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Management of coastal palaeowaters

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Abstract: Coastal regions of Europe have special water supply problems due to the population pressure, competing demands and the ever-present risk of saline intrusion from modern and old sea water. This is especially the case in southern Europe where touristic demands exacerbate water supplies, often in semi-arid regions. Palaeowaters emplaced at times of lowered sea level offer potential high-quality, high-value reserves in many areas, although a lack of understanding of the nature of the resource, together with exploitation for non-drinking purposes and indiscriminate drilling, may already have damaged the underground reservoirs and the reserves within them. These aquifers may, however, offer sites that are attractive for seasonal water storage.

Palaeowaters generally are of high quality and are demonstrably free of human impacts. Good drilling practice and operation are required to avoid contamination, the mixing of palaeowaters with more saline waters and avoidance of marine intrusion. Two case studies illustrating the management practice in areas containing palaeowaters – in the French Mediterranean coast and the Llobregat Delta area of Catalonia, Spain – are given. These demonstrate, above all, the need for integrated development, observation and planning, which involves all the stakeholders, especially the beneficiaries and end-users. There is a need for improved regulation for the protection, use and management of aquifers containing palaeowaters at both the national and European scale, to consider the intrinsic value of uncontaminated palaeowaters as a unique, non-renewable source of drinking water. The value of such aquifers for subsequent freshwater storage and also for use as a brackish water source for desalination may also be considered.

In many countries and regions of Europe, and elsewhere, the population and its activities tend to concentrate along the coasts. This is due to favourable climatic factors and the availability of flat land, easy transport and arable soil. Moreover, important infrastructures were built in the past when the seas were essential to trade and development. Currently, tourists and retired people from industrialized regions show a preference for coastal areas and islands in mild, even arid, climatic areas for secondary or permanent residence during the increasing life span after retirement.

Thus, in many coastal areas, or in nearby localities, there is an intense competition between urban, industrial, storage, touristic and farming space, which sometimes coexist uneasily. In these areas the availability of freshwater is, or may become, a major issue, having an impact on the sustainability of the regional economy. Common groundwater problems to be solved refer to quantity, quality and seasonality, as well as increasing pollution, saline intrusion and contamination, and sometimes interferences with valuable ecosystems and the natural environment. Often, people living in coastal areas demand drinking water free of anthropogenic constituents and this may become a difficult task in those areas downstream of human activities in the continent or on the island, except if palaeowaters are found.

In areas with favourable terrain and climate, agriculture is often the principal consumer of good quality water, and is a rival to urban water supply.

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Agriculture is a traditional activity that nowadays progressively expands and evolves towards intensive farming, taking advantage of the favourable coastal conditions, such as flat terrain, high local food demand and trade advantages. Often, agriculture is politically protected yet, at the same time, it is responsible for the deterioration of groundwater quality by enhancing saline intrusion as a result of groundwater abstraction, application of agrochemicals and the infiltration of saline return flows. Coastal urban areas, which demand large quantities of good quality water, create conditions for deterioration and pollution, including intensive abstraction that causes seawater intrusion. All this is well known and is the subject of numerous studies, especially in southern Europe (e.g. Custodio & Bruggeman 1987; Falkland & Custodio 1991; Custodio & Galofré 1993; Chilton *et al.* 1997; van Dam 1997).

Currently, deep wells are constructed in coastal aquifers for groundwater exploitation to supply all the different water needs, including industry and agriculture. Drilling down to several hundreds of metres is currently not uncommon. In many situations these wells exploit good quality palaeowaters – often without knowing it – and their unique properties are not considered. Palaeowater is a non-renewable reserve, having originated under climatic and hydrodynamic conditions different from today, free from anthropogenic pollutants. It is worth considering its most beneficial use, and setting specific management and protection norms.

The preservation of palaeowater in coastal aquifers and islands is the result of physical conditions that allow for storage of groundwater with long turnover times. This implies a combination of physical (low permeability formations enclosing the aquifers) and hydraulic (low water head gradients) conditions. The higher hydraulic gradients, which often prevailed during much of the Late Pleistocene, coincident with lower sea levels, allowed continental or island freshwater to penetrate into coastal permeable formations; subsequent and currently lower natural hydraulic gradients, due to small head differences, slow groundwater replacement.

Palaeowater can be found in several parts of continental Europe in the thick sedimentary basins, e.g. the Paris (Kloppmann *et al.* 1998), Po and Pannonian (Stute & Deak 1989) Basins. Similar situations are found along several parts of the European coast, some of which are described in detail in the present volume, where the unique influence of sea-level change has also had an impact on groundwater conditions. Important and well-developed coastal sedimentary basins are found along the eastern and southern coast of the Baltic Sea and continue along the North Sea coast. Other well-developed coastal basins are found in the UK, The Netherlands, Belgium and the Atlantic coast of France. Along the Iberian Peninsula and the northern part of the Mediterranean sea the closeness of the mountains to the coast reduces the extent of these coastal basins, but some large systems are still found, such as the Aveiro and Lower Tejo–Sado areas, the Guadiana and Guadalquivir coastal deposits and deltas, and the Mediterranean Miocene basins and the deltas of the Ebre, Llobregat, Rhone and Po. In all these areas, recent, low permeability deposits cover deep aquifers that are likely to contain palaeowater.

A wide variety of geographical and hydrogeological situations are described in this volume. Aquifers are described from the north of Europe to the southernmost areas in the Iberian Peninsula and the Canary Islands, from large coastal basins to carbonate and volcanic formations, from cold, wet climates to warm, dry areas, from rural to periurban areas, comprising a wide range of situations. These examples can be used to show how adequate management may deal with problems of aquifer development sustainability, profiting from the unique characteristics of palaeowater in such coastal formations.

Groundwater management may be considered as the set of rules and actions needed to obtain a given set of technical, economic, social and political objectives. These objectives refer to water supply, landscape and wetland preservation, and economic development of a region. Often it involves a tradeoff among conflicting interests, both in the short and long term, taking into account the sustainable use of the water resource and the preservation of its role in important natural processes. In the end, management involves scientific principles, technical operation, economic considerations, fulfilment of socio-political constraints and political decisions.

The objective of this chapter is to discuss the special characteristics of palaeowaters in coastal aquifers and the need to manage them correctly, presenting the main principles to make good use of and to protect these groundwater resources.

The role of coastal aquifers

Coastal aquifer systems in which palaeowaters may be located differ from other continental aquifer systems in three main respects. Firstly, particular hydrogeological conditions are to be found in the boundary zone between the continent in which erosion and transport carry sediments towards the coast, and the physical and chemical sedimentation environment created by the base level imposed by the sea elevation at the time and its salinity. Secondly, the discharge of continental groundwater into the sea-water body is restricted by marine water salinity and its greater density, so that the denser sea water tends to occupy the lower parts of aquifer systems. Putting aside the short-term oscillatory effect of tides, in the long term sea water does not flow in geological formations unless diluted by freshwater, or until relative sea-level changes are produced, or the freshwater flow pattern is modified by natural causes (climatic change) or under human influence (notably pumping). The third aspect refers to continental water quality: just a few per cent of sea water in freshwater drastically impairs its ability to be used and > 3–4% renders it practically unsuitable for most purposes; only costly desalination processes may upgrade it. In coastal aquifer systems sea water and trapped marine water in aquifers and aquitards may be in direct contact with continental groundwater. In coastal aquifers, therefore, detailed information on both freshwater and saline water distribution patterns and heads is needed, in addition to the common knowledge of aquifer properties and hydrodynamic conditions.

In spite of being more complex, coastal aquifers can be investigated, understood, developed and managed with well-known and established principles and means, and as such constitute important key elements in the water supply systems of coastal areas (Custodio & Llamas 1984, section 13; Custodio & Bruggeman 1987; Bear *et al.* 1999). Aquifers play the role of natural sources of water and of storage reservoirs in just those areas where surface waterworks and reservoirs are often difficult and expensive to introduce, due to the lack of space and adequate site conditions. Moreover, groundwater discharge in coastal regions may create valuable coastal wetlands and unique ecological situations that deserve due consideration.

Coastal aquifers can be developed as a continuous source of water or as a reserve for discontinuous use, or some combination of both, or as an emergency back-up in case of failure of other water supply systems. The operational rules depend on the state of the coastal aquifer, the existence and characteristics of other sources of water, the variability of demand, the restrictions imposed by the water distribution network and economic factors, as well as existing rights and legal constraints.

Peak water demand situations pose serious problems to water supply in many coastal areas. The most acute ones correspond to large increases in demand due to seasonal irrigation and tourism requirements. In some seaside resorts seasonal populations may increase by an order of magnitude, at the same time that agricultural demand also increases. To cope with this waterworks have to have the capacity to supply peak demands, implying underutilization at other times, or they have to be backed up by a separate storage of good quality water to be used at this time and then replenished over the rest of the year. In many cases, coastal aquifers may fulfil this role securely and economically, even the small ones, if correctly managed and duly protected.

The risk of sea-water intrusion and the potential for saline upconing below pumping wells and drains is an added complexity but this need not hinder aquifer development. Much of what is referred to in reports and in the literature as negative effects of coastal aquifer exploitation is often the result of lack of awareness of the nature of coastal groundwater, poor development and inadequate management. This is one of the myths referring to groundwater, mostly propagated by those who ignore groundwater properties or systematically oppose aquifer use in favour of surface water or desalination (Llamas & Delli Priscoli 2000). Sea-water intrusion can be tolerated to some extent; it is reversible under some circumstances and can be controlled by reducing abstraction rates and by careful monitoring, or by reducing the salt water head by pumping out saline water (Custodio & Bruggeman 1987).

The large freshwater storage volume in many coastal aquifers allows for intensive use during short periods of time (weeks to months) without serious deterioration of water quality and the environment. Under favourable circumstances the antecedent conditions may be recovered during a period of reduced pumping, if the discharge of freshwater into the sea is restored.

Freshwater coastal aquifers can often serve as water storage reservoirs by means of artificial recharge, by applying the most appropriate methods and by managing clogging effects. The operational cost is a main constraint to the practical feasibility, as well as the possible modification of aquifer water quality by substitution or by mixing with the artificially recharged water. This is a complex function of recharge siting, well characteristics and operation (Custodio 1986).

Storage capacity may also be found in brackish or saline coastal aquifers if existing groundwater can be effectively displaced. The body of artificially injected or recharged freshwater presents a mixing zone (dispersion zone) with native water, the width of which is controlled by aquifer properties and geometry, local heterogeneities, the buoyancy of freshwater in saline water and the operation of the injection–abstraction wells. However, introducing freshwater from the surface or through interaquifer (natural or forced) leakage also means introducing anthropogenic chemical, biological and radioactive contaminants, some of which may be a health concern, even at low concentrations. Thus, before deciding to use a coastal aquifer containing brackish or saline palaeowater for artificial storage it is worth considering whether this water may not be usable as a source of freshwater by desalination.

Coastal aquifer management has to consider the special characteristics mentioned above, mainly the existence of saline water and the risk of saline intrusion and other forms of salinization. This includes a knowledge of the saline groundwater origin, age of groundwater and the processes leading to intrusion and salinization.

Occurrence and quality of palaeowaters in coastal aquifer systems

The existence of palaeowaters in a coastal aquifer system is the result of parts of its waters having a long turnover time due to the right combination of low permeability and low groundwater head gradients. Palaeowaters are a non–renewable resource with a given volume similar, to some extent, to other fluid mineral reserves such as oil and gas.

Palaeowater occurrence may be represented by two extreme situations or a combination of them both (Zuber 1986; Custodio 1991). One of the extreme situations corresponds to the so-called piston flow model, in which a given volume of water pushes and replaces that existing downflow, without mixing with it, although really some diffusive and dispersive mixing in the displacement front and boundaries always exists. This may be the case of confined aquifers being recharged in one extreme and discharging through the other. The other extreme situation corresponds to the so-called good mixing model (often equivalent to an exponential mixing model), in which in the aquifer there are different flow paths, lengths and velocities so that, in a given place, water age varies with depth, generally increasing downwards. This is the case of an aquifer recharged from the surface and outflowing downflow in a small area, where different flow paths converge and groundwaters of different ages mix. The same happens when a long-screened borehole pumps out groundwater. Although some mixing is possible inside the aquifer, by diffusion and dispersion, most of it is due to advection at the natural or artificial outflow areas. Several combinations of these extreme models are possible but, in any case, there is a given volume of the aquifer or the aquifer system that may contain palaeowater, even if it is not closed. These palaeowaters can be exploited separately from the others, avoiding mixing, if abstraction is carried out with an understanding of the hydrodynamic conditions. In coastal aquifers, fluid density changes play an important role, as do the special sedimentary conditions and head gradients and their evolution with time.

When aquifers are open with respect to land surface, other aquifers or extensive aquitards, discharged or abstracted palaeowaters are progressively replaced, totally or partially, by recent water. Otherwise the aquifer is progressively exhausted – continuous groundwater level drawdown – and in the extreme case the aquifer is practically emptied. Generally, only a fraction of the total palaeowater volume is exploitable without mixing with younger water; this fraction is a function of well siting, screen position or open hole depth, and abstraction rate. In coastal aquifers replacement water may be saline water.

One of the main beneficial uses of fresh palaeowater is for drinking purposes. Not only do most palaeowaters have the advantage of good biological quality and relatively stable or slowly changing physical and chemical characteristics, common to most groundwaters, but they are free of artificial pollutants such as polycyclic hydrocarbons, halogenated solvents and disinfectants, pesticides and their derivatives, pharmaceuticals, industrial heavy metals, anthropogenic radioisotopes (fission and activation products), pathogens and viruses. This is especially important when safe treatment for potability is not available, is difficult (as in rural areas and small towns) or is too costly. In addition, in many areas of Europe there is an increasing popular demand for a good quality, tasteless, untreated water supply, and often palaeowater is or may be an important source for bottled water.

In several countries, high-quality palaeowater may have been used without recognition of its origin or its non–renewable character. The very high quality groundwater in the Triassic sandstone of the East Midlands, UK (Edmunds *et al.* 1982) is being used not only for public supply but also for high consumptive uses such as for cooling water for power stations (Fig. 1), where low total dissolved solids is an advantage from the point of view of corrosion and scale control. Similar situations are found, for example, in the Aveiro aquifer, Portugal, where industry is one of the main users of the high-quality palaeowaters (Condesso de Melo *et al.* 2001). In those areas where palaeowaters are recognized it is recommended they are used for drinking purposes and as a strategic reserve only. Elsewhere, the high quality and unique characteristics of palaeowaters are being exploited successfully. This is the case in Estonia, where a recently completed scientific evaluation (Vaikmäe *et al.* 2001) has enabled marketing of the bottled water and beer production (Fig. 2) based on the knowledge that the groundwater in the Cambrian–Vendian aquifer is demonstrably palaeowater

Fig. 1. In several countries, high-quality palaeowater has been used without recognition of its origin or its non–renewable character. The figure shows palaeowater used for cooling purposes in the Trent Valley area of the East Midlands, UK. The groundwater in the Triassic sandstone of the East Midlands is being used not only for public supply but for cooling water for power stations, where low total dissolved solids is an advantage from the point of view of corrosion and scale control.

Fig. 2. Estonia beer. Groundwaters from the Cambrian–Vendian aquifer in northern Estonia are demonstrated to be of Pleistocene age. They contain the lightest recorded isotopic signature of any groundwaters in Europe ($\delta^{18}O$ values as low as –22‰). The aquifer is used as a source of good quality groundwater for the coastal towns, although it is subject to pollution from industry as well as from marine intrusion from the Gulf of Finland. Local breweries now use this water, which can be demonstrated (from isotopic studies) to be genuine glacial meltwater, unaffected by human impacts.

derived as meltwater from the Devensian ice sheets, with a very light isotopic composition ($\delta^{18}O$ of –22‰). A brewery establishment in the Llobregat River Delta, Barcelona, Spain, in the late 1960s was also looking for palaeowater but, in this case, due to short groundwater turnover time, abstracted water was soon of recent age.

Unfortunately, fresh palaeowater may sometimes contain components that are undesirable, even toxic, which necessitate treatment before use. This is the result of the long contact time with aquifer minerals under diverse environmental conditions. The result may be an excess of some components such as F, V, As, an excess of Na with respect to other base cations, and perhaps slightly high radioactivity (mainly Rn gas). Under reducing conditions, an increase in metals (notably Fe and Mn) may be expected in palaeowaters and/or they may contain dissolved hydrogen sulphide, ammonia and some gases (CO_2, CH_4). Temperatures may be quite high for deep boreholes and in some areas there are high geothermal gradients. This may be an advantage in cold areas but may require some storage detention in warm areas to cool this water prior to its use. Hard palaeowaters with high equilibrium CO_2 pressures are a nuisance for domestic use (laundry, heating), possibly causing serious scaling in pipes. Reducing and acidic palaeowater may also enhance corrosion of pipes and appliances.

Palaeowaters are also used for agriculture, especially in the Mediterranean area where the largest water demand is for irrigation. High salinity, an excess of Na relative to other base cation concentrations and sometimes constituents like B of these palaeowaters may lead to problems for plants and the soil. Water treatment is likely to be too expensive, except for high value crops. Much of industry and agriculture, including livestock, require water of a lower quality than humans and may therefore use other water sources. Thus, as a general rule, non–renewable palaeowater resources should be preserved for use as drinking water. This general rule has to be adapted to local circumstances of actual palaeowater conditions and quality, water planning and management alternatives.

Although in many cases palaeowater is fresh and exempt from toxic substances, in other cases it may be saline or brackish. Since saline or brackish palaeowaters, if correctly exploited, are free of industrial chemicals and their degradation products and also of biological contaminants, they may become a suitable water source for desalination. This practice is growing in frequency in some arid or water-scarce coastal areas and islands. Salinity can be of marine origin (unflushed or partly flushed sea water) or the result of scarce recharge where most of the rainfall evaporates and may combine with the relatively high airborne salts due to the proximity to the coast and winds coming from the sea. In particular, this is the case for extensive areas of the eastern Canary and Cape Verde Islands.

Currently, reverse osmosis is the most usual desalination method for brackish groundwater but electrodialysis is also applied if water salinity is moderate. This is now common practice in Gran Canaria (Fig. 3) and Fuerteventura (Canary Islands), and is also being developed in the coastal areas of eastern Spain and the Balearic Islands. Desalination by means of membrane techniques is cheaper for brackish groundwater than for sea water. For plant efficiency, water salinity has to be relatively constant and free from troublesome components. Dissolved silica, for example, must be below reasonable limits or has to be controlled by pre-treatment. The lack of turbidity and the constant temperature, together with the lack of anthropogenic and biological contaminants, are distinct advantages in utilizing these palaeowaters. Desalination plants produce a return that is saline water or a brine; its safe and environmentally sound disposal may be a serious and costly problem.

Natural groundwater discharge of palaeowater is of vital importance for maintaining important wetlands in many regions of coastal Europe. The situation is well known in the Doñana National Park in southern Spain (Manzano *et al.* 2001). Dewatering of the area for agriculture had led to drying-up of flowing wells and desiccation of large areas. At the present day, deep groundwater, that has been proved in the studies described in this volume to be palaeowater, is pumped out to maintain some lagoons of the ecosystem on an emergency basis (Fig. 4).

Another possible use of brackish and saline palaeowater is as a source water for fish farms, where constant, slightly warm temperatures are advantageous. Fish and shellfish are, however, very sensitive to reducing conditions, ammonium and certain trace components, such as iron and some other heavy metals, which may be present in palaeowaters in deltaic sediments. This may hinder the direct use of this water or make it too costly if pre-treatment is needed. This has been tried in the coastal area of the Ebre Delta, Catalonia, Spain (Bayó *et al.* 1997), where palaeowater of marine origin exists.

Development of groundwater and palaeowater in coastal areas

The existence of palaeowater in coastal areas and islands is the result of special local characteristics. Drilling may greatly disturb the existing pattern of

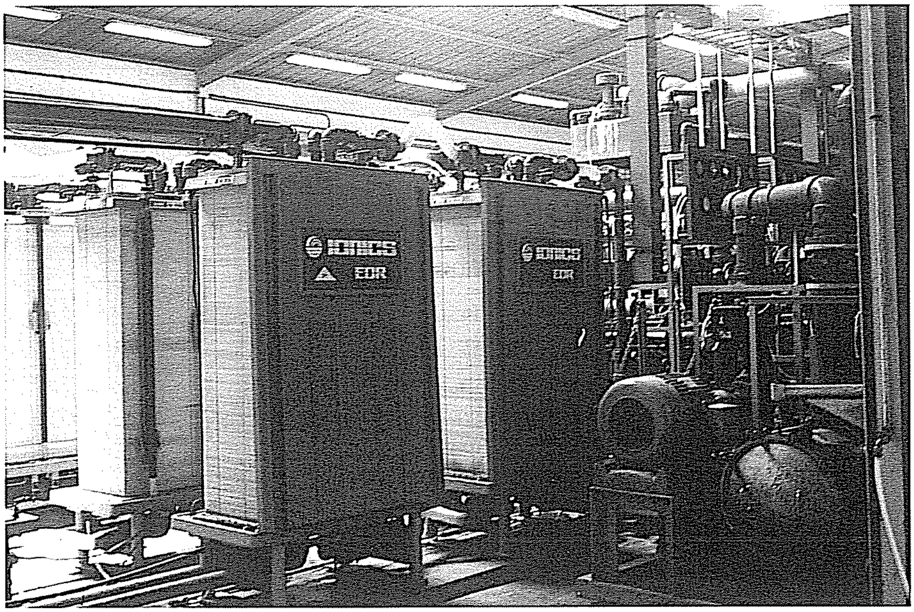

Fig. 3. Electrodialysis plant in Playa del Ingles, Gran Canaria, used to desalinate brackish palaeowater. Brackish water from the Amurga phonolite Massif is used for desalination near the Maspalomas–El Inglés large touristic complex in the south of Gran Canaria Island. This water contains no anthropogenic contaminants. The development intends to use brackish groundwater reserves without sea-water intrusion and deterioration by possible deep-seated saline water during the economic life of the plant. The desalinated water is later mixed with freshwater from other sources and reverse osmosis desalinated sea water.

young water and palaeowater by creating paths for vertical interconnection of aquifers and for the penetration of surface and phreatic waters under natural conditions, or as a result of groundwater abstraction. Inadequate drilling may permanently ruin a coastal aquifer, as in the Besós Delta, Barcelona, and the Pont d'Inca calcarenite aquifer, Mallorca (Custodio & Bruggeman 1987). Lack of awareness of the nature of the stratification is very common amongst well drillers, who generally attempt to obtain the maximum yield by placing a screen in any permeable layer encountered or by drilling as deep as is economically possible. In cased wells, steel corrosion also favours aquifer interconnection, as do poor welding or inadequate sealing of joints.

The design of a well, if there is not enough previous local experience, may require an exploratory borehole in which hydrogeophysical testing and logging should be conducted (see Buckley *et al.* 2001). Drilling in coastal and island aquifers, especially where palaeowater is expected to occur, must follow a careful design that includes: casing and grouting of the upper part to prevent the penetration of surface or phreatic water; emplacement of casing with correctly welded and sealed joints; restoring the isolation provided by low permeability layers by careful grouting and installation of multiple or telescopic casing, if needed; providing good grouting and/or protection against corrosion, such as using corrosion resistant casing such as plastic or fibreglass; using thick-walled casing to avoid collapse by external pressure at depth, especially during well development and pumping.

Any drilling method can be used providing that it is suitable for the formation and depth, from cable tool percussion to bottom-hammer air percussion and rotary systems, but the constraints imposed by casing and grouting have to be considered. Not all drilling methods and rigs are able to guarantee good construction – testing and the ability and experience of the driller is of paramount importance. Often, palaeowater is situated at depth and deep wells have to be drilled. When overflowing conditions are expected, as in low-elevation coastal plains, grouting must be able to resist the water pressure and to accommodate the installation of a well cap. Failures are relatively common and remediation may be costly. An uncontrolled

Fig. 4. Doñana National Park, Southern Spain. (**a**) Old cattle watering trough in the northern area, previously fed by a flowing well producing fresh palaeowater but now abandoned due to piezometric level drawdown after intensive development in nearby areas. (**b**) A pumped well discharging palaeowater to sustain the impoundment of a lagoon used by waterfowl in the dry season, in the Biological Reserve.

flowing well may waste, without any beneficial use, large quantities of non-renewable groundwater.

Management of coastal aquifer palaeowater

The unique characteristics of non-renewable palaeowaters introduce into the coastal or island aquifer system new constraints. Specifically tailored management rules to preserve the asset for as long as possible and to maximize the beneficial utilization may be needed. A consequence is that water management priorities need to be introduced to secure its preferential use for drinking purposes, even under peak demand and emergency situations. These rules may be in conflict with what is generally considered the best use of a coastal aquifer, since palaeowater protection for drinking purposes is more important than contributing storage space for recharge water. Furthermore the rules may be different for different areas or aquifers of the same system, and this is difficult to apply and to be understood by those who have to bear them. Good information, involvement of stakeholders and economic compensation is needed, and this is something that goes beyond common technical practices and requires widespread collaboration. This may be difficult in old-fashioned water agencies.

In order to protect palaeowater occurrence, the isolation of the resource has to be preserved. This relative isolation not only refers to possible barriers to horizontal flow (they may not exist) but also to horizontal layers above and below the aquifer containing the palaeowater. Often, the most effective natural confinement is due to the presence of thin, low-permeability layers in the formations that greatly reduce bulk vertical permeability. These layers have to be identified and well characterized hydrogeologically, and be the subject of special protection. Such rules exist in some provinces of The Netherlands. The Province of Limburg has a written regulation on 'Decision general rules for boreholes in groundwater and soil protection zones'. Isolation preservation means drilling without increasing aquifer interconnection and vertical permeability. This applies not only to exploratory drilling, exploitation boreholes and wells, but also to monitoring boreholes. Carefully engineered isolation includes grouting, correctly designed and emplaced screens, and casing resistant to degradation and failure by corrosion and mechanical stress. This also means that leaky or abandoned boreholes must be carefully grouted to restore former hydraulic conditions. The protection of the low hydraulic gradient conditions also becomes an important management objective.

There are now a growing number of examples where palaeowaters are being recognized and good practice being introduced. For example, the Aveiro Harbour Authority, Portugal, has to supply freshwater to visiting ships. Recently, this organization drilled a replacement for an existing borehole but decided this time to explore only the aquifer layers with low mineralized palaeowaters, despite their lower productivity. Sustainable development of the low salinity palaeowaters in Aveiro's deep coastal aquifer (Condesso de Melo *et al.* 2001) depends on correct design, construction and maintenance of wells. Regulations need to be followed by municipalities, which are the locally responsible authorities for permits to develop groundwater.

Maintaining low hydraulic gradients to delay penetration of recent and saline water can be achieved by adequate spacing of wells or boreholes, and by avoiding large-scale, isolated or clustered abstractions. This requires some trade-off between the benefits of reducing the number of wells and the costs of additional lengths of distribution pipes. Except in fully isolated aquifers, in which piezometric level drawdown will increase with increasing total water withdrawal, abstracted palaeowater will be replaced by new water, either continental or marine, after allowing for any reduction in storage. If the aquifer crops out at the surface it is not uncommon for formerly rejected recharge (i.e. the aquifer was full) to be progressively converted into induced effective recharge that replaces palaeowater as it is being abstracted. Modelling of aquifer behaviour is needed to determine the palaeowater volume reduction, the mixing with young water and the different contributions to pumping wells; the information is required in order to establish operational rules to optimize the use of the non-renewable palaeowater reserve. The application of hydrogeochemical modelling is also required to try to predict any adverse effects resulting from water–rock interactions as new water is introduced or, in fact, any beneficial effects, since contaminants such as nitrate may be reduced.

Regional drawdowns can be large and may induce consolidation in young formations. The consequence is some degree of local or regional subsidence that may modify inundation characteristics, the shape of the coastline itself and the drainage of coastal areas. Good examples can be found in Thailand, Japan and northeastern Italy (Venice); a review of known cases can be found in Poland (1985). In karstic coastal areas, water head drawdown and, especially, increased water head fluctuations due to groundwater abstraction may also increase the rate of local, sudden land collapse and sinkhole formation.

Two case studies of management practice in Europe

Astian aquifer, southern France

The Astian aquifer in the coastal region near Agde, southern France, in which palaeowaters have been identified in this study, consists of micaceous sands and covers a surface of 438 km^2 towards the Mediterranean coast (Dever *et al.* 2001). This sandy formation is confined by Plio-Quaternary, low permeability continental deposits and only outcrops over 17 km^2. Almost 600 boreholes are recorded in the Astian sands. The coastal area is a prime touristic region. In summer, the population multiplies sixfold (70 000 permanent residents plus 325 000 seasonal inhabitants in the coastal area). As a consequence of the specific hydrogeological situation and the touristic pressure, pumping of groundwater results in long-term decreasing piezometric levels, with increasing salinity coming from present-day sea water and from deep aquifers. Furthermore, casing corrosion adds to this problem by creating pathways for vertical interconnection with polluted waters (Laurent 1993).

A study commission directed by the Sous-Prefecture of Béziers, linking the 20 towns concerned, the territorial communities and national technical services, was initially created in 1988. The objective was to examine who was affected by the problem (water users, borehole owners, drillers), what kind of legislation already existed and the economic implications. Considering this situation the different towns concerned tried to form an aquifer users' association called Syndicat Mixte d'Études et de Gestion de l'Astien (SMEGA). Its main objectives were the continuous monitoring of the Astian aquifer (piezometric level, water quality), database management and mathematical simulation and to provide advice on management of the Astian aquifer and production of information.

SMEGA is made up of 28 members representing the different sectors involved: six for the General Council of Hérault, one for each of the 20 towns, one representative of the Chamber of Agriculture and another of the Chamber of Commerce and Industry. The financial participation of each member is related to the amount of water used. Subventions come from the General Council of Hérault, the water authority (Agence de l'Eau Rhône–Méditerranée–Corse) and from the French government (Ministry of the Environment and Ministry of Agriculture).

A range of installations and works have been carried out to monitor the aquifer. In 1989, SMEGA collaborated with DIREN (Direction Regionale Environnement) to obtain weekly piezometric observations in the dry season, with results transmitted to all the users. A database was created and different mathematical models have been constructed to perform simulations of the future evolution of the aquifer (Chastan *et al.* 1990; Laurent 1993). In June 1997, a contract was signed between SMEGA, the French government, the general council of the Hérault and the water authority to develop an integrated programme, involving quantitative management of the aquifer, evaluation of borehole quality (old boreholes have to be removed), water saving schemes, training and complementary studies related to the resource.

SMEGA became SMETA (Syndicat Mixte d'Études et de Travaux de l'Astien), a young hydrogeologist was employed and a sum of about three million euros per year was made available to deal with the monitoring tasks. The success of the model's application has been due to the involvement of all interested parties, both in financing and in the management.

Groundwater management of the Llobregat Delta coastal aquifer, Catalonia, northeastern Spain

The Llobregat Delta coastal aquifer system is a small alluvial formation just to the southwest of Barcelona, the capital of Catalonia, Spain, with a metropolitan population of *c.* 3.5 million inhabitants. In the 120 km^2 of the aquifer system there are up to 1000 wells, most of them boreholes penetrating the full thickness of the Quaternary sediments. Details can be found elsewhere (Custodio *et al.* 1971; Iribar *et al.* 1991, 1997; Manzano 1991; Manzano *et al.* 2001). Current groundwater use is up to 40% for town supply (actual abstraction depends on the need to complement surface water in a given year), up to 50% for industry and < 15% for agriculture.

Up to 130×10^6 m^3 a^{-1} were abstracted in 1972 but currently the figure has been reduced to 60×10^6 m^3 a^{-1} (*c.* 14% of total water demand in the full area), with an installed pumping capacity of *c.* 4 m^3 s^{-1}. A large part of the current recharge is river-water infiltration through unlined irrigation canals and on the irrigated fields, as well as directly from the riverbed, mostly along the lower river valley. The intensive groundwater exploitation maintains a permanent drawdown in the confined deep deltaic aquifer and in its water table extension into the lower valley. Water levels there are commonly below sea level and have been down to –30 m in the past. The result is the possibility of using up to 100×10^6 m^3 of underground storage capacity in the lower valley for annual regulation of water resources. This allows recharge from surface water but also creates conditions for pollution (river water has quite a high salinity, and groundwater hardens by soil CO_2 addition in irrigated fields and by reaction with carbonate sediments) and for sea-water intrusion through the offshore aquifer outcrop. Thus, part of the aquifer suffers from groundwater quality impairment.

Low salinity palaeowater existing in the deep aquifer of the delta was of pre-industrial age but was recharged during the Holocene, with flow rates high enough to flush out pre–Holocene marine water (Custodio *et al.* 1992). Development of the good quality groundwater reserves started in the last half of the twentieth century, mostly for domestic and rural supply but also for agriculture, but soon water-intensive industries were established and abstracted large quantities of groundwater. Thus, palaeowater was rapidly depleted and extensively substituted by recently recharged water, except for rural areas close to the coast, where sea-water intrusion is now established, and in a few less transmissive areas. As a consequence, the coastal aquifer system is now almost depleted of palaeowater, with most of the reserves already consumed in uses not requiring high-quality water.

The coastal aquifer system is a key element in the water resources system. This is well understood by the inhabitants of the area and was clearly stated and demonstrated by the water authority in the 1960s and 1970s, when most of the management actions developed. The starting point was the awareness of the danger created by the fingers of advancing sea-water intrusion, which are an aquifer heterogeneity effect, and the need to reduce industrial production costs in factories using large quanties of water. This meant raising the water level depth by decreasing regional drawdown. At that time, Barcelona's water supply company had already started artificial recharge in the lower valley by periodically conditioning the riverbed upstream and by injection of excess treated river water into deep wells.

A local well owners' association (users' association) was promoted in 1975 by a group of factory managers, with the help of the water authority and the later incorporation of Prat del Llobregat, which is the most affected municipality. In 1976, a managing board was created; work was started at the time the association's statutes were prepared and approved by the government in 1982, under the provisions contained in the 1876 Water Act, which considered groundwater to be the property of the abstractor and the surface water a public domain. After the enforcement of the 1985 Water Act, which considers all water to be in the public domain and promotes groundwater users' associations as a desirable management tool, the association was enlarged to cover the whole area affected by the aquifer system. The association is dominated by water supply companies (municipal or private) and industries, but farmers are also represented through the large number of wells they have or through the respective municipal representatives. The association has a board, a technical board and an arbitration panel. At the beginning, the main tasks were to keep an updated well inventory and to ask the water authority to carry out studies and investment in the area. But gradually the association has enlarged its own observation network, has carried out studies to protect the rights of existing users and has improved the information activities – all of this with a small budget (starting from 3000 to the current 50 000 euros per year) and the additional technical contributions of the most active members.

The main tasks so far accomplished are: (1) a complete updated inventory of wells; (2) advisory action and control of new drillings; (3) the cessation of aggregate extraction from the aquifer area, both above and below the water table; (4) control of landfilling in open pits; (5) periodical survey of groundwater levels and salinity, in addition to the network operated by the water authority; (6) promotion of water efficiency through improvements in industrial processes and leakage reduction, with the objective of slowing down sea-water intrusion and reducing groundwater abstraction costs; (7) protection and restoration of recharge areas when affected by major developments, such as roads or railways; (8) sealing of abandoned and corrosion-damaged wells; (9) rules to ensure the correct drilling of new wells and boreholes.

Sea-water intrusion progression is under partial control due to a series of industrial wells abstracting saline water, mostly for cooling purposes (Custodio & Bruggeman 1987; Iribar *et al.* 1997). This is a non–ideal situation that is very sensitive to the closing or abandonment of these wells. Attempts by the water authority for an engineered solution to reduce saltwater potential by means of temporarily pumped wells, or by artificial recharge of freshwater (using the upper aquifer as a filter and storage element), have failed up to now due to poor design and implementation, and the lack of understanding of the problem by decision-makers. However, this is now being redefined in connection with future use of advanced treated sewage water in a new large plant near the coast. The project under study and evaluation considers recharging the upper delta aquifer, creating a wetland and using groundwater in it to recharge the deep aquifer after controlling the chemical characteristics, such as CO_2 partial pressure and dissolved iron.

If the lower Llobregat Delta aquifer system is destroyed, the development of an equivalent water system will be required – in a complex area, with little space for new infrastructures. The investment for this alternative system is reckoned to be about 250 million euros, or about 0.5 euros m^{-3}. Thus, preservation of the aquifer system is a cheaper alternative and needs expenditure comparable to the operation costs of the surface-water works. The cost has to be supported by groundwater users, paid for either directly through general and special taxation or indirectly by some formula of compromise. When the solution is taxation, it can be expected that a part of it be used to preserve the area, by means of expenditure carried out directly by the water authority or through the users' association.

Monitoring and data use for management of coastal aquifer palaeowaters

Since palaeowater aquifers are commonly deep, water head distribution and evolution is only known through a reduced number of piezometers. At each site often more than one water head has to be measured, since the hydraulic potential may change with depth. Thus, sets of nested or multiple piezometers are often needed, which includes measuring water head in each of the aquifers and aquitards in the same vertical profile, as well as in both freshwater and saline water.

Water quality monitoring has to be adapted to the actual salinity distribution and to its future evolution. Water pumped from boreholes is likely to be a mixture of components from different depths and may not represent the true situation in the aquifer system. Hydrogeophysical logging, as described in this volume (Buckley *et al.* 2001), is needed to characterize the borehole flow and quality characteristics. Exploitation wells are suited for palaeowater quality sampling provided that the water comes from a well-defined horizon at a known depth. In this respect, the existence of long screened sections or several screens, which may be the origin of interscreen flows, is an undesirable situation.

In short-screened monitoring boreholes, opened in poorly permeable formations, the maximum pumping rate may be quite low, which means a long purge to renew the water inside the casing. Thus, in some cases, a submersible sampler is recommended after some pumping. Field sampling protocols should be established and adapted to the peculiarites of each particular case. Lost drilling water and residual drilling muds may persist and disturb sampling for a long period of time after construction. Thus, the selection of the drilling method and the operation of the drilling rig are important, since it is necessary to be able to identify if remnants of drilling fluid are still in the borehole.

Coastal palaeowater aquifer management needs reliable data, especially of the following types:

- water head measurements in the aquifer and related aquifers, and in some cases aquitards: monthly values are generally enough, provided that there is additional data from a few continuous piezometers to determine the short-term trends and tidal effects. When variable salinity water is involved, the density distribution through the column has to be known or deduced;
- sampling for chemical analysis in pumping wells and boreholes, generally once or twice a year, and weekly to monthly for salinity monitoring at a few points, together with temperature. Chemical analysis of major ions is generally sufficient, but a more complete analysis and more frequent sampling may be needed, following established norms for water supply monitoring. Environmental isotope analyses are not generally needed for monitoring but for establishing the initial condition and the 3D distribution of groundwater types. However, to determine the long-term (5–10 a) evolution of well fields, including palaeowaters, environmental isotope surveys are required;
- records of abstraction rate by wells or groups of wells, and yearly abstraction. This is easy for supply wells fitted with calibrated water meters but it is more complex for rural and agricultural wells lacking these meters; indirect evaluation has often to be applied, such as through irrigated surface area (assuming that yearly crop demand and application efficiency are reasonably known).

Data are the basis for modelling, once an adequate numerical code for simulation has been selected. The variable density of groundwater, mostly due to salinity changes, makes groundwater flow equations highly non-linear and coupled to dissolved solids transport. Salinity distribution may give rise to zones with high gradients, requiring high model resolution. Many real problems are 3D, requiring large capacity and fast computers for numerical simulation. In practice, important simplifications are introduced to reduce dimensionality or to couple vertical planar problems with the radial flow to wells. In many cases, the transition from freshwater to saltwater is assumed to be sharp, as an interface, allowing it to be treated as a free boundary condition between two immiscible fluids.

All this, especially the sharp interface (Ghyben–Herzberg) approach, has been widely used to consider coastal aquifer management possibilities (Custodio & Llamas 1984, section 13; Custodio and Buggeman 1987; Bear *et al.* 1999). In the case of a single pumping well, the position of the saltwater wedge toe was given by Strack (1976) and used to produce management options (Shamir *et al.* 1984; Willis & Finley 1988; Emch & Yeh 1998; Das & Datta 1999) for a field with various pumping wells (Cheng *et al.* 2000).

This is applicable to palaeowater in coastal aquifers when the sharp interface situation is a reasonable assumption, but generally this only happens under some confined conditions. Really, palaeowater is part of the water in the aquifer system and often presents complex relationships with the remaining water reserves, and interfaces may be changed for more or less wide transition (mixing) zones. Under these situations, models using coupled flow and transport equations may be needed, and simplifications have to be tailored to each case. Often, the most difficult problem is defining the boundary conditions, especially for transient state simulations.

Administrative and legal framework

The countries and regions of Europe have different legal water ownership status, ranging from private to public. This influences water administration but is not essential for management, since there is always the possibility of setting reasonable limits to private action for the benefit of the community and for preserving the vital and social role of freshwater. In addition, public ownership does not necessarily mean good management. The dominant factor is the political will – based on popular agreement and participation – and the ability of the water administration to really set and apply adequate rules and laws. Good and bad examples can be found both under private and public ownership of groundwater.

The current trend in freshwater administration and management is looking for the sustainable use of the freshwater resource system (Llamas *et al.* 2000; Custodio 2000). Sustainability is a complex concept that has to be flexible enough to adapt to a continuously changing world, subject to scientific and technical development, variable water needs and evolving social requirements. For a valuable and non-renewable resource such as palaeowaters this may mean reserving these waters for the most noble uses (drinking water) and as a back-up when other water sources fail.

The management of an aquifer containing palaeowater as a source of freshwater, or of water that can be converted into freshwater, has to include considerations similar to those used in mining (Young 1992; Conrad 1994; Gómez 1994): the total quantity is limited and non-renewable, with provisions to take into account that it can be spoiled by salinization and that it is vulnerable to contamination. Thus, the exploitation of palaeowater should be linked to the benefits it produces in order to use a part of these benefits (specifically or through general taxation) to pay for the development of a new source of good quality, non-polluted freshwater to replace palaeowater reserves as they diminish and, finally, are depleted. These include direct economic and indirect and intangible (mostly social) benefits, the influence of which depends on subjective and political factors. A combination of permits, taxes on abstraction, and quotas and limitations are needed, adapted to state or regional laws and accepted by stakeholders, mainly the beneficiaries and end-users.

Current administrative and legal systems, supranational (as in the European Union), national and regional, generally do not provide explicit norms to deal directly with palaeowater, since this is an aspect that, in general, has not been considered by managers and lawyers, and is mostly unknown to them. However, rules can easily be derived from groundwater protection and preservation norms and directives if the objectives are clearly explained and understood. These rules should include drilling norms for wells and boreholes, including their abandonment; distribution of wells and discharge rates; aquifer development plans, to be reviewed periodically; priorities for palaeowater use; and monitoring and specific management rules.

The effective implementation of management rules needs the framework and the administrative and political will to set them. This can be accomplished when the palaeowater aquifer is under the full responsibility of the management organization; however, it generally fails when other related aquifers, aquitards and their recharge areas are outside the control area. Rules may include provisions to prevent the indiscriminate exploitation of deep aquifers, that frequently contain palaeowater. Often, this means changes and additions to the existing water acts or equivalent legislation.

The constitution of aquifer water users' associations is illustrated by the two case studies presented above. The basis is that the different water-rights holders should give up some of their rights to the association. This is generally a good solution, and perhaps the only sustainable way to protect the aquifer and to obtain the best use of palaeowater. The users' association should be a public entity under specific statutes and rules, and should be regulated under a regional framework set by the water administration. The association – or similar legal denomination – has to have the capacity to enforce internal rules and to legally represent the water-rights holders in administrative and legal affairs, and be the subject for possible technical and economic public support and legal protection. Other water players or stakeholders have to have a voice as well. However, this requires the water management authority to transfer some of the management responsibility whilst retaining enough capacity to set general rules, to effectively assist the association in carrying out complex tasks and to help in raising the investments needed. Information should flow freely amongst them.

Conclusions

Coastal aquifers constitute a highly valuable source of water for human needs. They are key elements in water resources management as storage reservoirs. Deep coastal aquifers may often contain slow flowing groundwater, several centuries or millennia old, i.e. palaeowater, which is a non-renewable reserve of water which is free of modern pollutants; it deserves protection as a source of drinking water. Around the European coastline, palaeogroundwater is freshwater in many circumstances, but when it is brackish or saline it still may be a preferred source for desalination in water-scarce coastal areas.

Palaeowater in coastal aquifers can easily become contaminated and spoiled by poorly constructed, maintained and operated wells and boreholes. European water directives have to consider the intrinsic interest of coastal aquifer palaeowaters as a unique, non-renewable source of drinking water that are free of contaminants. Regulations for their protection, use and management are needed. Indiscriminate use of deep coastal aquifers for purposes that do not need such water high-quality water should be avoided by means of abstraction regulations. Coastal aquifers can be effectively managed if operational rules for exploitation and well drilling are available and enforced. The effective participation of water users in coastal aquifer palaeowater management is essential, as well as the transfer of part of the individual water rights to a common management body under the guidance and assistance of the water authority.

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