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A PHILOSOPHY ON THE OPTIMAL EXPLOITATION OF FRESH GROUND WATER IN AQUIFERS IN COASTAL AREAS

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ABSTRACT: This paper deals with the exploitation of fresh groundwater in coastal areas in the context of integrated water management. Saltwater is a threat. With the recharge as an upper limit for abstraction of fresh groundwater, sustainable exploitation is possible in different ways. For sustainable exploitation of fresh ground water a certain reserve must be available to overcome periods of overdraft and little recharge. A choice must be made for the combination of a sustainable rate of abstraction and the reserve of fresh groundwater in the aquifer system. The combination to be chosen determines the layout and management of the system of abstraction and recharge works.

INTRODUCTION

The principles for sustainable exploitation of fresh ground water in coastal areas are well-known, and have been presented at many occasions (e.g., Custodio 1982; van Dam 1992, 1993, 1994, 1997 and 1998; Oude Essink 1996). Nevertheless many failures have been reported and others are predicted. Many of such failures were unforeseen, by lack of insight or information. Others could not be prevented by lack of proper legislation. In such cases it is necessary to restore the spoiled situation and to reach ultimately a well defined sustainable situation. A restored situation needs not to be identical to any situation that existed in the past. It should be defined first, in terms of the distribution of fresh and saline groundwater, sustainable exploitation of the aquifer, rates of abstraction, volumes of fresh groundwater in reserve, phreatic groundwater tables and piezometric levels, with due attention for environmental aspects. A sustainable situation can, within naturally imposed restrictions as for instance recharge, be defined and realized in many different ways. The choice can be based on the philosophy developed in this paper. The paper is. restricted to Darcian flow in simplified cases with sharp interfaces in order to present the fundamental aspects as clear as possible. After an analysis a number of measures is listed. For brevity only one of them, the abstraction of saline groundwater, is presented in this paper. For a description of the other measures reference is made to van Dam (1998).

EXPLOITATION OF FRESH GROUNDWATER IN COASTAL AQUIFER SYSTEMS AS AN ELEMENT I N INTEGRATED WATER MANAGEMENT

The exploitation of fresh groundwater in coastal aquifer systems can not be considered separately. It should always be done in connection with other available or potential water resources and with the water requirements, both in terms of quantity and quality, for the various present and future water requirements. Moreover the environmental aspects of all

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elements of the complete water management plan for an area should be considered and weighed. In other words the exploitation of fresh groundwater in coastal aquifer systems should form part of an integrated water management policy, such that an optimal allocation of the water resources is attained both in terms of economic and of environmental aspects, within the prevailing physical constraints. In the present times there is great concern for, and increasing understanding of, the environmental aspects.

Fresh water resources in coastal areas can be groundwater or surface water, both either locally available or from greater distance, or desalted saline groundwater or seawater. It is obvious that a proper exploitation of fresh water resources is only possible, if sufficient and reliable data are available. The collection, storage, processing and retrieval of all relevant data is indispensable.

The optimal allocation of the available fresh water resources should be based on the geographical distribution of the water requirements. This picture is never constant over time. So any integrated water management plan should also account for future developments and even the control of such developments. In this context the term adaptive water management has also been introduced.

The foregoing lines of thought point also to the necessity of adequate legislation.

FRESH AND SALINE GROUNDWATER IN COASTAL AQUIFER SYSTEMS

When dealing with the exploitation of fresh groundwater in coastal aquifer systems the key issue is salt water intrusion. Salt water intrusion in groundwater is defined as the inflow of saline water in an aquifer system. This inflow can be in a steady state but mostly it is a transient process. In the latter case the inflowing saline water replaces fresh groundwater which was originally present in the system. The fresh water disappears by outflow at a rate roughly equal to the rate of inflow of saline water. This simultaneous outflow of fresh groundwater can take place either in a natural way, on the bottom of coastal waters or in estuaries, by seepage in low-lying landareas, or, artificially, by abstraction. The result is an increase of the volume of saline groundwater and a decrease of the volume of fresh groundwater.

Before discussing the ongoing processes of saltwater intrusion it is necessary to describe the origin and occurrence of saline groundwater. Saline groundwater occurs in landareas where seawater has occurred in the geologic history and not or not fully been replaced by fresh water so far. This holds in particular for the present coastal and deltaic areas.

In practice the distribution of fresh, brackish and saline groundwater in the subsoil appears to be very complex, with great variations both in lateral and vertical direction. This is partly due to natural causes, but, in the present time, also due to human activities.

Both these causes and their effects will be described in the next two sections.

NATURAL CAUSES AND THEIR EFFECTS ON THE DISTRIBUTION OF FRESH AND SALINE GROUNDWATER

The salinity distribution of the groundwater in coastal and deltaic areas is capricious as a result of past and ongoing natural processes as climate change, geologic processes and land subsidence, resulting in changes of the sea level relative to the land surface (van Dam 1993).

Changes of climate have caused changes in sea levels throughout the geologic history. In the present time the sea level rises; rising temperatures make the seawater expanding and the polar ice caps and glaciers melting. Climate changes can also bring about changes in the rate of natural recharge of the fresh groundwater (van Dam 1999).

Eustatic and tectonic movements have caused changes of the land surface and sea bottoms with respect to the sea level, either upheaval or down warping. When the sea level rises with respect to the land level the seawater invades unprotected landareas; this is called a transgression. The opposite, a retreat of the sea, is a regression. Transgressions and regressions have occurred throughout the geologic history, au of them at a very slow rate (in the order of centimeters per century and lasting for many thousands of years).

The natural causes take place slowly. Moreover their effects lag far behind those causes. The displacement of large volumes of fresh groundwater by saline groundwater or the other way round takes place slowly.

HUMAN ACTIVITIES AND THEIR EFFECTS ON THE DISTRIBUTION OF FRESH AND SALINE GROUNDWATER

The flows of fresh and saline groundwater are determined by the levels and gradients of the groundwater table and piezometric levels, which in turn are determined by boundary conditions. These can also change by human activities, such as groundwater abstraction, artificial recharge, land reclamation and land drainage.

The effects of human activities are often much more radical and take place much faster than those by natural causes, but generally they appear in areas of smaller extent, than those of natural causes.

Salt water intrusion is, in most cases, recognized by the responsible geohydrologists. However, the actual extent of the problem is often not enough quantified due to lack of data. As in the process of salt water intrusion tremendous volumes of fresh groundwater are replaced by saline groundwater it takes considerable time to reach a new state of equilibrium. Moreover, before any new state of equilibrium is reached the rates of groundwater abstraction have often been gradually increased such that the corresponding states of equilibrium, which still have to be reached, have also changed gradually, often to unacceptable states.

Salt water intrusion is invisible, in the subsoil, and the information on the actual salinity distribution in the subsoil is always scarce. There is often not enough information on the extent of saltwater intrusion and consequently no or insufficient insight into measures to be taken and their effects. Once the picture is clear indeed, it becomes evident that intensive and costly measures are required in many cases which are already in an alarming phase. The lessons learned from such cases should also serve for the prevention of new failures elsewhere.

Proper measures will be summed up in a special section further on. Regrettably such measures are not always taken timely because in many cases there is no, or not yet, adequate legislation. So the present interests of e.g. some industrial parties can spoil the future situation.

For economic, social, legal, and even political reasons, such measures can often not be taken immediately, which can result in further deterioration and even abrupt breakdown of water supplies .

ANALYSIS

From the foregoing it is obvious that any increase of groundwater abstraction, under otherwise unchanged conditions (no artificial recharge, no relative sea level rise), leads to a

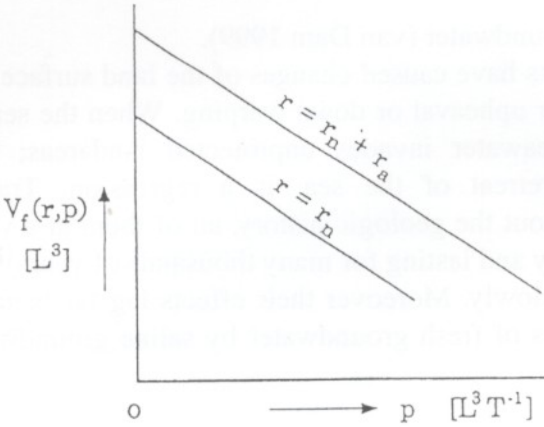

Fig. 1 Volume of fresh groundwater $V_f(r, p)$ as a function of the rate of abstraction p for different values of the recharge rn or $r_n + r_a$

decrease of the volume of fresh water in the aquifer, simultaneously with an equal increase of the volume of saline water by inflow from the seaside. The rates of decrease respectively increase are also equal. Figure I presents, in a styled way, just for illustration, the relationship between the rate of abstraction p $[L^3 T^{-1}]$ (p stands for production) and the volume of fresh groundwater in the subsoil $V_f(r, p)$ $[L^3]$, for different rates of recharge r $[L^3 T^{-1}]$, whether natural (r_n) or natural (r_n) and artificial (r_a) together ($r_n + r_a$). The volume of phreatic or confined groundwater is bounded by its contact with the sea, either at the coastline (for phreatic groundwater) or at some distance off the coastline (for confined groundwater), the impermeable base and a chosen boundary somewhere inland, beyond the presence of the saline groundwater. Part of this volume is fresh, the other part is saline. The recharge r is either of local or regional origin or consists of inflow from the uplands or a combination of the two. The abstraction p is concentrated in wells or in well fields. In case of a great many of small wells, distributed over the area the abstraction may, in this explanatory context, be considered as being uniformly distributed over the surface. The relationships presented in Fig. 1 hold for a fixed configuration of abstraction works. The relationships drawn in this styled figure, though drawn as straight lines, are not necessarily linear.

Figure 2 shows $V_f(r, p)$ as a function of time in case of a sudden increase, at $t = 0$, of the rate of abstraction p, from p_1 to p_2 and with constant recharge r. From the instant of this increase the curve goes down, from the volume $V_f(r, p_1)$, asymptotically to the volume $V_f(r, p_2)$, according to the relationship of Fig. 1. The loss in volume of fresh water is equal to the increase in volume of saline water, indicated as:

$$\int_0^t i_S(t)dt \tag{1}$$

where i_S is the rate of inflow $[L^3 T^{-1}]$ of the saline water. When neglecting the relatively small storage terms, for both the phreatic storage and the elastic storage, the groundwater balance for the total volume of groundwater, both fresh and saline, in the bounded area reads at any time t:

$$r(t) + i_S(t) = p(t) + o_f(t) \tag{2}$$

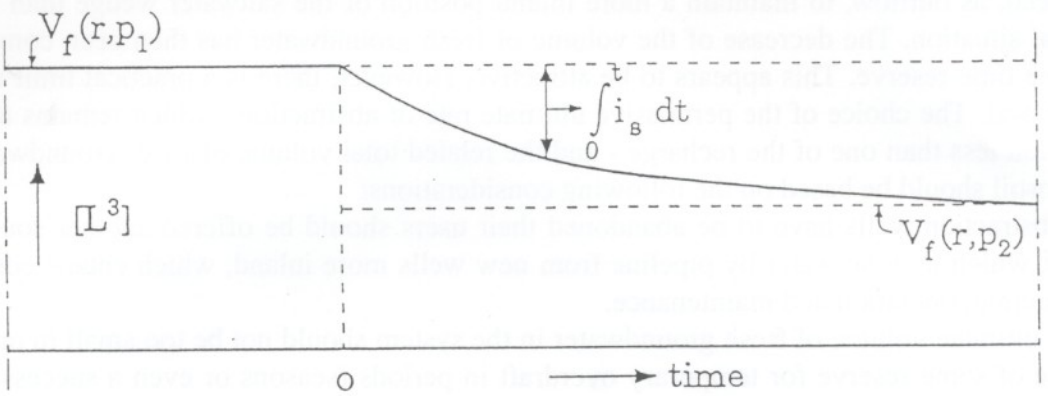

Fig. 2 Volume of fresh groundwater $V_f(r, p)$ as a function of time in case of a stepwise increase of the groundwater abstraction rate (The accumulated inflow of saline water i_s is indicated)

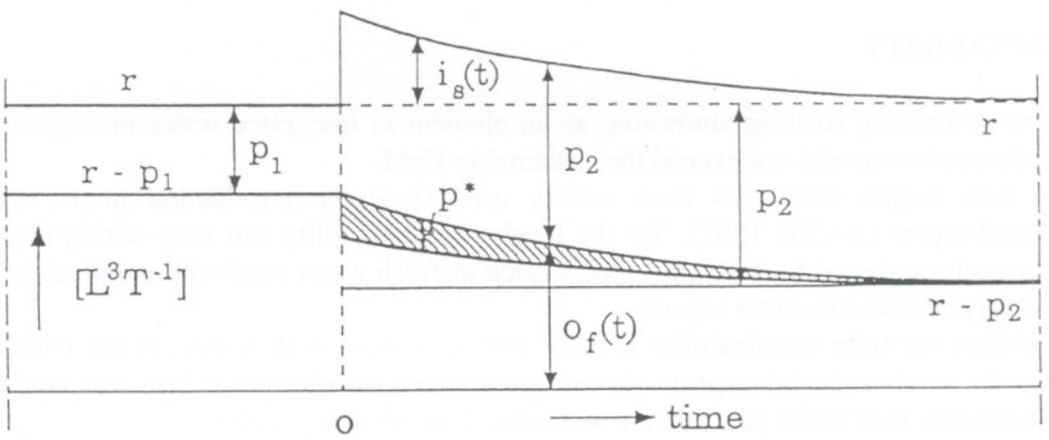

Fig. 3 Effect of a sudden increase of the rate of abstraction p^* (The rate of p^* is partially lost, the other part can be recovered)

where o_f is the rate of outflow [L^3 T^{-1}] of the fresh groundwater. This relationship is graphically presented, for the above-described case, in Fig. 3. The rate of outflow of the fresh groundwater, o_f is a loss. This loss could, at least partly, be recovered by temporary pumping an additional rate p^* of fresh groundwater, as tentatively indicated by the hatched area in Fig. 3. The distribution over time of p^* could be different from what has been drawn, for example stepwise. This volume of water can be pumped only once. This is called mining of fresh groundwater. The sooner the volume of fresh groundwater is taken - before it is partly lost by outflow - the better. This is what has been done in practice, mostly unconsciously. By pumping more fresh groundwater than a permissible fraction of the recharge the volume of fresh groundwater decreased. By the time that some deep wells had to be abandoned because of the rising interface between fresh and saline groundwater new wells were drilled more inland and exploited thus mining another volume of fresh groundwater. This process can be repeated until no further retreat is realistic. The ultimate situation is one where a greater fraction of the recharge may be sustainably abstracted, because less fresh water needs to be sacrificed, as outflow, to maintain a more inland position of the saltwater wedge than in the original situation. The decrease of the volume of fresh groundwater has then been consumed as a one time reserve. This appears to be attractive. However, there is a practical limit to this withdrawal. The choice of the permissive ultimate rate of abstraction - which remains always a fraction less than one of the recharge - and the related total volume of fresh groundwater in the subsoil should be based on the following considerations:

1. If abstraction wells have to be abandoned their users should be offered another source of supply, which may be water by pipeline from new wells more inland, which entails costs for construction, operation and maintenance.
2. The ultimate volume of fresh groundwater in the system should not be too small in order to dispose of some reserve for temporary overdraft in periods (seasons or even a succession of extreme years) of less recharge or greater demand or a combination of these two. This is a matter of risk assessment and policy in decision making.

Obviously decisions on the optimal exploitation of fresh groundwater in coastal aquifer systems should be based on economic criteria and on environmental criteria taking into account hydrological and environmental risk assessments and the agreed up to date policy for integrated water management as described in the first section.

SUSTAINABILITY

When abstracting fresh groundwater, as an element in integrated water management, the rate of abstraction should not exceed the sustainable yield.

The term sustainability has been widely used since its introduction in the so-called Brundtland-report (WCED 1987). Yet the level of sustainability can vary widely depending on the weights assigned to different aspects, such as fresh water production, agriculture and a great variety of environmental aspects.

Nowadays the term sustainability is more and more used with respect to the concern and care for the environmental aspects (in particular flora and fauna), which are much better understood now than in the past and are still subject to intensive studies.

The philosophy of sustainability poses limits to the draw down of groundwater levels and piezometric levels and to the reduction of natural outflow of groundwater. As a result the sustainable yield is always only a fraction of the recharge (natural or artificially increased). Still this leaves space for discussion because, apart from the area of nature to be maintained, a choice should be made of what type of nature is to be aimed at either to maintain the present situation, or to restore a historic situation or even to create new nature. Whatever the choice is, it should be made and maintained for a long time ahead. This is because the transition from the present state to the state of nature aimed at takes a long period of time, in the order of several decades. This long lasting natural process should not be interfered by changes in policy.

MINING OF FRESH GROUNDWATER IN COASTAL AREAS

Mining of fossil fresh groundwater, which is presently not recharged, can be considered as a temporary source of fresh water. For economic reasons (the cost of construction, operation and maintenance of abstraction works) it should last for at least a few decades. This one-time reserve could either be used first - pending the availability of other resources later or to postpone the higher costs of more expensive sources as e.g. desalting - or be kept as a reserve for emergencies.

The environmental consequences should be studied and can be an impediment. The draw down of groundwater tables or piezometric levels, for instance, might have geotechnical consequences or effects on the vegetation. Moreover adjacent groundwater flow systems might be affected.

Mining of a fraction of a fresh groundwater body, which is currently subject to natural recharge, is a possibility in the transitional phase from the present state to a defined state which is strived after. Of course this possibility exists only in case the present volume of fresh groundwater is greater than that in the defined state which is strived after. See also the relevant texts of the preceding sections.

MEASURES TO RESTORE DISTURBED GROUNDWATER SYSTEMS IN COASTAL AQUIFERS

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

1. 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.
2. the desired state after restoration, in terms of sustainable rates of abstraction, the abstraction works and the 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 but where continuity of a controlled exploitation must be assured.

The following measures 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.

All these measures are discussed in van Dam (1998). For brevity only the abstraction of saline groundwater will be discussed in the next section as an illustration of the principles outlined before.

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

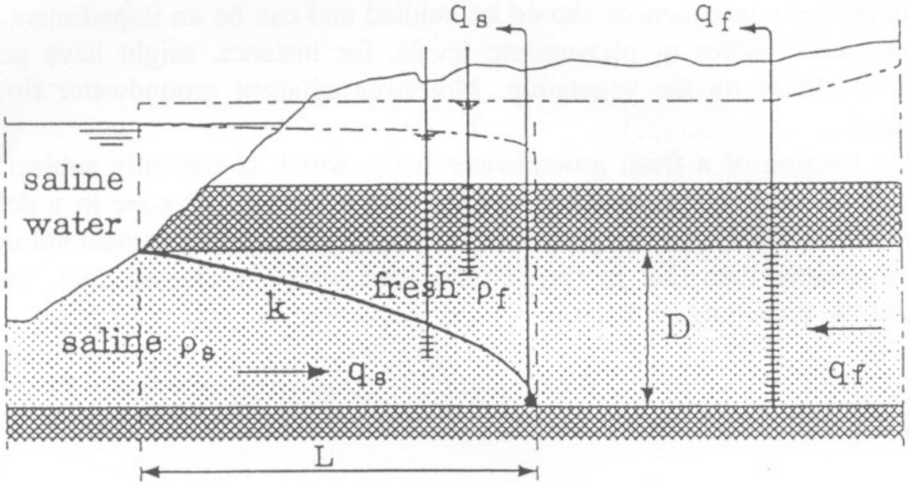

Fig. 4 Abstraction of saline groundwater in the tip of the salt water wedge below confined fresh groundwater at such a rate that no fresh groundwater is lost by outflow at the seaside

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.

The disposal of the abstracted saline water can be a problem. The same holds for the brine in case the abstracted saline groundwater is desalted as an additional source of fresh water.

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 as was outlined before deserves serious attention. In case of scarcity of fresh water it is worthwhile to reduce the loss by outflow of fresh groundwater, theoretically even to zero. The effect of pumping saline groundwater is best illustrated by the extreme, theoretical, situation, in confined groundwater, as presented in Fig. 4. For clear illustration the interface is assumed to be sharp. The saline groundwater is pumped, theoretically, in the tip of the saltwater wedge at such a rate, in this extreme theoretical situation, that the piezometric level of the fresh groundwater above the saltwater wedge is horizontal. In that case the fresh groundwater above the saltwater wedge is stagnant. There is no loss of fresh groundwater by outflow into the sea and the flow of fresh groundwater can be abstracted totally. The length L of the saltwater wedge, of parabolic shape, and the inflow of seawater q_S are related as follows:

$$L = \alpha^* kD^2 / 2q_S \tag{3}$$

where $\alpha^* = (\rho_S - \rho_f)/\rho_S$

As was said before, the situation of Fig. 4 is an extreme, theoretical, situation, chosen for a clear illustration of the principle only. In reality a drain in the inland tip of the saline water body will attract fresh water as well, due to the effect of dispersion. Therefore the practical solution is a line of wells at some distance seaward of the tip of the body of saline water of Fig. 4. Such a configuration is shown in Fig. 5. The saline water flows towards that line of

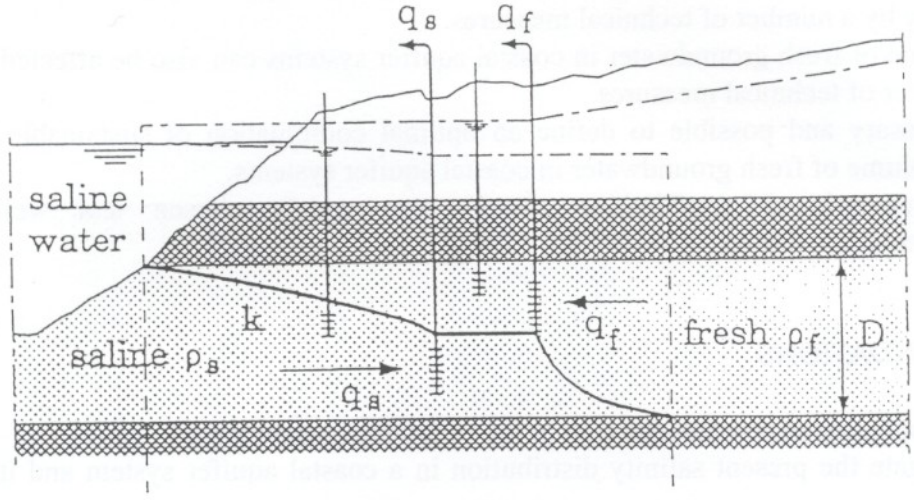

Fig. 5 Practical configuration for implementation of the principle illustrated in Fig. 4

wells and is pumped completely by that line of wells. Behind that line of wells the saline water is stagnant. Between the lines of wells for abstraction of saline groundwater (q_s) and for fresh groundwater (q_f) the interface is horizontal because there neither the fresh nor the saline groundwater flows. The flow of fresh groundwater (q_f), from recharge, is totally abstracted by the line of wells with well screens in the fresh groundwater. At the inland side of these wells the interface has another parabolic shape as depicted in Fig. 5. The location of the abstraction wells and the determination of their capacity is an interesting optimization problem.

Distinction can be made between regional or large scale effects and local or small scale effects. So far this section dealt with the regional effects only. For the local problem of upcoming, the installation and operation of so-called “scavenger wells” is a good curative solution. Such wells, next to or nearby pumped wells have their wellscreen at some depth below that of the pumped well in the fresh groundwater. The wellscreen 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 upcoming. The upward cone of saline groundwater can sink down either by stopping the abstraction of fresh groundwater for some time before pumping both wellscreens 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 upcoming 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 favourable distribution of fresh and saline water in the subsoil and less loss of fresh water by outflow to the sea.

CONCLUSIONS

1. The sustainable yield of fresh groundwater in coastal aquifer systems is a fraction less than one of the natural and artificial recharge.

2. The sustainable yield of fresh groundwater in coastal aquifer systems can be affected favourably by a number of technical measures.
3. The volume of fresh groundwater in coastal aquifer systems can also be affected favorably by a number of technical measures.
4. It is necessary and possible to define an optimal combination of sustainable yield and reserve volume of fresh groundwater in coastal aquifer systems.
5. The aforementioned combination should also satisfy chosen and well defined environmental conditions.

RECOMMENDATIONS

The aforementioned conclusions lead to the following recommendations:

1. to investigate the present salinity distribution in a coastal aquifer system and its changes over time.
2. to define the desired sustainable state of a coastal aquifer system.
3. to design and to execute the technical and legal measures to reach and to maintain the aforementioned state.
4. to check the foreseen development of the salinity distribution in the coastal aquifer system over time.

REFERENCES

Custodio, E. and Bruggeman, G. A. (1987). Groundwater problems in coastal areas. Studies and Reports in Hydrology, No. 45, UNESCO, Paris.

Dam, J.C. van (1992). Problems associated with saltwater intrusion into coastal aquifers and some solutions. Proceedings, Seminar on Problems of Lowland Development, Institute of Lowland Technology, Saga University, Japan.

Dam, J.C. van (1993). Impact of sea level rise on salt water intrusion in estuaries and aquifers. Keynote lecture, International workshop "Seachange'9 3", Noordwijkerhout, Tidal Waters Division (presently RIKZ), Directorate General for Public Works and Water Management (Rijkswaterstaat), Hague, the Netherlands.

Dam, J.C. van (1994). Groundwater hydrology in lowland. In: Miura, N., Madhav, M.R. and Koga, K. (editors), Lowlands, Development and Management. A.A.Balkema, Rotterdam/Brookiield.

Dam, J.C. van (1997). Seawater intrusion in coastal aquifers: guidelines for study, monitoring and control. In: Dam, J.C. van (editor), FAO Water Reports, 11 FAO, Rome.

Dam, J.C. van (1998). Chapter 4: Exploitation, restoration and management of fresh groundwater in coastal aquifers. In: Bear, J., Cheng, A. H-D, Sorek, S., Ouazar, D. and Herrera, I. (Editors), Seawater Intrusion into Coastal Aquifers: Concepts, Methods and Practice. Kluwer Academic Publishers, Dordrecht.

Dam, J.C. van (1999). Impacts of climate change and climate variability on hydrological regimes. Final report of the working group, UNESCO IHP-IV Project H-2. l, UNESCO/Cambridge University press.

Oude Essink, G.H.P. (1996). Impact of sea level rise on groundwater flow regimes: A sensitivity analysis for the Netherlands. Ph.D. thesis, Delft University of Technology, Delft, the Netherlands.

WCED (World Commission report on Environment and Development) (1987). Our Common Future (the Brundtland report). Oxford University press, Oxford, U.K.