MANAGEMENT OF GROUNDWATER IN SALT WATER INGRESS COASTAL AQUIFERS

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1.0 INTRODUCTION

Coastal zones contain some of the most densely populated areas in the world as they generally present the best conditions for productivity. However, these regions face many hydrological problems like flooding due to cyclones and wave surge, and drinking fresh water scarcity due to problem of salt water intrusion. Features which affect coastal aquifers are summarized in Figure 1.

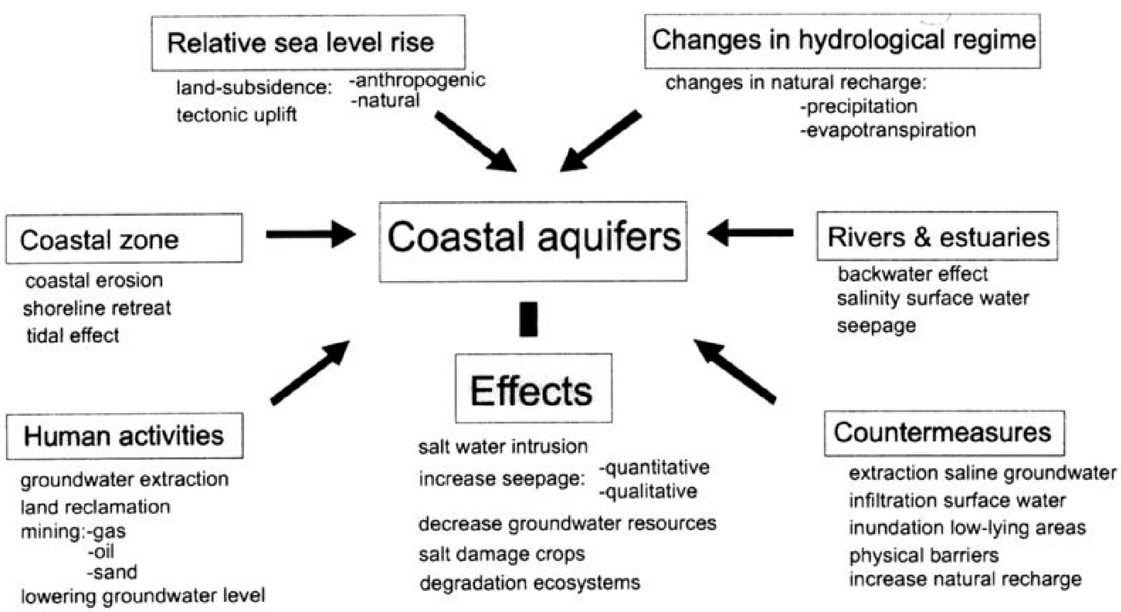

Figure 1: Features Affecting the Coastal Aquifers

When dealing with exploitation, restoration and management of fresh groundwater in coastal aquifers, the key issue is saltwater intrusion. The natural balance between freshwater and saltwater in coastal aquifers is disturbed by groundwater withdrawals and other human activities that lower groundwater levels, reduce fresh groundwater flow to coastal waters, and ultimately cause saltwater to intrude coastal aquifers. Although groundwater pumping is the primary cause of saltwater intrusion along the coasts, lowering of the water table by drainage canals also lead to saltwater intrusion. Other hydraulic stresses that reduce freshwater flow in coastal aquifers, such as lowered rates of groundwater recharge in sewered or urbanized areas, also could lead to saltwater intrusion, but the impact of such stresses on saltwater intrusion, at least currently, likely is small in comparison to pumping and land drainage.

The variability of hydrogeologic settings, sources of saline water, and history of groundwater withdrawals and freshwater drainage along the coasts has resulted in a variety of modes of saltwater intrusion. Saltwater can contaminate a freshwater aquifer through several pathways, including lateral intrusion from the ocean; by upward intrusion from deeper, more saline zones of a groundwater system; and by downward intrusion from coastal waters. A few of these pathways are illustrated on Figures 2. Some authors have used the term *saltwater encroachment* to refer to lateral movement of saltwater within an aquifer and the term *saltwater intrusion* to refer to vertical movement of saltwater. Another term that has been used to describe a specific type of vertical saltwater intrusion is *saltwater upconing*, which refers to the movement of saltwater from a deeper saltwater zone upward into the freshwater zone in response to pumping at a well or well field (Reilly and Goodman, 1987).

Saltwater intrusion reduces freshwater storage in coastal aquifers and can result in the abandonment of freshwater supply wells when concentrations of dissolved ions exceed drinking-water standards. The degree of saltwater intrusion varies widely among localities and hydrogeologic settings. In many instances, the area contaminated by saltwater is limited to small parts of the aquifer and has little or no effect on wells pumped for groundwater supply. In other instances, contamination is of regional extent and has substantially affected groundwater supplies. The extent of saltwater intrusion into an aquifer depends on several factors, including the total rate of groundwater that is withdrawn compared to the total freshwater recharge to the aquifer, the distance of the stresses (wells and drainage canals) from the source (or sources) of saltwater, the geologic structure and distribution of hydraulic properties of the aquifer, and the presence of confining units that may prevent saltwater from moving vertically toward or within the aquifer. Moreover, the time required for saltwater to move through an aquifer and reach a pumping well can be quite long. Depending on the location and lateral width of the transition zone, many years may pass before a well that is unaffected by saltwater intrusion suddenly may become contaminated.

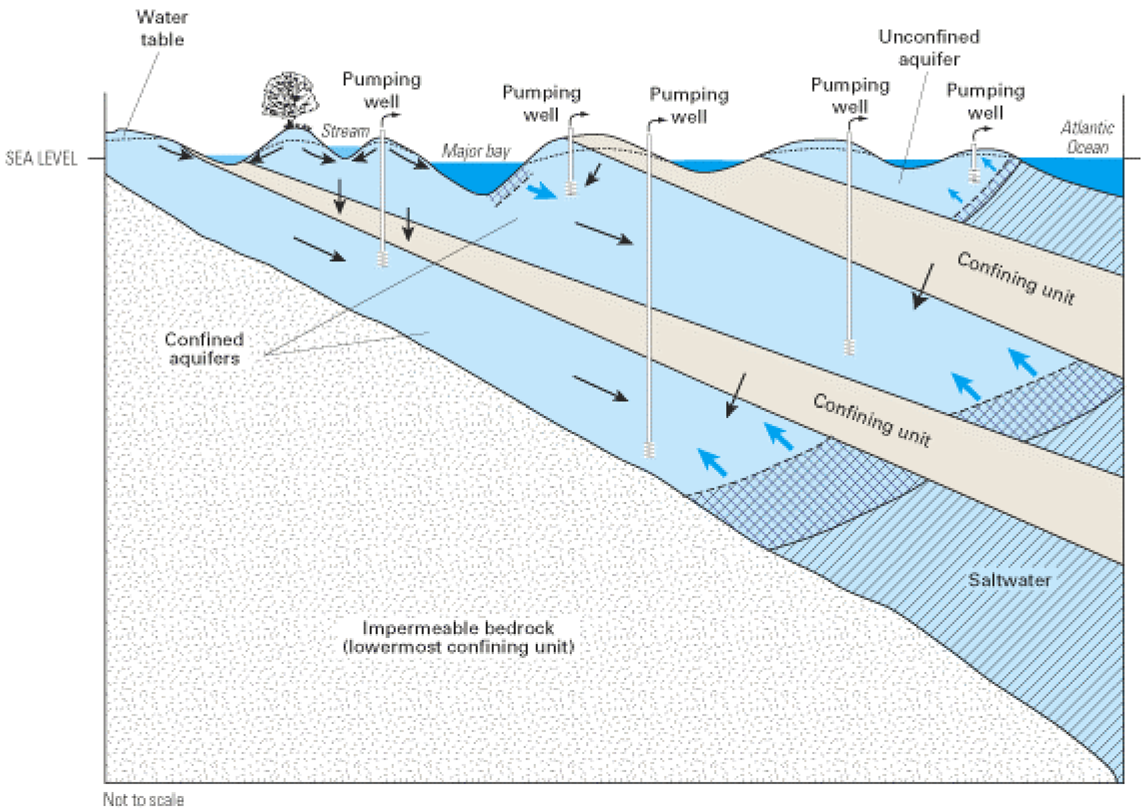

Figure 2: Schematic illustration of some of the modes of saltwater intrusion in a multilayer, regional aquifer system caused by groundwater pumping at wells. Saltwater moves into the unconfined aquifer from the ocean and into the shallow part of the top confined aquifer from the major bay. The two freshwater-saltwater interfaces at the seaward boundary of each of the confined aquifers also move landward as saltwater is drawn inland from offshore areas.

2.0 NUMERICAL MODELING OF COASTAL AQUIFERS

Numerical modeling has emerged over the past 40 years as one of the primary tools that hydrologists use to understand groundwater flow and saltwater movement in coastal aquifers. Numerical models are mathematical representations (or approximations) of groundwater systems in which the important physical processes that occur in the systems are represented by mathematical equations. Several textbooks and articles are available on numerical modeling of groundwater flow systems, including those by Anderson and Woessner (1992) and Konikow and Reilly (1999). A review of several computer codes that have been developed for saltwater-intrusion modeling is provided by Sorek and Pinder (1999).

The governing equations are solved by mathematical techniques (such as finite-difference or finite-element methods) that are implemented in computer codes. The primary benefit of numerical modeling is that it provides a means to represent, in a simplified way, the key features of what are often complex systems in a form that allows for analysis of past, present, and future groundwater flow and saltwater movement in coastal aquifers. Such analysis is often impractical, or impossible, to do by field studies alone.

Numerical models have been developed to simulate groundwater flow solely or groundwater flow in combination with solute transport (the movement of chemical species through an aquifer). For a number of reasons, numerical models that simulate groundwater flow and solute transport are more difficult to develop and to solve than those that simulate groundwater flow alone. Coastal aquifers are particularly difficult to simulate numerically because the density of the water and the concentrations of chemical species dissolved in the water can vary substantially throughout the modeled area.

To address these difficulties, one of two approaches generally is used to simulate freshwater-saltwater interactions (Reilly and Goodman, 1985; Reilly, 1993). In the first approach, the freshwater and saltwater zones are assumed to be immiscible (that is, they do not mix) and separated by a sharp interface. In the second approach, the freshwater and saltwater are considered to be a single fluid having a spatially variable salt concentration that influences the fluid's density; this approach is referred to as density-dependent groundwater flow and solute-transport modeling.

3.0 DETECTING AND MONITORING SALTWATER OCCURRENCE AND INTRUSION

Since the early 1900s, numerous field studies have yielded a wealth of information on the occurrence and intrusion of saltwater in freshwater aquifers along the coasts. Field studies document the location and movement of saline water in coastal aquifers and, in a broader sense, are the basis for understanding the mechanisms that cause saltwater intrusion in different hydrogeologic settings (Reilly and Goodman, 1985; Bear and others, 1999). Several geochemical and geophysical techniques are used to directly or indirectly monitor saltwater in coastal aquifers. Because of the very high concentration of chloride in seawater (typically about 19,000 mg/L), the chloride concentration of groundwater samples has been the most commonly used indicator of saltwater occurrence and intrusion in coastal aquifers. However, other indicators of groundwater salinity, such as the total dissolved-solids concentration or specific conductance of groundwater samples, also are used frequently.

The geochemical techniques include the commonly used approaches for characterizing saline water and less-frequently applied methods using isotope geochemistry. Geochemical isotopes are important tools in coastal-aquifer studies because they provide a means to differentiate among alternative sources of saline water. Although the case studies are focused primarily on methods for detecting and monitoring saltwater in coastal aquifers, it should be emphasized that a thorough understanding of the factors that affect the distribution and movement of saline water in a coastal aquifer also requires definition of the hydrogeologic framework, hydraulic properties, and physical boundaries of the aquifer and the distribution of groundwater levels and locations of groundwater withdrawals in the aquifer (Reilly, 1993). Recent summaries of many of the geochemical and geophysical approaches used in the study of freshwater-saltwater environments are provided by Jones and others (1999) and Stewart (1999), respectively.

Geophysical methods measure physical properties of the earth that can be related to hydrologic or geologic aspects of an aquifer, such as pore-water conductivity (Stewart, 1999). Although there are a variety of geophysical techniques that commonly are applied in groundwater investigations, two types of techniques - electrical methods and seismic methods are particularly useful in coastal environments. Electrical methods have been widely applied in coastal and island environments because of their ability to detect increases in the conductivity of an aquifer that result from increases in pore-water conductivity (Stewart, 1999). The electrical conductivity of an aquifer is controlled primarily by the amount of pore space of the aquifer (that is, the aquifer porosity) and by the salinity of the water in the pore space; increases in either the porosity or the concentration of dissolved ions result in increases in the conductivity of the groundwater. Because seawater has a high concentration of dissolved ions, its presence in a coastal aquifer can be inferred from measurements of the spatial distribution of electrical conductivity. Seismic methods, on the other hand, do not detect saltwater, but can be used to delineate the distribution of geologic units within an aquifer that affect the distribution and movement of saltwater (Stewart, 1999).

4.0 GROUNDWATER AND COASTAL ECOSYSTEMS

The landward flow of saltwater into freshwater aquifers and saltwater contamination can have adverse effects on coastal groundwater supplies. Equally important, however, are the seaward flow of fresh groundwater to coastal ecosystems and the role of groundwater in delivering nutrients and other dissolved constituents to these systems. There are several ways in which groundwater interacts with, and affects, coastal ecosystems. Groundwater discharge, or baseflow, to streams sustains the flow and aquatic habitats of coastal streams during periods when surface runoff is low. Groundwater discharge also helps to maintain water levels and water budgets of freshwater lakes, ponds, and wetlands. Dissolved chemical constituents discharged with groundwater affect the salinity and geochemical budgets of coastal ecosystems and play a role in the biological species composition and productivity of these systems.

The role of groundwater in delivering contaminants to coastal waters has become an area of growing interest and concern. Although coastal groundwater systems have been contaminated by many types of chemical constituents, much of the concern to date has focused on the discharge of excess nutrients, particularly nitrogen, to coastal ecosystems. Nutrient contamination of coastal groundwater occurs as a consequence of activities such as wastewater disposal from septic systems and agricultural and urban uses of fertilizers. One of the most common effects of large inputs of nutrients to coastal waters is acceleration of the process of eutrophication, which is the enrichment of an ecosystem by organic material formed by primary productivity (that is, photosynthetic activity).

Nutrient overenrichment can lead to excessive production of algal biomass, loss of important habitats such as seagrass beds and coral reefs, changes in marine biodiversity and distribution of species, and depletion of dissolved oxygen and associated die-offs of marine life (National Research Council, 2000).

Groundwater reaches coastal environments either by direct discharge or as baseflow in the streams and rivers that drain coastal areas. Coastal water-resource management activities often have been directed toward riverine sources of contaminants. However, it is becoming evident that in some coastal settings, direct groundwater discharge can be a substantial contributor of freshwater and dissolved constituents, particularly in coastal watersheds that consist of highly permeable soils that enable high rates of groundwater recharge and low rates of surface runoff. Because groundwater moves slowly, the flushing of contaminated groundwater from an aquifer can take many years, even several decades. To manage and protect coastal ecosystems, information is needed on the relative importance of groundwater as a source of freshwater and contaminants in different types of coastal ecosystems.

In many coastal ecosystems, the hydrogeologic controls on groundwater discharge and contaminant loading are not well understood. This lack of knowledge results from the limited number of comprehensive studies of groundwater flow and geochemistry in different coastal settings and from the relative difficulty of measuring groundwater discharge and contaminant loading to coastal waters. Quantifying groundwater and contaminant discharge to coastal ecosystems and understanding the role of groundwater in maintaining the biological health and geochemical balances of these systems increasingly require the integration of data-collection and data-analysis techniques from a diverse set of scientific fields. For example, hydrologists and oceanographers have independently developed techniques for measuring groundwater discharge rates to coastal waters, yet only recently have experiments to evaluate, compare, and improve the different measurement techniques been undertaken (Burnett and others, 2002). Innovative technologies for measuring and monitoring groundwater in coastal environments continue to be developed and tested.

5.0 MEASURES TO RESTORE GROUNDWATER SYSTEMS IN COASTAL AQUIFERS

When dealing with the restoration of disturbed groundwater systems in coastal areas, it is necessary to assess:

- The present state, in terms of groundwater tables, piezometric levels and salinity distribution and in terms of exploitation, i.e. location and rates of abstraction.

- The desired state after restoration, in terms of sustainable rates of abstraction and the means and locations thereof, groundwater tables and piezometric levels and the volume of fresh groundwater that should be permanently present in the aquifers as a strategic reserve for emergencies and to cope with fluctuations in the rates of recharge and abstraction.

Once the present state is sufficiently known and the desired state has been defined, within the natural, technical and economic limits posed by the aquifer system and its exploitation, the necessary actions can be taken for restoration, where needed. The same actions can and must be taken in those cases which need not to be restored, yet where continuity of a controlled exploitation must be assured. The following measures (van Dam, 1999) can or must be taken to achieve these goals:

- Reduction of the rates of abstraction, in order not to exceed the sustainable yield.
- Relocation of abstraction works – this measure aims at reduction of the losses of fresh groundwater by outflow.
- Increase of natural recharge – this measure is to increase the recharge and therewith the sustainable yield.
- Artificial recharge – this measure is also to increase the recharge and therewith the sustainable yield.
- Abstraction of saline groundwater – this measure aims at increase of the volume of fresh groundwater and at reduction of the losses of fresh groundwater by outflow. The abstracted saline groundwater can under certain conditions be used as a source for desalting.

5.1 Reduction of the Rates of Abstraction

The rates of abstraction can be reduced when the water demand is reduced. This can be reached by a number of measures, such as:

- Information to the general public and the industrial community of the necessity of saving water and, if necessary, to forbid certain uses as for instance car washing and garden watering in periods of scarcity, and use for cooling in industry only.
- Reduction of losses from the water transport and distribution systems – these losses can be considerable.
- Recycling of water in industrial processes, after appropriate treatment before the successive uses.
- Reuse of waste water, after some treatment, for other applications such as cooling, irrigation and injection in the subsoil to maintain a barrier against saltwater intrusion.
- Reduction of the water requirements for irrigation by choosing crops which require less water and application of water saving techniques such as drip irrigation and canal lining.

5.2 Relocation of Abstraction Works

In confined groundwater, a more inland position of the abstraction works is more favorable than a more seaward position. This is because in inland direction, the thickness of the freshwater lens increases, and the danger of upconing of saltwater decreases accordingly. A more inland position of the abstraction works allows for a further inland penetration of the saltwater wedge in its permanent ultimate position. With a further inland position of the saltwater wedge, less fresh groundwater will be lost by outflow due to a smaller gradient of the piezometric level of the outflowing fresh groundwater. Part of the original volume of fresh groundwater can be mined. So, in defining the desired ultimate position of the saltwater wedge, a choice has to be made between a greater rate of continuous and constant abstraction of fresh groundwater with a higher risk of pumping saline water under extreme conditions versus the opposite combination of the two.

In phreatic groundwater in islands and in sand dunes along a coast, the abstraction works should be located at such a short distance from the coastline that the largest possible fraction (but still less than 1) of the recharge can be recovered before it is lost by outflow under the coastline. On the other hand, this distance should not be too small as the thickness of the freshwater lens decreases towards the coastline and this thickness must still be great enough under the abstraction works so that, even under extreme situations of temporary overdraft, no upconing of saltwater can occur. A more inland position of the abstraction works leads however to a smaller volume of fresh groundwater for strategic reserve.

5.3 Increase of Natural Recharge

The natural recharge can be increased somewhat by proper land use (natural vegetation and choice of crops), land tillage practices (e.g. contour ploughing in sloping areas, terraces), the installation of check dams and weirs in surface waters, so as to raise the water levels therein and to divert water to adjacent spreading grounds. The guiding principle of all these measures is to hold up the water as long and as much as possible in order to give it more time for infiltration, rather than to let it run off directly. Most of these measures are also favorable for erosion control.

With respect to the increase of the natural recharge, it is worth mentioning here that in the present time, flood control measures are also taken up in many urban areas, whereby the runoff is retarded and given more opportunity to infiltrate in open areas and through more pervious pavements. This is favorable from the point of view of recharge in quantitative terms, but the quality of the water infiltrating in urban areas may be doubtful.

5.4 Artificial Recharge

Artificial recharge is not only applied for restoration but also as an element in the continuous optimal exploitation of aquifers. Artificial recharge of groundwater is applied for many reasons, such as to increase the sustainable yield, to control the groundwater table or the piezometric level (in order to restrict or to slow down land subsidence), to increase the volume of fresh groundwater available for emergencies, and/or as a barrier against inflow of saline groundwater.

Artificial recharge can be realized by (increased) infiltration at the land surface or in surface waters or by means of recharge wells with well screens in aquifers at any desired depth. For the recharge of phreatic groundwater, both techniques can be applied. Confined and semi-confined groundwater in aquifers at some depth can not be recharged from the land surface or surface waters due to the high hydraulic resistance between the land and water surface and the aquifers at some depth below the land and water surface.

At present, there is a growing opposition against artificial recharge by infiltration at the land surface or in surface waters. The objections are the occupancy of large surface areas and undesirable ecological effects due to changes in the phreatic groundwater regime, both in terms of groundwater tables and water quality. The first objection holds particularly in intensively used areas. The second objection holds in particular in case of scarcity of nature and its uniqueness.

A special form of artificial recharge is induced recharge, where groundwater is abstracted along and at short distance from rivers. If the rate of abstraction exceeds the rate of natural flow of groundwater towards the river, inflow of river water is induced and the abstracted water consists partly of river water. This affects the quality of the abstracted groundwater. In the most downstream reaches of rivers and in estuaries, the inflowing groundwater may be brackish or even saline (Savenije, 1992), depending on the tidal regime and on the magnitude of the river flow. This should be checked before undertaking any project for induced recharge.

The potential sources of water for artificial recharge are surface water or pumped groundwater after its first use and proper treatment after that. Surface water can be taken from rivers or estuaries, and be transported either by canals or by pipelines. It is obvious that the water should be fresh. Therefore, the intakes should be beyond the reach of saltwater intrusion in the rivers and estuaries (Savenije, 1992), or the estuaries should be provided with dams and sluices. The quality of the water at the source should satisfy certain standards. Such standards depend mainly on the use of the water after recharge and subsequent recovery but also on the requirements for transport and subsequent recharge. These two latter aspects in itself may already require some pretreatment. This holds in particular for recharge by means of recharge wells, in order to avoid clogging of these wells.

Apart from pretreatment of the water for recharge, the rate of recharge per well should be limited. Despite pretreatment of the water, the capacity of the recharge wells decreases during operation. Therefore, regeneration of the recharge wells is needed from time to time. Due to intensive research, much progress has been made both with respect to the pretreatment required for water of different quality and with respect to the techniques of regeneration.

In the phreatic case, more groundwater can be abstracted sustainably and the interface between fresh and saline groundwater can be pushed down by application of artificial recharge. This latter fact implies that the reserve for temporal overdraft becomes greater. This holds for islands in the sea as well as for sand dunes along the sea coast. If in the latter case, the controlled groundwater tables at the land side of the sand dunes are below mean sea level, the inflow of saline groundwater underneath the freshwater lens in the sand dunes is reduced or, depending on the depth to the impermeable base, even halted.

With respect to the mutual location of recharge ponds, canals or wells and the abstraction works, the following considerations hold. In order to assure a minimum residence time for improvement of the water quality, these works should be located at a minimum distance which can be calculated. The longer the residence time of the infiltrated water, the greater also the smoothing out of the fluctuations in the quality of the infiltrated water. A more constant quality of the abstracted water is generally appreciated by the consumers. Fluctuations can even more be flattened by applying variable distances between the lines of recharge works and abstraction works respectively. Therefore, in the design of the combined recharge and abstraction system, one should make use of the topographic features of the terrain also with respect to the aspect of water quality fluctuations.

Another consideration relates to the question whether to locate a line of abstraction works in between two lines of recharge works (or in the center of a more or less elliptic configuration of recharge works) or the other way round, the line of recharge works surrounded by two lines or a more or less elliptic configuration of abstraction works. The latter layout has the advantage that the phreatic groundwater tables will be higher and, accordingly, the depths to the interface greater. This implies the availability of a larger volume of freshwater for emergencies. Moreover, due to the greater thickness, the residence times will be somewhat longer and somewhat more spread out. The regime of desired or accepted groundwater tables should also be judged in relation to the topography and the ecological features of the terrain.

Depending on the variation of the water requirements over time, as determined by the climate and weather, and on the availability of water of good quality for artificial recharge, the actual rates of abstraction and artificial recharge of groundwater may vary with time, periodically and incidentally. So the volume of fresh groundwater will also vary with time, and the boundary between fresh and saline groundwater will not only move up and down, but also the transition between fresh and saline will become less sharp due to the effects of dispersion and retardation.

Attention should also be paid to the question where the displaced brackish and saline groundwater goes and what effects it has in the surroundings. So, for instance, increased seepage of brackish or saline groundwater in adjacent areas will generally not be appreciated. Therefore, the effects of the combined system of abstraction and recharge in the wider surroundings must be foreseen, predicted and judged before undertaking any artificial recharge project.

5.5 Abstraction of Saline Groundwater

The saline or brackish groundwater, which is present below fresh groundwater in coastal and deltaic areas, can also be abstracted. It can be used for cooling purposes or as a source for desalting. Such abstractions cause the volume of fresh groundwater to grow and the volume of brackish and saline groundwater to decrease. Complete control of the interface is possible by simultaneous abstraction of fresh and saline groundwater, in mutually adjusted proportions. For such watchmakers work, a good monitoring system is indispensable.

Disposal of the abstracted saline groundwater can be a problem. The same holds for the brine in case the abstracted saline groundwater is desalted as an additional source of freshwater. The possibility of abstracting saline groundwater with the objective to reduce the outflow of fresh groundwater, which is otherwise required to maintain the body of fresh groundwater, deserves serious attention. In case of scarcity of freshwater, it is worthwhile to reduce the loss by outflow of fresh groundwater, theoretically even to zero.

For the local problem of upconing, the installation and operation of so-called scavenger wells is a good curative solution. Such wells, next to or nearby pumped wells have their well screen at some depth below that of the pumped well in the fresh groundwater. The well screen of the scavenger well is installed in the saline groundwater at some depth below the original depth of the interface or the transition zone between the fresh and saline groundwater. By pumping the saline groundwater, the piezometric level of the saline groundwater is lowered with the effect that there will be no more upconing. The upward cone of saline groundwater can sink down either by stopping the abstraction of fresh groundwater for some time before pumping both well screens simultaneously or by continuing the abstraction of fresh groundwater and pumping the saline groundwater at a higher rate in the beginning than later on. In both cases, the rate of pumping of the scavenger well should be adjusted to the position and movement of the interface or transition zone, which should be monitored frequently or continuously. The disposal of the pumped saline groundwater may be a problem.

Scavenger wells prevent upconing of saline water on the small scale of individual wells, but have large scale effect as well. The large scale effect is twofold; a more favorable distribution of fresh and saline water in the subsoil and less loss of freshwater by outflow to the sea. In semi-confined groundwater, the position of the interface or transition zone depends very much on the piezometric level of the saline groundwater.

6.0 GROUNDWATER MANAGEMENT

The exploitation and restoration of fresh groundwater in coastal aquifer systems should form part of integrated water management, comprising surface water and groundwater, both in terms of water quantity and water quality, and taking into account the demands. This requires cooperation, information, study, planning and legislation.

The organizational structure for water affairs differs from country to country. Integrated water management can be realized only by cooperation between all authorities which have some responsibility for water. Some of the most important responsibilities are public works, domestic and industrial water supply, agriculture and environment. The responsible authorities can be organized either sectorial or regional. Moreover, the regional responsibilities are often organized hierarchically (state, province, district). The geographical boundaries of the regions where the various sectorial authorities have their responsibilities can be different and overlapping. These boundaries can be either administrative or natural, i.e. based on water divides, the catchment approach. For water affairs, this latter approach is very much to be preferred. Regrettably, most of the boundaries are administrative boundaries. This complexity urges for mutual cooperation, based on consultation and information.

Missing information must be collected in the field, by research and by modeling. Then a water policy must be formulated, based on all available information, including that on the requirements. It is clear that in this process, choices will have to be made, taking into account economic, environmental and social aspects. Obviously, the policies must be reviewed periodically, to take into account new developments. The chosen and agreed policy must be implemented by planning and realization of the necessary works and measures. The measures require proper legislation and its observation.

6.1 Data Collection and Monitoring

A great variety of data is required for integrated water management studies. These are generally collected, processed and stored by many different institutions and organizations. Therefore, it is necessary to know what data is available, where and in which format. It is also necessary to have access to the data of other institutions and organizations and to dispose of facilities for calling in those data. The types of data required for groundwater studies in coastal and deltaic areas, where saltwater intrusion plays a role, are given below.

1. The subsoil
   - The geologic structure of the subsoil
   - Hydrogeological constants

2. The natural input
   - Climate data, in particular precipitation and evapotranspiration
   - Natural recharge

3. Water levels
   - Groundwater levels and piezometric levels
   - Surface water levels

4. Groundwater quality
   - Chemical and isotopic composition, in particular salinity, but also any other contamination
   - Sources of groundwater pollution

5. Surface water
   - Natural outflow
   - Availability and quality of surface water for artificial recharge

6. Present and past exploitation
   - Present and past abstractions of fresh and saline groundwater

- Present and past artificial recharge, if any

7. Water demands, at present and estimates for the future

8. Ecology
   - Flora and fauna, and their relation to the groundwater table regime

9. Relative sea level rise.

More detailed information about the importance and the collection of each of these types of data is given below.

1. Information on the geologic structure of the subsoil comes from the geologists, who obtain their information from boreholes and geophysical prospecting, mainly the geo-electrical methods (van Dam, 1976) but also from seismic prospecting. Moreover, geophysical well-logging in the boreholes gives additional geophysical information. The hydrogeological constants are determined by pumping tests in the same boreholes, but also from water balance and model studies and from the response of groundwater tables and piezometric levels to other impulses such as fluctuations of surface water levels. Remote sensing of the earth surface features is useful in itself, but it can give important indications about the underlying geological structures as well, e.g. the presence of faults.

2. The natural input into the groundwater system comes, apart from lateral inflow, from natural recharge, determined by the climate variables precipitation and evapotranspiration, the soil moisture, the vegetation and the depth of the groundwater table, all of which vary with time. So the natural recharge is a function of time, with a seasonal distribution and stochastic variations over it, thus with extremes. Apart from the short term variations in all these input data, climate change can affect the natural recharge in the long run. This is the domain of the climatologists.

3. It is important to study and follow the groundwater levels and piezometric levels as a function of location and of time as they are indicators of the groundwater flow and of the depth of the interface or the transition zone between fresh and saline groundwater and thus for the volume of fresh groundwater in storage. The observations of groundwater levels and piezometric levels should be carried out with intervals of a few weeks, for instance twice a month. The surface water levels are equally important as boundary conditions for the groundwater system and as indicators for the streamflow. Depending on the variability of these levels, their observation intervals could vary from one to several days.

4. Groundwater quality is determined by a great number of chemical and isotopic parameters, which determine the suitability of the water for the

various uses, directly or after treatment. Moreover, the chemical and isotopic compositions are indications of the origin of the water. The most important quality parameter of the water is, in the context of this chapter, its salinity. The groundwater quality can also be influenced by percolation of certain contaminants from human activities at the land surface. As these contaminants can make the water unfit for use, it is important to find out the origin of these contaminants as well, so that, possibly, proper measures could be taken. Groundwater quality can be determined from water samples taken from filters at different depths in observation wells. If these filters are in different aquifers, the perforation of the aquitards in between the successive aquifers should be filled up with clay around the tubes of the individual filters in the different aquifers. This is to avoid undesirable connections between the different aquifers, with generally different piezometric levels and different groundwater quality. Such connections give an incorrect picture of the undisturbed reality. The salinity distribution can also be derived roughly from the specific electrical resistivities, determined by geo-electrical prospecting, by electrical well-logging and by so-called salt-watchers, which are systems of electrodes installed permanently in boreholes without permanent steel casing. As groundwater flows slowly, such measurements can be made at relatively large intervals of time, say two to four times a year. There is, however, one exception. This is in case of upconing of saline groundwater just under an abstraction well or in combination with a scavenger well. Then a suitable interval is, for instance, two weeks. When studying karstic aquifers, the application of artificial tracers and the measurement of water temperatures can provide important additional information for proper understanding of the groundwater system.

5. Surface water leaving an area is fed by surface runoff and by outflowing groundwater. It is important to quantify this outflow as a term in the groundwater balance of the area under consideration. In case, artificial recharge is or will be applied, one should know the characteristics and the reliability of the source of water, for instance a river or lake inside or outside the area under consideration. At the same time, other present or future claims to that source should be recognized.

6. In order to have a complete and correct picture of the water and salt balance of the groundwater system, it is necessary to know the present and past abstractions of fresh and saline groundwater and the present and past artificial recharge, if any. It is necessary to know their locations, the filter depths and their capacities and salinities, both as functions of time.

7. It is obvious that the present and estimated future water requirements must be known in order to be able to anticipate timely on the future by expanding the capacity of the water works, including artificial recharge and abstraction of saline groundwater. If it appears to be impossible to

satisfy the future water requirements by expansion of the present waterworks, it will be necessary to prepare for other solutions as, for instance, import of water from more remote sources.

8. There is, at present, great concern for the ecological aspects of any change in the groundwater regime. Though in recent times, much progress has been made in the understanding of the relationships between the groundwater regime and nature, there is still insufficient knowledge. Therefore, all relevant information about flora and fauna, now and in the past, should be documented. Only then, the relations can be fully understood and an optimal solution for groundwater exploitation and nature control can be achieved by adequate water control measures. Geographical information systems (GIS) are pre-eminently suitable for recording this type of, geographically distributed, information and to couple this information with the input or output of groundwater model studies.

9. The relative sea level rise has no effect on saltwater intrusion in a confined groundwater system as long as the natural outflow of groundwater remains unchanged. The same conclusion can be drawn for phreatic groundwater in islands or in sand dunes where the controlled groundwater table at the land side remains equal to the sea level, except when the width of the island or the sand dunes decreases due to relative sea level rise. In that case, the total recharge decreases proportionally and therewith the thickness of the fresh groundwater lens, also proportional. In case, the sea level rises at the seaside of sand dunes relative to the groundwater table at the landside of the sand dunes, inflow of saline groundwater will occur or increase, depending on the depth of the impermeable base. So, it is important to take into account the estimates for the future rates of relative sea level rise.

6.2 Modeling

The effects of any foreseen action, either the realization and exploitation of technical works, such as groundwater abstraction and artificial recharge, or drafting relevant legislation, must be studied beforehand. A wide variety of models are available for modeling of groundwater with variable densities as in the case of saltwater intrusion. A complete model to describe saltwater intrusion should be three-dimensional, transient, and account for varied densities and for dispersion. Such a model is not only complicated, but requires also a lot of input data which are mostly not available. Even in areas rich in data, it is never enough and the ever heard complaint of lack of data will remain forever. The modeler will have to learn the art of drawing acceptable conclusions and to indicate the range of their reliability from the available data.

The most recent development in modeling is the coupling of the model with a geographic information system (GIS) for the input data and presentation of the model output. Where no comprehensive sophisticated model and/or computer capacity is available, or in the absence of sufficient knowledge or experience with such models, one can resort to simpler models. Simpler models are, for instance, those ignoring dispersion and assuming sharp interfaces or, even more simplified, those dealing with only two dimensions, either in a vertical or in a horizontal plane, and in steady state. It is surprising how much can be learned from the results of these simpler models. The results obtained by the more sophisticated models are obviously more detailed because they are based on more detailed input data, but after all, they appear to be roughly in line with those of the simpler models. Irrespective of the degree of sophistication of the models, they enable us to study the sensitivity of the results for variation of the values of the hydrogeological constants and other input data and to compare the effects of different ways of groundwater exploitation.

6.3 Legislation

In addition to the technical measures, legislative measures are required to control and allocate the available fresh groundwater resources properly. By proper rules to control, to restrict or even to stop abstractions, the sustainability of the exploitation of a groundwater system can be safeguarded. Such rules aim at halting or, where needed, even pushing back the saltwater intrusion. Before imposing any restriction on the abstraction of groundwater, the existing abstractions should first be registered. Then licenses could be issued for the present rates of abstraction until some fixed date in future. After expiration of this period, the given license could be continued or not either for the same or for another rate of abstraction. Such a decision depends on the overall picture of the inventory of the existing abstractions and a master plan for the future in which all available water resources are allocated to or reserved for the various users taking also into account the water quality requirements for different user categories.

For obtaining a license, a levy might have to be paid. This should not be considered as buying the water but rather as a compulsory contribution to the cost of the necessary investigations, measures and works and the administration by the responsible authority. The specifications in the license may also include the obligations to measure the rates of abstraction, some groundwater quality parameters, and groundwater tables and piezometric levels at a number of locations and depths at specified intervals of time and to submit this information to the responsible authority.

Observation of the rules should be enforced by sanctions. This and the allocation of the fresh groundwater can lead to socio-economic problems, for instance for small farmers who need water for irrigation. Therefore, the water users must be informed and have the opportunity to participate in the decision process. There should also be proper legislation to prevent pollution of groundwater and surface waters and, where necessary, also to impose measures for restoration of the present water quality.

7.0 CHALLENGES AND OPPORTUNITIES

The focus of this chapter has been to describe the current understanding of groundwater in freshwater-saltwater environments. Much progress has been made in understanding the natural distribution of saltwater in aquifers and the geologic, hydrologic, and geochemical processes that control freshwater and saltwater flow and mixing in coastal aquifers. The geologic processes carry critical roles in determining the composition and structure of coastal aquifers and the short-term and long-term dynamic forces that drive the flow of freshwater and saltwater within these aquifers. In many aquifers, the natural occurrence and movement of saltwater has been changed by the development of groundwater resources for human uses. Groundwater development has lowered water levels and caused saltwater to intrude into many of the most productive aquifers. In response, substantial effort has been directed toward understanding the several pathways and processes that control saltwater movement through freshwater aquifers and the development of water-quality observation-well networks and other monitoring approaches to detect and track saltwater movement.

The different modes of saltwater intrusion are the result of the variety of hydrogeologic settings, sources of saline water, and history of groundwater pumping and freshwater drainage; and effective monitoring and management of saltwater intrusion require that these factors be known. Less well understood are the mechanisms and rates of groundwater discharge and contaminant loading to coastal ecosystems. These ecosystems are of high intrinsic and economic value, yet the health of these systems can be threatened by changes in the amount and quality of water that is discharged to them.

Recent population increases along the coastal zones suggest that demands on the groundwater resources of these regions will grow in the coming years. The need for water to support coastal populations and economic prosperity will present scientists, water-resource managers, and public decision-makers with a number of challenges and opportunities for understanding and wisely managing coastal groundwater resources. Hydrologic studies and data-collection activities, as they have in the past, will contribute to the development and management of coastal groundwater resources. However, there are a number of scientific issues related to groundwater in freshwater-saltwater environments that will need to be addressed. Some of these issues are described in the following paragraphs:

- *Periodic evaluation of the adequacy of groundwater monitoring networks and estimates of groundwater use*

  Observation-well networks that monitor groundwater levels and groundwater quality are indispensable for determining the effects of groundwater development on groundwater levels and groundwater storage and for monitoring the location and movement of saline water in coastal aquifers. Although many such networks are already in place along the coasts, recent increases in population will require periodic evaluation of the adequacy of these networks to monitor changes in groundwater levels and the movement of saline groundwater. Such evaluation is particularly important in areas where groundwater development has only recently begun or is substantially increasing. Similarly, water-use estimates are vital for understanding human impact on water and ecological resources and for assessing whether available water supplies will be adequate to meet future needs. Commonly, however, estimates of groundwater use are not available to identify trends in water use and the potential for overuse of the resource.

- *Improved understanding of the controls on saltwater occurrence and intrusion*

  Much work has been done to understand the geologic, hydrologic, and geochemical controls on saltwater occurrence and intrusion in freshwater aquifers along the coasts, particularly where saltwater intrusion is a recognized problem. As coastal populations expand into previously undeveloped areas, it is likely that new patterns of saltwater occurrence and intrusion will be identified that will require scientific analysis and monitoring.

- *The role of groundwater in coastal ecosystems*

  There is a continuing need to quantify the relative importance of groundwater as a source of freshwater and contaminants to different types of coastal ecosystems. Coastal water-resource management activities often have been directed toward riverine sources of contaminants. A better understanding is needed of the hydrogeologic and geochemical controls on the rates, locations, and quality of groundwater discharge to coastal ecosystems that receive substantial groundwater discharge in comparison to other sources of discharge. Understanding groundwater contributions to coastal ecosystems will require an integrated effort from the fields of hydrology, geology, geochemistry, and biology. A related need is to quantify the residence times and travel times of groundwater and associated contaminants in coastal aquifers. Because groundwater moves slowly, the flushing of contaminated groundwater from coastal aquifers to receiving wetlands and surface waters can take many years or decades.

- *Scientific evaluations to support groundwater management*

  There are several areas in which scientific evaluations are needed to support traditional and emerging approaches for groundwater management in coastal regions. As water use increases, communities are beginning to look for more effective ways to conjunctively use ground- and surface-water resources and to seek alternative groundwater supplies from aquifers that have not been previously used. The use of desalination and aquifer storage and recovery systems is becoming more widespread in coastal regions, and their use is likely to increase in the future. Scientific studies can contribute to the success of desalination systems by identifying brackish and saline groundwater resources that are appropriate for desalination and by characterizing the hydrogeologic and geochemical conditions of the aquifers that contain the brackish and saline waters. Similarly, scientific evaluations can be conducted to characterize the hydrogeologic and biogeochemical controls that affect the efficiency of aquifer storage and recovery systems. New developments in groundwater flow and transport modeling and in computer-visualization techniques will increase the ability of hydrologists to simulate the effects of proposed groundwater development scenarios on groundwater and surface-water resources and on the paths and rates of saltwater intrusion, and to better communicate the results of these simulations to water-resource managers.

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