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Improving fresh groundwater supply—problems and solutions

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Abstract

Many coastal regions in the world experience an intensive salt water intrusion in aquifers due to natural and anthropogenic causes. The salinisation of these groundwater systems can lead to a severe deterioration of the quality of existing fresh groundwater resources. In this paper, the characteristics of variable-density groundwater flow and the concept of an interface between fresh and saline groundwater are introduced. Problems associated with these groundwater resources are discussed, such as upconing of saline groundwater caused by excessive overpumping and salt water intrusion caused by global mean sea level rise. Possible human activities to compensate and control the salinisation of coastal aquifers are presented. Most countermeasures appear to be expensive, laborious and should be taken in time. Finally, the effect of lowering piezometric heads on the salinisation of the subsoil is illustrated in a Dutch aquifer system.

1. Introduction

Many coastal zones, especially low-lying deltaic areas, accommodate high density populations. For example, about 50% of the world population lives within 60 km of the shoreline. For ages, mankind is attracted to these areas because of the availability of an abundance of food (e.g., fisheries and agriculture) and the presence of economic activities (e.g., trade, harbours, ports and infrastructure). Due to increasing concentration of human settlements, agricultural development and economic activities, the shortage of fresh groundwater for domestic, agricultural, and industrial purposes becomes more striking in these coastal zones.

Compared to surface water, the advantages of groundwater are the high quality, hardly seasonal effects (constant temperature), the low storage costs (no spatial

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Table 1
Mondial distribution of (a) water on the Earth and (b) fresh water [1]

Form	Volume, $10^6\,km^3$	%
(a) *Mondial distribution of water on the Earth*		
Oceans and seas	1351.0	97.5
Fresh water	35.0	2.5
Total quantity of water	1386.0	100.0
(b) *Mondial distribution of fresh water*		
Ice	24.4	69.7
Surface water	0.1	0.3
Groundwater	10.5	30.0
Total quantity of fresh water	35.00	100.0

limitations) and the huge available quantities. Nevertheless, fresh water is rather scarce. Table 1 shows that only some 2.5% of all water on the Earth is fresh. At present, one third of fresh water used is groundwater. This fraction is growing because the demand of fresh groundwater increases due to

- the rise of world population and economic growth,
- the loss of surface water due to contamination,
- the availability of huge quantities,
- the high quality, relative to surface water.

Disadvantages of groundwater are the high mineral content, the potential of land subsidence, high extraction costs, and finally, the threat of salt water intrusion.[1] Salt water intrusion in the subsoil may not only be a threat for the public and industrial water supply but also for agriculture and horticulture. Although technical methods for desalinisation of saline or brackish water are available and applied, it is (still) an expensive method.

The present distribution of fresh, brackish and saline water in the subsoil has developed in geologic history and has been and still is affected by several natural processes, and also by human intervention. Brackish and saline groundwater can be found in coastal aquifers,[2] but also further inland. Processes which affect coastal aquifers are summarised in Fig. 1. Already at this moment, many coastal aquifers in the world, especially shallow ones, experience an intensive salt water intrusion caused by both natural as well as man-induced processes. Human interferences, such as mining of natural resources (water, sand, oil and gas) and land reclamation (causing subsidence) threaten coastal lowlands. Consequently, salinities of surface water systems increase and land degradation occurs because soils become more

[1] Salt water intrusion is a permanent inflow of saline groundwater in an aquifer which contains fresh groundwater.

[2] An aquifer is a permeable geologic formation, where groundwater is permitted to move through.

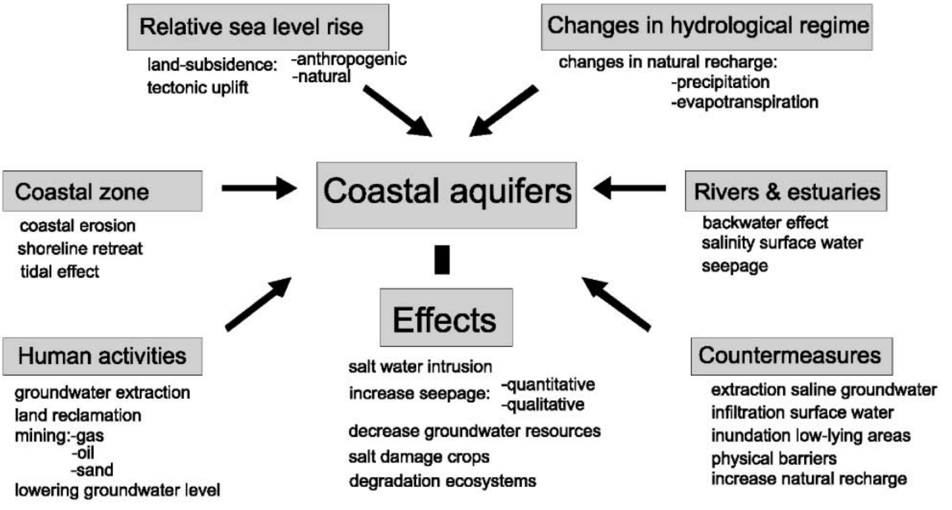

Fig. 1. Processes which affect the coastal aquifers.

saline. As a result, poor crop yields are produced due to salt damage and indigenous crops might be substituted by more salt-tolerant crops. If even the salt-tolerant crops cannot withstand the high salinities, the population might eventually migrate from the barren land and resettle in more fertile arable territories, which could cause social commotions.

In addition, coastal aquifers within the zone of influence of mean sea level (MSL) are threatened by an accelerated rise in global MSL. This rise in global MSL, 50 cm for the coming century as the present best estimate, could even more jeopardise vulnerable coastal aquifers than they are threatened today. Subsequently, the salinisation of coastal aquifers will accelerate. This could mean a reduction of fresh groundwater resources. In addition, the present capacity of the discharge systems in several coastal low-lands may be insufficient to cope with the excess of seepage water, especially in those coastal areas which are below M.S.L. This seepage will probably have a higher salinity than at present.

1.1. Outline

In this paper, the characteristics of groundwater flow in coastal aquifers are introduced. The concept of an interface between fresh and saline groundwater is given, which is illustrated by the features of upconing of saline groundwater. Problems with fresh groundwater supplies in coastal zones are discussed. Examples of countermeasures to control the salinisation process of coastal aquifers are described. Finally, variable-density groundwater flow in a specific area in the Netherlands is briefly discussed.

2. Characteristics of groundwater flow in coastal aquifers

2.1. Introduction

Variations in groundwater density, resulting from variations in salinity, can have an important effect on groundwater flow. In the management of coastal groundwater resources, it may be very important to take the impact of this phenomenon into account. In this section, a background of variable-density groundwater flow in a porous medium is given.

2.2. Equation of groundwater flow

Flow of groundwater in a porous medium takes place through a complex network of interconnected pores or openings. A porous medium is a persistent solid matrix (e.g. soil, sand, sandstone, fissured rocks or karstic limestone) and a void space which is occupied by one or more fluid phases (e.g. water and air). The so-called groundwater flow equation is based on the equation of continuity as well as on the equation of motion. See Refs. [2,3] for a mathematical description of the equations.

2.3. Equation of solute transport

Solutes present in water can substantially affect the density of water, if the concentration of solutes is high enough. Groundwater flow will be density dependent and the variation of densities should be taken into account. Under these circumstances, the transport of solutes in the groundwater is described by the two-dimensional advection–dispersion equation. This concept is applicable in coastal aquifers, where the density is not constant. With regard to the transport of a conservative[3] solute, such as the chloride ion Cl^-, the advection–dispersion equation can be described as

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(CV_i) + \frac{(C - C')W}{n_e D}, \tag{1}$$

where C is the concentration of the dissolved solids $(\mathrm{M/L^3})$, D_{ij} the coefficient of hydrodynamic dispersion $(\mathrm{L^2/T})$, $V_i = q_i/n_e$ the effective velocity of the groundwater in the direction of x_i (L/T), C' the concentration of the dissolved solids in a source or sink $(\mathrm{M/L^3})$, W the general term for sources and sinks (L/T) and D the saturated thickness of the aquifer (L). The first term on the right-hand side represents the change in concentration of solutes due to hydrodynamic dispersion. The second term represents the effect of advective transport which is the movement of solutes attributed to transport by owing groundwater. The third term represents the contribution and removal of solutes due to fluid sources and sinks.

[3] A solute is conservative if no chemical reactions such as adsorption and radioactive decay are taking place.

Hydrodynamic dispersion is defined as the combined effect of two processes:

- mechanical dispersion, which is caused by velocity variations at the microscopic scale. The spreading depends on both fluid flow and the characteristics of the pore system through which the flow takes place,
- molecular diffusion, which is caused by the random movement of molecules in a fluid and depends on concentration gradients, the properties of the fluid and the soil.

Under normal groundwater flow conditions, molecular diffusion is of marginal importance with respect to mechanical dispersion. The exact determination of the hydrodynamic dispersion is very difficult, if not impossible, because it depends on many features such as scale dependency, fingering, transient effects, aquifer heterogeneity and anisotropy [4,5]. The advection–dispersion equation and the groundwater flow equation are coupled with each other through the effective velocity, the concentration and the density.

2.4. Density of water

Under normal groundwater flow circumstances the influence of pressure and temperature (Fig. 2) on the density can be neglected with respect to the influence of dissolved solids concentration. Therefore, the density of water is often only related to the concentration of the total dissolved solids TDS in the water. Since in coastal groundwater chloride (Cl^-) is the predominant negative ion, the interest is often focused on the distribution of this ion. A classification on chloride concentrations into three main types of fresh, brackish or saline groundwater is as follows [7]: fresh $Cl^- \leqslant 300\,mg/l$, brackish $300 < Cl^- < 10,000\,mg/l$ and saline $Cl^- \geqslant 10,000\,mg/l$. The drinking water standard in the European Community has been $150\,mg\ Cl^-/l$ [7], while according to the World Health Organisation, a convenient chloride concentration limit is $200\,mg\ Cl^-/l$ [8]. Note that a chloride concentration equal to approximately $100\,mg\ Cl^-/l$ indicates the taste limit of human beings [9], whereas ocean water has a chloride concentration of $19{,}000\,mg\ Cl^-/l$. Several conversion formulas relating density to chloride concentration, total dissolved solids, temperature and pressure can be found in literature [10–13].

2.5. The concept of a fresh–saline interface

Though the differences in density in coastal aquifers appear to be small, they can have a significant effect on the flow of groundwater. In this section, the interface approximation based on the Badon Ghyben–Herzberg principle is considered to take into account density flow in a simple way. This straightforward concept is applied as an educational means to gain a clear insight into the behaviour of fresh and saline groundwater in coastal aquifer systems.

2.5.1. Badon Ghyben–Herzberg principle

The so-called Badon Ghyben–Herzberg principle [14,15] describes the position of an interface between fresh and saline groundwater (Fig. 3). Eq. (2) represents the

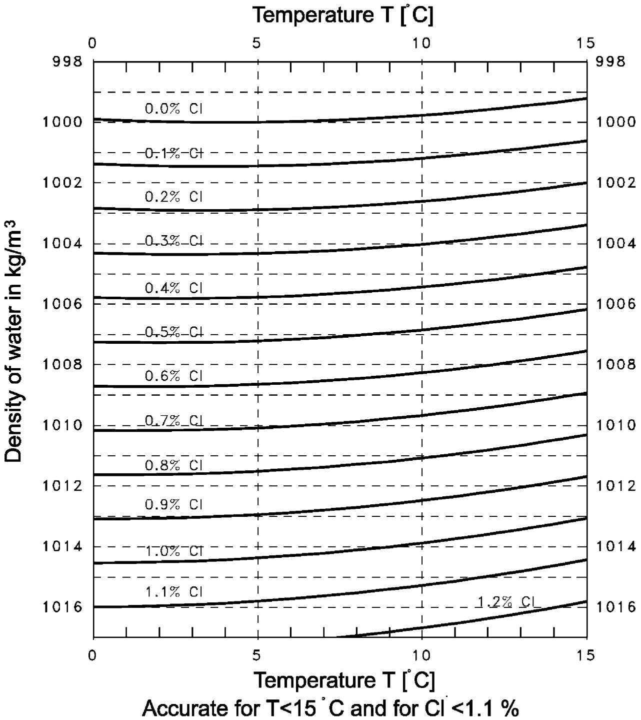

Fig. 2. Density of water as a function of the chlorinity and temperature [6] and pressure, can be found in the literature [10–13].

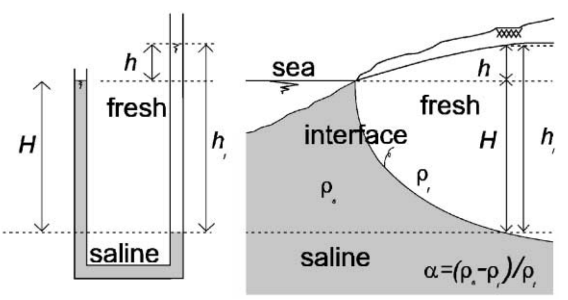

Fig. 3. The Badon Ghyben–Herzberg principle: a fresh–salt interface in an unconfined coastal aquifer.

Badon Ghyben–Herzberg principle, which describes the position of an interface between fresh and saline groundwater:

$$h = \frac{\rho_s - \rho_f}{\rho_f} H \Leftrightarrow h = \alpha H, \tag{2}$$

where h is the piezometric head of with respect to mean sea level (L), H the depth of the fresh–salt interface below mean sea level (L), ρ_f the reference density, usually the density of fresh water without dissolved solids ($\mathrm{M/L^3}$), ρ_s the density of saline groundwater ($\mathrm{M/L^3}$) and $\alpha = (\rho_s - \rho_f)/\rho_f$ the relative density difference (dimensionless).

For $\rho_s = 1025\,\mathrm{kg/m^3}$ (typical ocean water) and $\rho_f = 1000\,\mathrm{kg/m^3}$, the relative density difference α equals 0.025. The Badon Ghyben–Herzberg principle (BGH) is originally formulated for the situation that the transition zone between fresh and saline groundwater is only a small percentage of the thickness of the saturated freshwater body (thus, mostly in the order of several metres). Under these circumstances, a fresh–salt interface should be applied. This situation occurs in unspoiled sand-dune areas or (coral) islands, where the freshwater lens evolves by natural groundwater recharge. In reality, however, such systems seldom occur. This means that the formula leads to (small) errors, especially in the vicinity of the coastline near the outflow zone. Nevertheless, though the position of the interface is not completely correct, the use of the equation still gives a rather good approximation of the real situation.

Analytical formulae for the interface between fresh and saline groundwater are available for unconfined and confined aquifers in one-dimensional as well as axial-symmetric situations. These analytical solutions increases the understanding of groundwater flow and fresh groundwater resources in coastal areas. For the exact mathematical description of the formulae, the reader is referred to [16–18]. In this paper, the one-dimensional analytical formulae are only illustrated with some simple examples.

2.5.2. *Unconfined aquifer (1D situation)*

Freshwater lenses have evolved in unconfined (phreatic, water table) aquifers due to natural groundwater recharge (Fig. 4a). The following analytical formulae can be derived [16,17]:

$$H = \sqrt{\frac{-fx^2 - 2C_1x - 2C_2}{k(1+\alpha)\alpha}}, \quad h = \alpha H, \quad q = fx + C_1, \tag{3}$$

where q is the groundwater flow per unit coast length ($\mathrm{L^2/T}$), k the horizontal hydraulic conductivity (L/T), f the natural groundwater recharge (L/T) and x the horizontal position (distance from the axis of symmetry) (L).

Example 1 (*Elongated island*). A one-dimensional phreatic groundwater flow is considered through an elongated island or a strip of sand-dunes, where a freshwater lens has evolved due to natural groundwater recharge (Fig. 5a). The depth of the fresh–salt interface becomes

$$H = \sqrt{\frac{f(0.25B^2 - x^2)}{k(1+\alpha)\alpha}}, \tag{4}$$

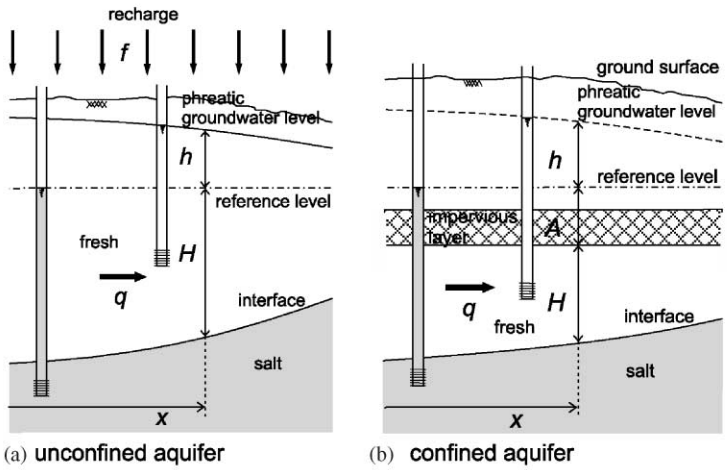

Fig. 4. The fresh–salt interface in two different types of aquifers: (a) unconfined aquifer and (b) confined aquifer.

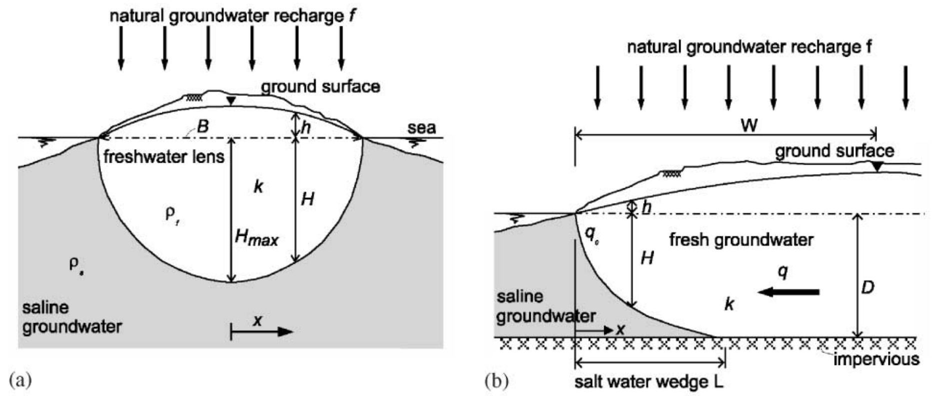

Fig. 5. The position of a fresh–salt interface (a) in an elongated island and (b) in a shallow unconfined aquifer.

where B is the width of sand-dunes (L). As can be seen, the depth of the fresh–salt interface H is proportional to the width B of the sand-dune area. For example, if $B = 2000\,\mathrm{m}$, $\alpha = 0.025$, $k = 10\,\mathrm{m/day}$ and $f = 1\,\mathrm{mm/day}$, the deepest position of the interface $H_{\max}$ (in the middle of the lens) is 62.5 m and the highest phreatic groundwater level is 1.56 m. If the shoreline retreats 100 m at each side due to a sea level rise and the natural groundwater recharge drops 20% due to climate change, $H_{\max}$ becomes only 50.3 m.

Example 2 (*Salt water wedge*). In many shallow phreatic aquifers with thickness D, the freshwater body touches the impervious base. As such, a salt water wedge of

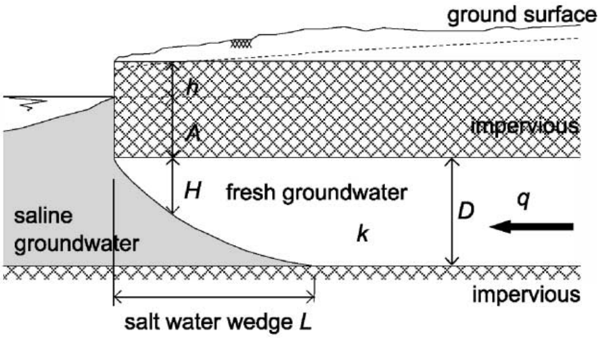

Fig. 6. The salt water wedge in a confined coastal aquifer.

length L has been created (Fig. 5b). The corresponding equations of this case are [16,17]

$$H = \sqrt{\frac{-fx^2 - 2q_0x}{k(1+\alpha)\alpha}}, \quad h = \alpha H, \quad q = fx + q_0, \quad q_0 = -fW,$$

$$L = -\frac{q_0}{f} - \sqrt{\left(\frac{q_0}{f}\right)^2 - \frac{k}{f}D^2(1+\alpha)\alpha}, \tag{5}$$

where q_0 is the natural groundwater outflow at the coastline $x = 0$ (negative sign) (L^2/T), L the length of the salt water wedge, D the thickness of the aquifer and W the width of the coastal aquifer up to the water divide (L). For example, if $W = 3000$ m, $f = 1$ mm/day, $\alpha = 0.020$, $k = 20$ m/day and $D = 50$ m, the length of the salt water wedge L is 175.1 m.

2.5.3. Confined aquifer (1D situation)

A confined aquifer is an aquifer enclosed by two aquicludes.[4] The governing equations are (Fig. 4b)

$$H = \sqrt{-\frac{2q_0x}{k\alpha} + C}, \quad h = \alpha(H + A), \quad q = q_0, \tag{6}$$

where q_0 is the fresh groundwater flow from recharge in the uplands per unit coast length (L^2/T) and A the height of the sea level with respect to the top of the aquifer (L).

Example 3 (*Salt water wedge in a confined aquifer*). The freshwater body touches the impervious base, thus creating a salt water wedge (Fig. 6). The corresponding

[4] An aquiclude is an impervious layer through which groundwater flow is not possible, e.g. a thick clayey layer.

equations are

$$H = \sqrt{\frac{-2q_0 x}{k\alpha}}, \quad h = \alpha(H + A), \quad q = q_0, \quad L = -\frac{kD^2\alpha}{2q_0}. \tag{7}$$

The length of the salt water wedge L is determined (inversely proportional) by the fresh groundwater flow q_0. The fresh groundwater flow could differ due to changes in recharge in the uplands. Possible causes of reduced recharge are changes in the hydrologic regime (e.g. climate change) or human activities such as groundwater extraction.

3. Problems with fresh groundwater supplies in coastal zones

3.1. Introduction

Worldwide, excessive overpumping of especially coastal aquifers is the most important anthropogenic cause of salt water intrusion. In coastal aquifers, saline groundwater is nearby and upconing of saline groundwater can easily occur. Exploiting and mining of groundwater regularly take place to mitigate droughts or supply irrigation projects, especially in (semi)-arid areas. Fossil and non-renewable groundwater basins are utilised for domestic, industrial and agricultural water supply. Furthermore, reducing recharge areas to develop touristic centres causes a decrease of outflow of fresh groundwater, inducing an inland shift of the salt water wedge. Note that the Eqs. (5) and (7) show that the length of the wedge is inversely proportional by the fresh groundwater outflow q_0.

Lowering of piezometric heads caused by excessive overpumping can also induce a severe land subsidence. For instance, Table 2 shows the land subsidence in some coastal megacities. In some areas, land reclamation (e.g. in the Netherlands from about the 17th century on) caused a lowering of piezometric heads, and subsequently, sea water has rapidly intruded the coastal aquifer ever since. Nowadays, lowering of the piezometric heads due to overpumping already occurs in many aquifers around the world. It is obvious that, for those systems, the impact of a (relatively small) sea level rise (e.g. 50 cm per century) on the aquifer will be of

Table 2
Land-subsidence in some coastal megacities [19]

Megacity	Maximum subsidence, m	Date commenced
Shanghai	2.80	1921
Tokyo	5.00	1930s
Osaka	2.80	1935
Bangkok	1.60	1950s
Tianjin	2.60	1959
Jakarta	0.90	1978
Manila	0.40	1960
Los Angeles	9.00	1930s

marginal importance compared to the effect of an increase in extraction rate. However, changes in global MSL will probably directly affect the coastal surface water system, rivers and estuaries.

In the next two sections, two problems with fresh groundwater resources will be discussed in more details: upconing of saline groundwater and the effect of a relative sea level rise.

3.2. Upconing of saline groundwater

In areas where saline groundwater is present below fresh groundwater, the interface between fresh and saline groundwater may rise when piezometric heads are lowered due to well extraction. This phenomenon is called interface upconing (Fig. 7). Especially in overpumped areas, e.g. in a semi-arid zone as the Gaza Strip, upconing of saline groundwater has become a serious threat to domestic water supply. Solutions are often difficult to invoke as water is scarce in these areas and illegal extractions are not easy to be stopped. In case of a continuous extraction of fresh groundwater, the interface will rise until it reaches the pumping well. From that moment on, the quality of the extracted groundwater deteriorates, and the pumping have to be stopped. In order to avoid or to limit these negative effects, one should keep the extraction rate, and so the lowering of the piezometric head, below a certain limit. After reducing the extraction, the interface may descend to a lower position, though at a very slow rate. Another solution is to replace the extraction well to a location where saline groundwater is positioned at greater depth from the well.

Example 4 (*Upconing of saline groundwater under an extraction well*). A analytical solution is given which approximates the upconing of the moving interface underneath a pumping well as a function of time t [20–22] (Fig. 8):

$$z(r,t) = \frac{Q}{2\pi\alpha k_x d}\left[\frac{1}{(1+R'^2)^{1/2}} - \frac{1}{[(1+\gamma')^2 + R'^2]^{1/2}}\right], \tag{8}$$

$$R' = \frac{r}{d}\frac{k_z^{1/2}}{k_x}, \quad \gamma' = \frac{\alpha k_z}{2n_e d}t, \tag{9}$$

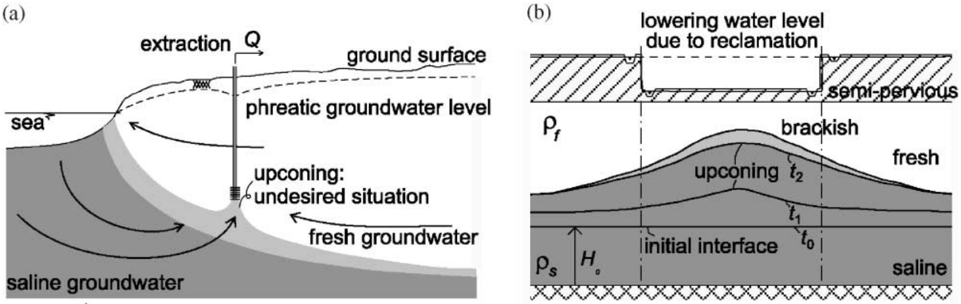

Fig. 7. Upconing of saline groundwater: (a) under a pumping well and (b) under a low-lying area.

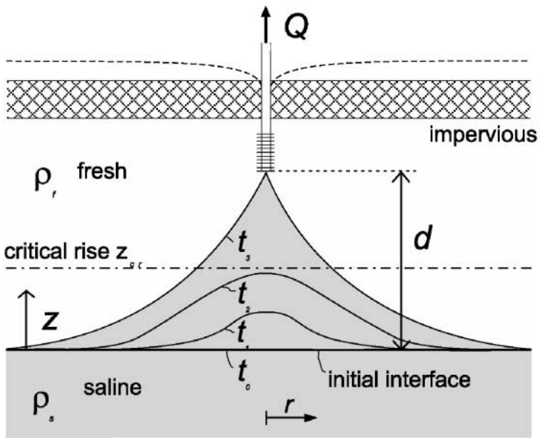

Fig. 8. Upconing of saline groundwater under a pumping well: schematisation for an analytical solution.

where $z(r, t)$ is the rise of interface above its initial position at place r and time t (L), Q the extraction rate of the well (L^3/T), d the distance between well screen and the initial position of fresh–saline interface at $t = 0$ (L), k_x, k_z the horizontal and vertical hydraulic conductivities, respectively (L/T), n_e the effective porosity (dimensionless) and t the time elapsed since start of pumping (T). For upconing of the interface directly underneath the pumping well at $r = 0$, the ultimate position of the interface at $t \to \infty$ becomes

$$z(0, t \to \infty) = \frac{Q}{2\pi\alpha k_x d}. \tag{10}$$

In case the upconed interface passes a so-called critical rise $z_{cr} = \theta d$, it will reach the pumping well with a sudden jump. Thus, assuming an abrupt interface such that the salinisation of the pumping well occurs only for $z > z_{cr}$, the maximum permissible pumping rate without pumping of saline groundwater is given by

$$Q_{\max} \leqslant z_{cr} 2\pi\alpha k_x d \quad \text{or} \quad Q_{\max} \leqslant 2\pi\alpha k_x \theta d^2. \tag{11}$$

In literature, the value for θ varies from 0.25 to 0.6. As such, a well-distributed system of shallow wells with small extraction rates is advantageous. These relatively small extractions cause little upconing. As such, shallow well screens offer a better starting position against salinisation.

3.3. Impacts of a relative sea level rise

The impacts of a relative sea level rise on the coastal surface water system, rivers and estuaries, and coastal aquifers are discussed below:

- The coastal surface water system will directly sense the impacts of sea level rise. Increases in storm surges, wave attack, flooding, and collapses of coastal

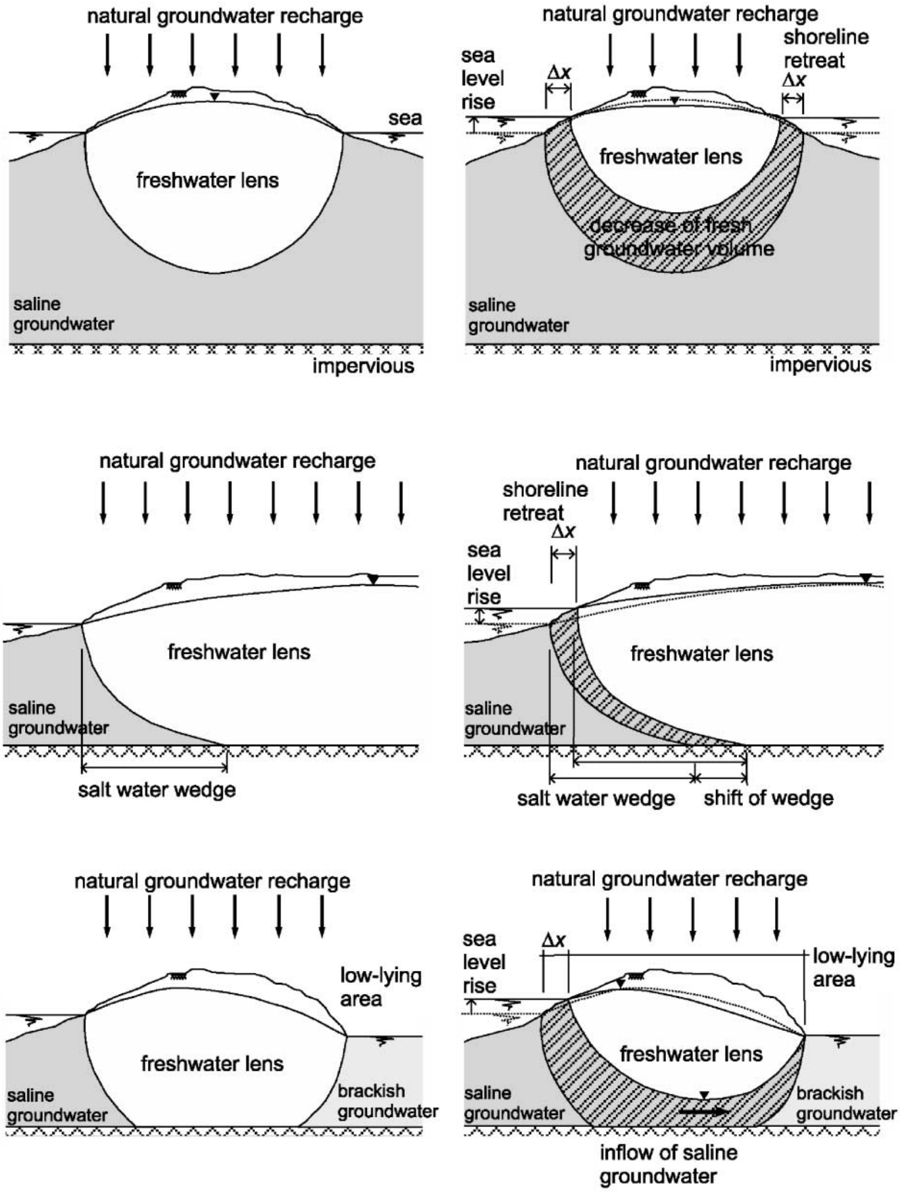

Fig. 9. Effects of a sea level rise on coastal aquifers.

protection defences could directly induce the inundation of populated areas and loss of lives must be feared. Furthermore, in the medium term, sea level rise would cause an increase in coastal erosion. If no compensating measures such as sand-suppletion are taken, it could result in severe shoreline retreat. Shoreline retreat will also affect coastal aquifers (Fig. 9), e.g., by reducing the width of the sand-dunes along the coastline where fresh groundwater resources are situated and by diminishing the length over which natural groundwater recharge occurs. Both events may lead to a decrease in fresh groundwater resources.

- Rivers and estuaries will experience an increased salt water intrusion in case of sea level rise, if the river bed elevation cannot match with sea level rise. Because the sediment load at many river mouths is reduced significantly these last decades among others due to human activities (building dams, sand-mining), quite some rivers and estuaries are expected to have an increased salt water intrusion. This could threaten adjacent aquifers along rivers and estuaries from which groundwater is extracted. Furthermore, the backwater effect of sea level rise would also decrease the safety against flooding over large distances upstream the river mouth. Especially, areas adjacent to rivers with valley slopes only slightly steeper than river slopes have to be protected by embankments.
- Coastal aquifers within the zone of influence of MSL can be threatened by sea level rise (Fig. 9). Intrusion of salt water is accelerated into these aquifers, which could result in smaller freshwater resources. Furthermore, seepage will increase quantitatively in those areas and this seepage could contain more saline groundwater. In consequence, crops may suffer from salt damage and fertile agriculture land might change into barren land. In addition, the mixing zone between fresh and saline groundwater will be shifted further inland. Extraction wells, which were previously located beyond the salinisation zone, will then be situated in areas where upconing of brackish or saline groundwater can easily occur. This can be considered as one of the most serious effects of sea level rise for every coastal aquifer where groundwater is heavily exploited.

It is important to recognise that impacts of sea level rise must be considered in relation to impacts of human activities. It is very likely that not sea level rise, but human activities will cause a severe salinisation of most coastal aquifers in the future. A reason for this assumption can, among others, be deduced from the time lag between causes and effects. Sea level rise takes place progressively. The time characteristic of sea level rise is in the order of decades. On the other hand, the time characteristic of human activities, such as groundwater extraction projects, is in the order of years. Before negative impacts, such as upconing, are recognised, it may be too late to take countermeasures.

4. Solutions to compensate and control the salinisation process

4.1. Introduction

It takes time before the salinisation of aquifers due to the negative effects of human activities (e.g. lowering of the piezometric heads due to excessive overpumping) or a relative sea level rise is actually observed. The main reason is that in the salinisation process enormous volumes of fresh groundwater have to be replaced by saline groundwater. As such, countermeasures to compensate the salinisation process should be taken in time, since the time lag is considerable (several decades to centuries) before these measures result in effective changes in the salinity distribution of the aquifer.

4.2. Human countermeasures to control salt water intrusion

The following technical countermeasures to prevent or retard the salinisation process can be considered (Fig. 10):

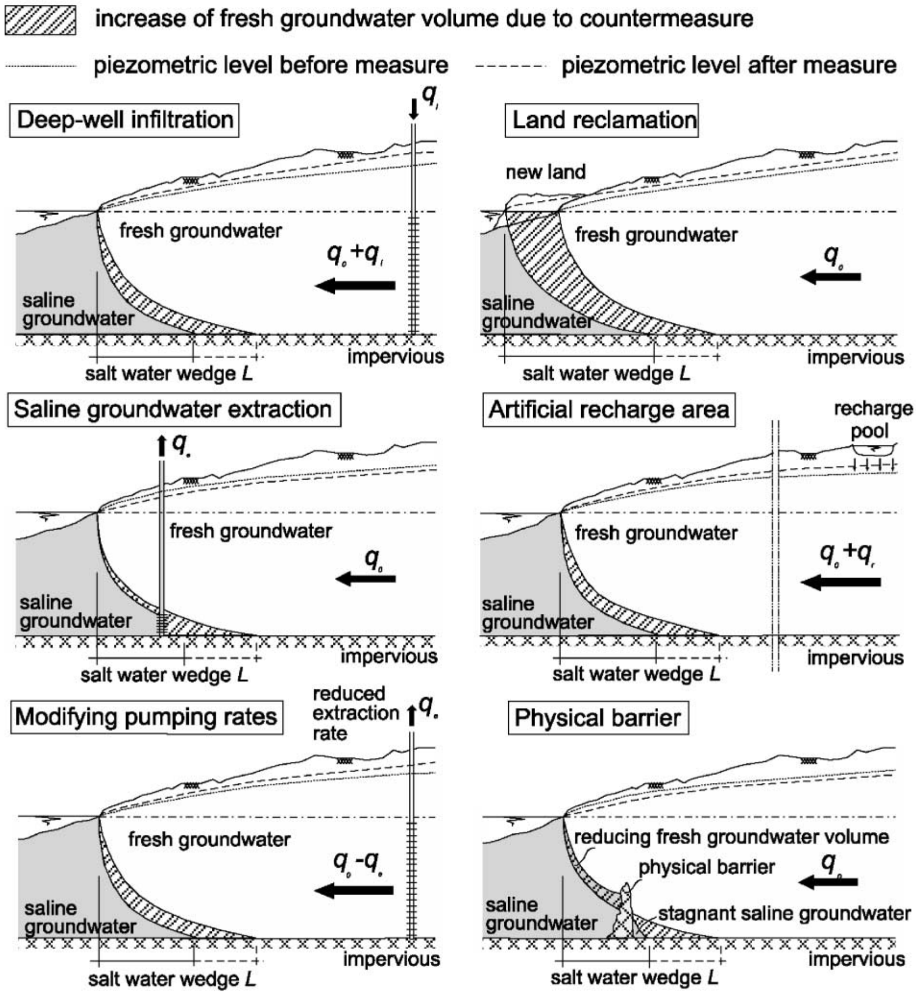

Fig. 10. Countermeasures to control salt water intrusion.

(1) Freshwater injection barriers through injection or (deep-well) infiltration of fresh (purified sewage) water near the shoreline. This is already applied in Israel, at Long Island and in Los Angeles.
(2) Extraction of saline and brackish groundwater. However, this could regrettably result in undesirably low piezometric heads, especially in shallow coastal aquifers. Furthermore, the disposal of the extracted saline or brackish groundwater could meet with problems.
(3) Modifying pumping practice through reduction of withdrawal rates or adequate relocation of extraction wells. The desired extraction rate should preferably be extracted by well-distributed shallow wells to prevent excessive upconing. Groundwater withdrawal for domestic, agricultural and industrial water supply may not be reduced during periods of droughts, so that salt water intrusion tends to occur anyway.
(4) Land reclamation, thus creating a foreland where a freshwater body may develop which could delay the inflow of saline groundwater.
(5) Increase of (artificial) recharge in upland areas to enlarge the outflow of fresh groundwater through the coastal aquifer, and thus, to reduce the length of the salt water wedge.
(6) Creation of physical barriers, such as sheet piles, clay trenches and injection of chemicals. This solution is only applicable in shallow aquifers and at high cost. A small physical barrier by injecting pumping cement grout has been implemented at Okinawa-Jima Island in Japan.

The economic feasibility of countermeasures should be investigated. For instance, it is recommended to derive the optimum position of well lines and rates of extraction or infiltration. Moreover, the countermeasures should be adapted and optimised in the course of the realisation of the measure, based on changes in the salinity of the subsoil.

5. Instruments for sustainable development of fresh groundwater resources

5.1. Introduction

Besides technical countermeasures, other instruments are available to cope with salt water intrusion problems. For instance, an intensive cooperation between (local) authorities and water users is essential to control the extraction per capita. Educating, training, informing the water users, and participation of water users in regular decisions could be very effective in coming to a lower water use. In addition, groundwater extractions could be restricted through a system of permits. It may be necessary to reduce agricultural activities and move to other places. A shift to more salt resistent crops could enlighten the need to extract groundwater of high quality. Finally, in some areas (e.g. tropical islands), desalinisation of saline water could relieve the stress on groundwater resources though at the expense of high energy costs. In this section, the instruments monitoring and numerical modelling are discussed in more detail.

5.2. Monitoring of the salinisation process

Coastal well systems have to be safeguarded to prevent them from salinisation. Monitoring the quality of groundwater on a regular basis is important in coastal areas where salt water intrusion may be expected. The conventional way is to analyse samples of salinities and piezometric heads. Besides this, geophysical exploration techniques have proven to be useful. At present a special application of an electrical resistivity method is often used in combination with observation wells. With this method it is possible to repeat (automated) measurements as often as desirable. A network of observation wells around the well system should be set up and groundwater samples and piezometric heads should be analysed. These wells should be located at different levels and at such a distance that in case of salinisation the eventual progression of the saline front can be observed and appropriate and timely countermeasures can be taken. If saline water is already present in deeper layers also observation wells have to be situated underneath the extraction wells and deep enough to detect upconing already at an early stage. Gradients in piezometric head indicating flow from saline parts of the aquifer towards the extraction wells should be avoided because flow lines through the transition zone will always carry brackish water to the extraction system (Fig. 7a).

5.3. Modelling of salt water intrusion

5.3.1. Introduction

Numerical modelling can be a tool to analyse processes which threaten fresh groundwater supplies in coastal areas. At present, three-dimensional numerical modelling of solute transport is the state of the art from a salt water intrusion modelling point of view. Nevertheless, there are some restrictions in modelling salt water intrusion in three dimensions [23]. The most important restriction is that reliable and accurate groundwater data, which is required for calibration and verification of the models, are not available in large quantities.

5.3.2. Salt water intrusion in Noord-Holland, the Netherlands

In this case, salt water intrusion is briefly analysed in a three-dimensional coastal hydrogeologic system of Quaternary deposits in the northern part of the province Noord-Holland, the Netherlands (Figs. 11 and 12) [24]. This case-study serves as an example to demonstrate an instrument how to obtain more knowledge of the salinisation of the subsoil. Based on numerical modelling with the computer code MOCDENS3D [25,26], it appears that a severe and irreversible salinisation already occurs in this system with an area of approximately 2000 km^2. Within a few tens to hundreds of years, the salinity of the top layer will increase substantially (Fig. 13). This process is generated by human activities such as large groundwater extractions during the past decades, but especially the reclamation of the low-lying areas during

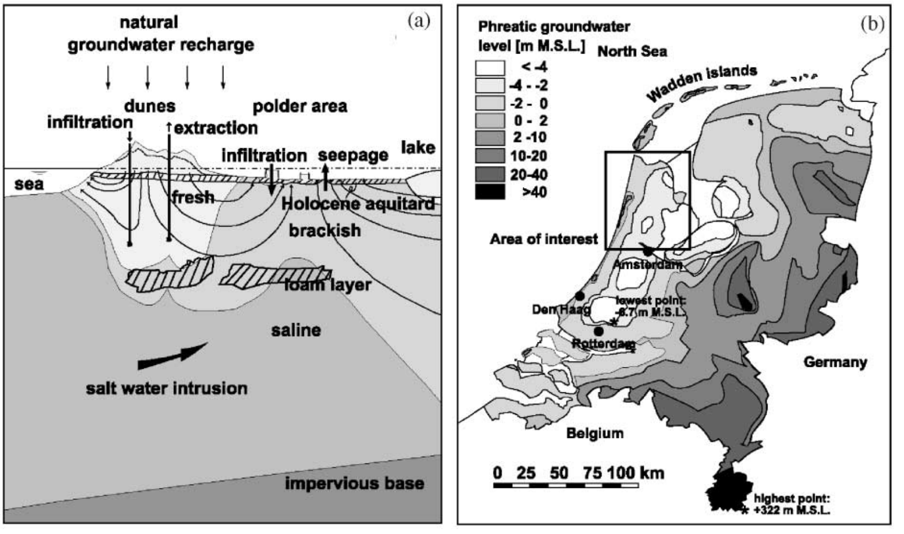

Fig. 11. Salt water intrusion in the Netherlands: (a) a schematic outline of the geometry and (b) ground surface in the Netherlands.

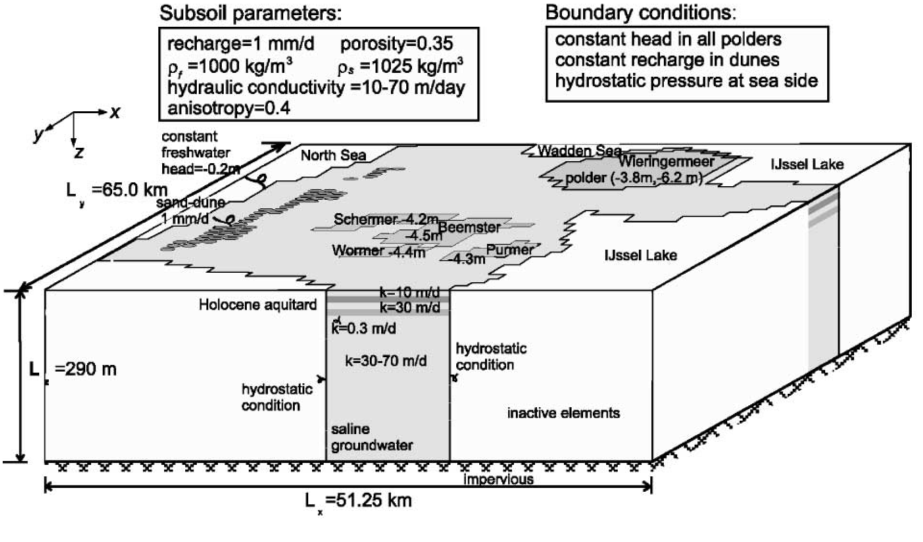

Fig. 12. The geometry of the groundwater system in the northern part of Noord-Holland.

the past centuries, causing a low phreatic groundwater level. The salt load through the Holocene aquitard in the low-lying polder areas will increase significantly. In addition, it is to be expected that a relative sea level rise of 50 cm per century intensifies the salinisation process, inducing an increase in salt load.

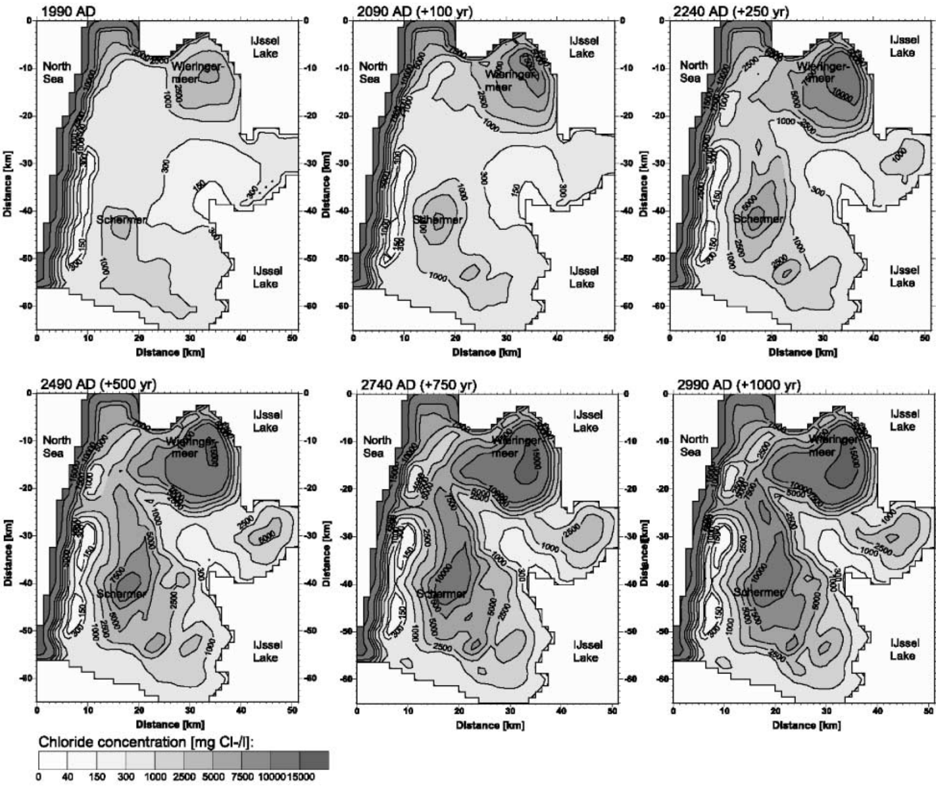

Fig. 13. Chloride concentration at −5 m N.A.P. in the aquifer system at six moments in time: 1990, 2090, 2240, 2490, 2740 and 2990 AD.

6. Conclusions

Fresh groundwater supplies in many coastal aquifers throughout the world are threatened by natural and anthropogenic causes. A relative sea level rise but especially upconing of saline groundwater due to excessive overpumping will lead to a severe salt water intrusion. This intrusion of salt water can be counteracted by technical countermeasures such as creating recharge areas or deep-well infiltration of fresh groundwater. Desalinisation of saline water could be applicable only at a small scale due to its high energy costs. However, restriction of present groundwater extractions through permits is also a necessity. Moreover, sustainable management of fresh groundwater resources in these coastal regions requires intensive cooperation between authorities and water users. Monitoring the present salinisation process is useful to participate in time possible threats to fresh groundwater supplies in the near future. In addition, numerical modelling can be considered to be a tool to enhance the knowledge of salt water intrusion and anticipate on the salinisation process.

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