spreads the influence and delays the process.

There are scientific and technical issues, but the decisive ones are economic, social, administrative and legal in nature. Quantitative approaches are possible after a good conceptual model is available, which generally needs, besides hydraulic data, hydrogeochemical and environmental isotope studies. Water samples should be obtained not only from existing wells and boreholes but from short-screened boreholes especially constructed to monitor the brackish and saline water bodies and the aquitards.

The tools that are currently available allow numerical modelling under common situations, even in three-dimensions if that is really needed. Numerical modelling is greatly reinforced by considering mass transport (salinity and individual components)

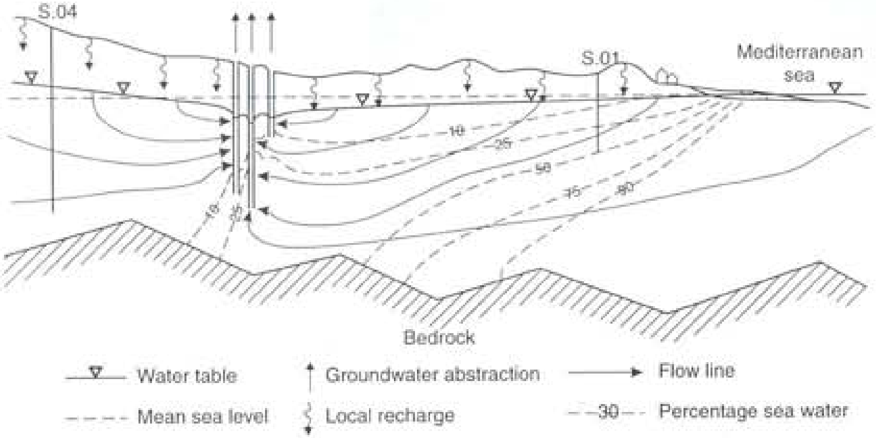

Figure 11. Sketch of freshwater–saltwater mixing in a coastal aquifer of high permeability which is intensively exploited in inland areas. Abstracted water is in part freshwater from the continental side and partly marine water arriving together with recharge in the coastal strip (after Pascual & Custodio, 1990). The mixing in the wells is variable according to location, well depth and exploitation regime.

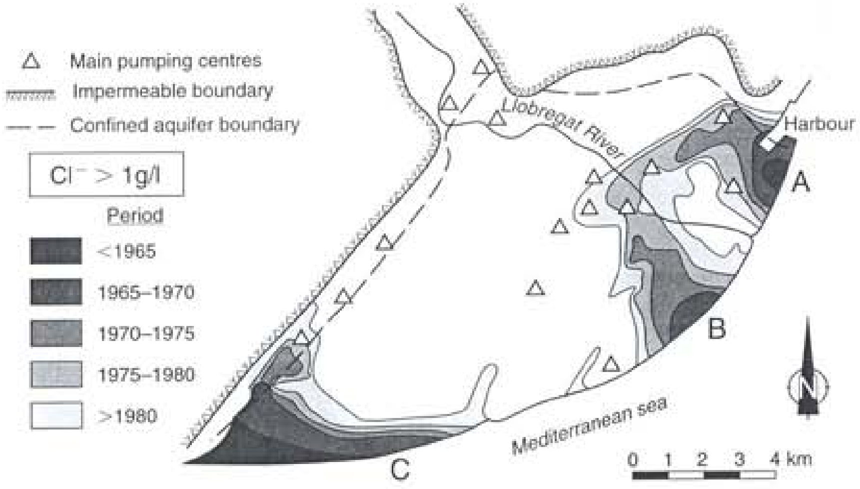

Figure 12. Progress of sea water encroachment in the confined aquifer of the Llobregat delta, Barcelona, as a consequence of abstractions (modified after Iribar & Custodio, 1993). The areas correspond to a chloride content higher than 1 g/l at different times. Three main encroachment fronts exist: A – corresponds to coarse piedmont and alluvial fan sediments; B – corresponds to the late Pleistocene river channel; C – is an area of low altitude, recent sediments, in which marine water was being displaced; the process is now reversed as a consequence of groundwater exploitation and there is saline water encroachment through the more permeable materials near the delta boundary. These areas are separated by less permeable sediments. Encroachment is delayed in them. The confined aquifer outcrops about 4 km offshore, at about 100 m below present sea level.

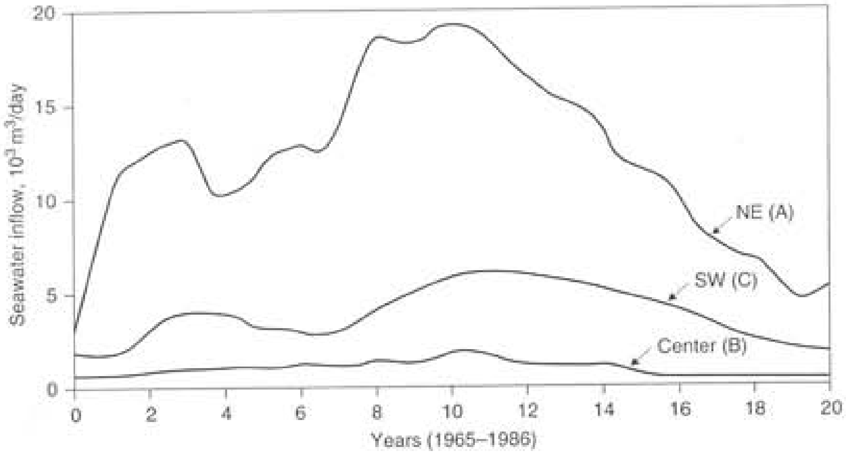

Figure 13. Evolution of seawater encroachment through the submarine outcrop of the confined aquifer of the Llobregat delta, Barcelona, NE Spain (see Figure 12), after Iribar et al. (1993). It is obtained by automatic calibration of a 2-D homogeneous fluid numerical simulation of flow and salinity transport, using 20 years of historical data (1965–1986). Groundwater abstraction increased until 1975 and later on decreased, especially in the upstream and eastern part. The changes are quite fast since it is a small (80 km^2), highly transmissive confined aquifer that is intensively exploited. The maximum rate of seawater encroachment was 30 Mm^3/year, that was reduced to 8 Mm^3/year in 1985, or about 10% of total groundwater abstraction. It concentrates in some highly saline water wells used for industrial cooling. This explains that the system tends towards a steady state when the abstraction pattern does not change and the recharge sources are protected.

besides groundwater flow transport (see Bobba, 1993; Sandford & Konikow, 1985; Voss, 1985; Voss & Souza, 1987; Kipp, 1987; Molson & Frind, 1994 for further details on basic principles). Simmons et al. (1999) explains the application to the complex situation of the Netherlands.

The change in salinity produced by the intrusion of sea water and other saline waters, when it can be monitored, gives clear signals on what is happening through conspicuous processes of ion exchange and the related dissolution-precipitation of minerals (Beekman, 1991). Some of these appear with small changes and thus may be used as early warning signals (Van Dam, 1997).

Coastal aquifer system management has to take into account the following considerations.

- Fresh groundwater abstraction means reducing freshwater discharge into the sea or estuaries, with a parallel increase in the volume of the groundwater system, which is filled with brackish and saline water, and some redistribution of groundwater bodies.
- Under given restrictions, an optimal quantity and pattern of freshwater abstraction can be found that is a trade-off between the benefits from freshwater availability and the cost of reducing freshwater storage, affecting habitats and abandoning some of the existing wells and water infrastructures. The result is not an exact figure but a series of possibilities, that also may change with time.

- Collective management is needed. This means that individual stakeholders' water rights have to be totally or partly given to a water management institution or users' association, which proposes and enforces water shares under some equity rules (Hernández-Mora & Llamas, 2001).

The number of wells that may be affected by salinization for a given coastal aquifer system development depend not only on total aquifer abstraction but also on the circumstances of each well, such as discharge, penetration, distance to the coast, abstraction regime and local aquifer characteristics. Upconing of saline water – be it recent or old marine water, or deep-seated saline water – is a common process for deep wells and intensively exploited wells. Sometimes it is not easily identified.

Often trends that are easy to observe are sought to define when there is excessive groundwater abstraction. It is often called overexploitation, although this term is not a useful one and should be abandoned (Custodio, 2002). There are trends that are not easy to observe – or plain facts – that can be substituted for a sound aquifer system study. Such a study is often justified when the benefits derived from groundwater exploitation and sustainable use have to be considered and a permanent monitoring network to update the information is needed. Intensive development of aquifers produces social benefits as well as other issues and costs that need careful study if valuable opportunities are not to be lost (Llamas & Custodio, 2003), and this is especially true for coastal aquifers.

A continuous drawdown over some years is not a sure sign of pumpage exceeding recharge but may be the result of the transient stages between the initial situation and a new one. The application to a coastal aquifer is more complex since head changes may not be clearly seen in practical terms due to the positive hydraulic barrier effect of the sea, but groundwater quality degradation due to the admixture of saline water may occur. Any freshwater abstraction from a coastal aquifer means a landward and upward displacement of saline water, as well as an expansion of the mixing zone. Then, some wells may be affected by salinization well before total abstraction approaches recharge in average terms.

Poor coastal aquifer management can be linked to the following factors.

- Too much abstraction relative to recharge, even if recharge is not exceeded. This happens more often when high-yielding wells can be drilled, especially close to the shore. Abstraction capacity is easily mistaken by non-experts as aquifer freshwater resources. Strict control of well use is needed.
- Wells and drains are too close to the shore. Salinization is often the consequence of saline upconing. Placing the wells far from the shore helps to prevent sea water contamination, but exploitation costs are higher and longer distribution mains are needed when the water demand centres are close to the coast.
- Individual wells pumping too much water. To avoid upconing and/or lateral saltwater encroachment discharge has to be limited, sometimes to a small fraction of the well yield. This is seldom understood by abstractors, but has to be enforced by management rules and supported by a groundwater users' association.
- Poor well construction or design, such as excessive depth, screens facing salinized or easily salinizable layers, and poor protection against corrosion around saline water aquifers or aquitards. It may be necessary to close down or partially grout some wells.

Large confined coastal aquifers may still contain freshwater recharged during the Pleistocene low sea level stand (palaeowater) and this water may be an important reserve for human supply if correctly exploited and managed (Custodio et al., 2001).

COASTAL AQUIFERS AS COASTAL HYDRAULIC INFRASTRUCTURES

In many cases coastal aquifers have a large water storage capacity. This capacity is mostly in unconfined aquifers but can also occur in deeper formations with saline water if it can be effectively replaced by freshwater. Freshening a saline water aquifer may be a complex problem. Aquifer exploitation may increase the storage capacity of the unconfined aquifers by depleting the water table in areas not controlled by a nearby base level.

Therefore coastal aquifers may become important elements for human water supply and guarantee that if they are properly managed. Surplus water that is available at a given moment may be stored to be used later or freshwater storage may be depleted in periods of high water demand or in emergency situations, to be restored naturally or artificially during periods of low water demand and/or increased recharge. An important aspect is the ability to use freshwater storage in the ground for emergency situations. The main difference to continental aquifers is the need to monitor and forecast the saline water position and its slow movement in the aquifer system, and distribute wells and groundwater abstractions in such a way that the risk of saline water contamination is minimized. This means not only adequate monitoring and the operation of simulation models by a responsible institution, but also the capacity to decide when and where to abstract and recharge water in the whole aquifer system. Moreover, the part of the aquifer with saline water, or temporary intruded sea water, will need an excess of freshwater – often a large excess – to flush out trapped saline water in heterogenities and to restore sorbed ions on exchange sites.

Artificial recharge is one of the means to operate coastal aquifers as hydraulic infrastructures. There is enough experience to solve most practical problems related to recharge water, the methods to introduce water into the ground, the maintenance of recharge capacity and the recovery of introduced water (Custodio, 1986). The design and operation is something that depends largely on local conditions and must be tailored to each particular situation.

The effect of artificial recharge and the results of management activities can be numerically modelled provided adequate monitoring exists, but the operation of the facilities needs local experience and sometimes have to been preceded by pilot projects and plants. This also happens during the design, construction and operation of many other hydraulic infrastructures, for which the time and economic resources invested are considered part of the project and carried out carefully. The main difference is that the aquifer already exists and does not have to be constructed.

Often people take natural infrastructures for granted and consequently do not consider they have a value. Economically this is not true. The value of an aquifer system that is capable of performing a series of beneficial tasks can be estimated as the cost of the cheapest alternative infrastructure to perform the same task. In many coastal areas, where land is expensive, there is little available space for the construction of hydraulic structures and aquifers become especially valuable elements that also have a strategic worth.

The relatively small (80 km) but highly productive (up to 150 mm in 1975) lower Llobregat Aquifer (the lower valley and delta), with an associated regulation capacity of about 100 mm (Custodio, 1992), is an important element for supplying water for human and industrial use to a proportion of the four million inhabitants of Metropolitan Barcelona, in north-east Spain, and also provides key emergency storage of freshwater. Recharge and water abstraction facilities are threatened by the high pressure for urban and industrial expansion, and for new space for roads, railways, the airport and the harbour. The aquifer's value is reckoned at 300–600 million Euros, which justifies the effort to sustain its use and to force public authorities to invest in protection and rehabilitation, coordinating with the existing effective groundwater users' association.

Individual stakeholders does not generally have any idea of the value of the system they are using and are not aware that they share the aquifer with many others. Only the combination of institutional and collective participation in management can put things in real perspective and direct economic activity towards sustainable use. This is the means of avoiding the 'tragedy of common property' – one of the 'hydromyths' to be ousted (Custodio, 2002).

Strategies for coastal aquifer exploitation may include using brackish or saline water, either intentionally or as the result of other freshwater sources being unavailable. Some benefits are derived from using these brackish or saline waters. They can provide water of almost constant temperature, advantageous for cooling – after coping with the greater corrosiveness and hardness – or be the source of water for desalination. This groundwater is already filtered, has no fouling micro-organisms and has relatively stable physical and chemical characteristics. After correcting for the presence of possible undesirable contents, like high hardness and high silica content, this may be a cheaper alternative to using sea water directly, especially if groundwater is brackish and no large salinity changes are expected during exploitation. In this case pressure membrane processes lower than for sea water are employed for desalination and especially reverse osmosis.

Groundwater with a salinity close to that of the sea water may be used to supply fish farms. But in many circumstances such waters are anoxic, with some ammonia (as in deep deltaic aquifers rich with organic matter) and other deleterious ions, such as heavy metals and especially As in some cases. This limits their direct utilization and the benefit of getting a constant temperature source that saves energy may be reduced.

Pumping saline water from wells decreases saltwater head in the aquifer and consequently limits saltwater encroachment in the aquifer, even when freshwater heads are maintained below mean sea level. This prevents salinization of other landward wells, but is a temporary solution. The abstracted saline water may have a beneficial use, such as cooling for industrial plants. The use of brackish or saline groundwater, directly or after being mixed with freshwater to reduce salinity, presents a series of drawbacks:

- it jeopardizes the possible re-use of treated waste water when saline water is disposed into or penetrates the sewerage system
- it may decrease agricultural output and produce soil salinization and alkalinization
- it may impair the water-table aquifer quality, either through leaks in distribution mains and pipes, or in the disposal pipes and canals to the sea, or by generation of saline return irrigation flows.

Direct coastal aquifer protection measures, beyond improved management and imported new freshwater sources for the area, include barriers to control sea water encroachment. They are discussed elsewhere (Custodio & Llamas, 1983; Custodio & Bruggeman, 1987) and some details and also relevant references are given in Custodio (1986).

Physical barriers have been envisaged and projected repeatedly for small, well-bounded coastal alluvial formations. But it seems that no significant physical barrier has been constructed up to now. The cost is very high relative to the small increase in water resources such barriers provide, besides construction problems, doubts about efficiency and associated quality problems, due to impaired exportation of solutes.

Hydraulic barriers consisting on a line of injection wells have been constructed in California, the oldest of which is near Los Angeles (Bruington et al., 1987; Bruington & Seares, 1965). This is an expensive solution to sustain domestic supply wells in large areas of low-density housing, but the construction of a water supply network in extensively salinized areas was an even more costly solution. The barrier restores freshwater outflow to the sea, provides flushing of inland trapped saltwater and produces a net aquifer recharge. In the same area saltwater pumping barriers or combined freshwater injection and saltwater pumping barriers have been experimented with, the design being adapted to local aquifer circumstances. Since a large part of the injected freshwater is to restore the flow to the sea, carefully treated tertiary sewage effluent has been used in some cases, as near Los Angeles, California (Argo & Cline, 1985, in Asano, 1985) or is being planned in other areas, as Metropolitan Barcelona.

These are solutions adapted to local circumstances. They are not necessarily the right solution for other aquifers. For the confined aquifer of the Llobregat Delta, Barcelona, currently the best solution seems to be temporal pumping of saline water in the more permeable areas, restoration of recharge in the lower valley and substitution of some groundwater pumping stations by supplying freshwater from other sources (Custodio, 1992, 1993).

REMEDIAL ACTION FOR IMPAIRED COASTAL AQUIFERS

Coastal aquifer salinization, except for local upconing, is a slow process that involves the replacement of large volumes of freshwater by brackish and saline water. Remediation is therefore a slow process that includes not only replacing the volume of salinized groundwater for freshwater but also the need to flush out saline water trapped in heterogeneities and to replace the sorbed cations. This means high costs and long time, in contrast to the rapid results sought by investors and politicians, and expected by the media and lay people, and also by hydrogeologists who only consider homogenous groundwater flow. Again preservation appears as a necessary management goal. Well-documented experience on remediation is still scarce and mostly refers to small, highly permeable alluvial formations and karstic aquifers. Non-reactive displacement can be simulated (Travis and Song, 2001), but full consideration of ion exchange processes and changes in formation permeability are still ongoing.

Abandoning a coastal aquifer may be technically and economically a sound decision, if accompanied by the provision of a new freshwater source. But from the point of view of securing water supply, and freshwater storage for emergency situations, and of strategic value, aquifer abandonment is not generally a sound decision. In fact the recent European Union Water Framework Directive, ratified in 2000 and now being incorporated into national legislations, and developed into specific directives, sets out the need to restore and remediate aquifers. The particular application of this principle to already deteriorated coastal aquifers is still developing.

The abandonment of a former intensively exploited aquifer is followed by water table recovery and salinization of the previously drained vadose zone. This may mean significant damage to land use and urban infrastructures, as in the case of Mar del Plata, Argentina and Barcelona, Spain (Bocanegra & Custodio, 1995).

Remediation involves a series of actions such as careful grouting and isolation of wells that allow the movement of saline water from one layer to another, closing of pumping wells, enhancement of recharge, artificial recharge, forced drainage of saline water and the elimination of saline water disposal and leakage. This should be accompanied by an adequate monitoring network.

CONCLUSIONS

Coastal aquifers can be a sustainable source of freshwater if correctly managed and exploited according to recharge and local hydrogeological characteristics. Freshwater outflow to the sea controls sea water wedge penetration and the thickness of the mixing zone thickness. Management strategy has to decide how much freshwater is left for this role and to sustain groundwater-related habitats, and adapt the abstraction pattern to the resulting saltwater wedge penetration. Transient periods can be long and produce the false feeling that a given exploitation pattern is safe. As part of the long-term water planning of a region, freshwater in a coastal aquifer can be intentionally mined for beneficial use for a limited time, after which the aquifer becomes salinized; then other sources of water have to be brought in or water use has to be reduced (Llamas & Custodio, 2002).

An adequate monitoring network is needed to measure and take samples of fresh, brackish and saline water. A set of point boreholes for each site is the correct solution when vertical head gradients are to be expected or created by groundwater exploitation. Long screened boreholes may easily disturb salinity stratification.

Coastal aquifer management is not only a technical issue but an administrative, social and legal issue as well, in which aquifer water users have an important role once common goals are settled and individual rights are adapted to them. The local legal framework and administrative regulations condition how things can be solved. But in any case the right solution for management and sustainable use seems to be power sharing between a public institution and stakeholders with collective participation.

Aquifer protection implies protection of the role of low permeability layers, adequate well and borehole design and construction, and the plugging and sealing of abandoned wells and boreholes. Protection does not mean that every well or water right has to be protected. Management implies a trade-off between allowable saltwater penetration and sustainable groundwater abstraction in a dynamic framework.

Management and protection issues when the saltwater source is the sea are different from situations in which there are other sources of salinity. Identification of the true source of salinity and understanding of salinization dynamics is key starting points for management decisions, protection and remedial measures.

Remedial measures include the restoration of enough freshwater discharge to the sea and allowing enough time for saltwater displacement and diffused salt in low permeability heterogeneities to be flushed out, and for ionic exchange complexes to equilibrate again. Saltwater replacement can be forced artificially by saline water pumping and disposal into the sea, but at a cost. When human activities have changed the aquifer by actions like drilling boreholes through low permeability layers, constructing multiple screened wells or over-excavating canals and trenches, remedial action has to consider the possibility of restoring the natural situation.

Coastal aquifers are not only permanent sources of freshwater but storage reservoirs in areas where other storage reservoirs are often difficult or costly to construct. This is important for emergency purposes (droughts, breakdowns or pollution of other water supply sources) and has a strategic value. Coastal aquifers can be over-pumped for some time without undesirable results due to the slow movement of groundwater, provided there is no saltwater below the wells or there are natural clay layers that delay saltwater upconing.

Saline water in the ground may not easily be displaced by freshwater. Freshening may be a slow process that needs several equivalent volumes of freshwater, depending on salt diffusivity from low permeability heterogeneities and the total cation exchange capacity.

Physical, chemical, demographic, economic, geographical, social, legal and political circumstances make every coastal aquifer unique. Managerial solutions to its problems are also specific. This means that solutions have to be tailored to the aquifer characteristics, using all the knowledge and experience derived from other areas, but not simply by copying them. Otherwise expensive errors that are difficult to correct can be made. The most important step is obtaining a representative and workable conceptual model of the coastal or island aquifer system flow and salinity transport. Development, preservation and restoration activities must fit within this.

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