FRESH AND MODERATELY BRACKISH GROUNDWATERS IN COASTAL PLAINS AND CONTINENTAL SHELVES: PAST AND ONGOING NATURAL PROCESSES

GROEN, J., KOOI, H., POST, V. & DE VRIES, J.J.
Hydrology Department, Faculty of Earth Sciences
Address: de Boelelaan 1085, 1081 HV, Amsterdam.
Email grok@geo.vu.nl

ABSTRACT

Salinity distributions is coastal and offshore areas are often complex, as a result of changing geological boundary conditions. In most textbooks on hydrogeology this aspects is not discussed in depth. Observations indicate that fresh to moderately brackish groundwater, may protrude many kilometers into the offshore sediments. Under certain conditions these meteoric groundwater bodies are part of gravity driven flow systems controlled by the present Holocene conditions of sea level, climate and coast morphology. They also may be relicts of Late Pleistocene flow systems and not in equilibrium with present conditions (paleowaters). In this article the conditions and processes are discussed, which lead to the formation of meteoric offshore groundwater and the waning of these bodies by slow salinization (diffusion and density driven flow). Also techniques in the field of hydrodynamic and solute transport modelling and geochemical and isotopic tracers are shown, applied by the hydrology research group of the Vrije Universiteit, Amsterdam.

INTRODUCTION

Salt water intrusion studies are mainly concerned with salinisation of coastal aquifers resulting from recent man-made or catastrophic changes in boundary conditions. A key element in these studies is the pre-existing, natural salinity distribution and flow regime on which these changes are imposed. Here we discuss this natural background condition in coastal and offshore sediments as an unsteady-state result of geological processes of large temporal and spatial scales. With geological processes we refer to changes in sea level, coastal morphology and climate, which affect the boundary conditions of coastal flow systems. In that respect, we find ourselves in a unique period of time. The effects of the fast 130 m sea level rise in the period between 15000 and 6000 BP can still be felt in the flow systems and the salinity distributions in coastal and offshore sediments. By ignoring these effects hydrogeologists often adhere to simplified concepts on fresh and saline groundwater in coastal areas and in the offshore. This is particularly evident in most hydrogeological text-books which depict fresh – saline boundaries as sharp or diffuse interfaces close to the coastline. These pictures are largely based on steady-state mathematical/numerical models with simple boundary conditions. Due to their frequent use, the results displayed by these pictures have gradually become “realities”. These simple and in some cases incorrect concepts persist as long as they are not falsified by observations and as long as mathematical models based on these concepts do not prove to be inadequate tools in solving coastal hydrogeology problems.

Though still scarce, observations of ocean drilling programs, offshore oil wells and water wells on islands provide ample evidence that fresh and brackish groundwater bodies are not restricted to the onshore, but in some places extend 10 to 100 km into the sea. Prime examples are the Atlantic coast of the USA (Hathaway et al. 1979), the coast of Suriname (Groen et al. 2000) and Indonesia (Maathuis et al., 1996) (figure 1). This phenomenon of offshore fresh and brackish groundwater cannot be readily understood using the conventional text-book hydrogeological ideas, but requires additional concepts based on the paleohydrological development of coastal areas. This article gives a concise overview of recent work in this direction by the Hydrogeology Group of the Faculty of Earth Sciences of the Vrije Universiteit of Amsterdam. The work consists of the integration of new and old ideas regarding coastal and offshore groundwater processes and their application in case studies.

STEADY-STATE CONDITIONS

One of the key questions regarding offshore fresh and brackish groundwater occurrences is to what extent they are part of active coastal groundwater flow systems which extend into the marine realm. That submarine discharge does occur is well-known from submarine springs, mostly along coasts with karstic limestones (Kohout, 1966; Zektzer, 1973). By comparison, very little is known about diffuse discharge in siliciclastic sediments. Only very recently this process is being studied by seepage meters (Simmons, 1992) and chemical and isotopic tracers like TDS (Guglielmi & Prieur, 1997), chloride (Piekarek-Jankowska, 1996), methane (Chanton et al., 1996), barium (Shaw et al, 1998), ^{222}Ra isotope (Cable et al., 1996) and ^{226} Ra isotope (Cable et al., 1996; Moore, 1996).

Groundwater models have similarly paid little attention to the offshore domain. Due to severe simplifications, sharp-interface models based on the Badon Ghijben-Herzberg principle do not allow for offshore fresh water. Glover (1959) relaxed some of the assumptions and gave an analytical sharp-interface solution for groundwater flow in a phreatic aquifer with a submarine discharge zone, which under favourable conditions is only a few hundred meters wide. Kooi and Groen (2000) derived a similar solution for a semi-confined coastal aquifer based on earlier work by Edelman (1972). This solution suggests that fresh water wedges and submarine discharge zones may reach tens to hundreds of kilometers offshore beneath clay layers.

A major shortcoming of the sharp-interface models, however, is that they do not account for dispersive and diffusive mixing. This limitation of these models is particularly restrictive because submarine groundwater discharge implies an unstable density stratification with sea water overlying fresh or brackish groundwater which may lead to convective mixing. This process occurs as follows. Downward diffusive salt transport against an upward flow field tends to form a steady-state (exponential) vertical salinity profile or horizontal boundary layer beneath the seafloor. A boundary layer Rayleigh number then determines its stability (Kooi et al., 2000). As the thickness of the boundary layer is inversely proportional to the flow rate, instabilities and fingering occur when the upward flow rate is too small and the thickness of the boundary layer (and its Rayleigh number) become too large. Kooi and Groen (2000) used these principles to propose a modified approximate analytical solution for the width of the zone of submarine discharge for the semi-confined aquifer problem. Their results indicate that convective mixing occurs where the diffusion front penetrates the confining layer and reaches the underlying aquifer (figure 2). This place marks the end of the active gravity driven part of the fresh-brackish groundwater wedge. Kooi and Groen (2000) verified the approximate solution with variable density groundwater flow and solute transport modelling using the METROPOL code. Both the analytical and numerical calculations showed that the sharp-interface approximations significantly overestimate the offshore extent of the steady-state fresh-water wedge, although it still may extend many tens of kilometres from the coast under favourable conditions, like high onshore hydraulic heads and large aquifer transmissivity.

EFFECTS OF THE WEICHSELIAN REGRESSION

The wedges along the Atlantic coast of the USA (Hathaway et al, 1979) and Suriname (Groen et al, 2000) extend more than 20 km beneath the sea and exceed by far the lengths calculated by the steady-state model, described above (Kooi and Groen, 2000). Therefore, these offshore groundwaters cannot be part of active continental flow systems and, instead, are considered to be relics of (paleo)flow systems acting during Pleistocene regressions, when large parts of the continental shelfs were exposed (figure 3). We use the term paleowater for these waters, which we define as meteoric groundwater cut off from the original flow system after the flow domain has changed or has disappeared as a result of changes in climate, morphology and sea level. These paleowaters are also found in aquifers below Holocene coastal plains. The average sea level during the Weichselian (U.S.: Wisconsin) regression was about -50 m with respect to the present level with a minimum of -100 to –130 m during the last glacial maximum (LGM) between 25,000 to 15,000 BP (Linsley, 1996). Groundwater in the coastal plains near Paramaribo and Jakarta is indeed of Late Weichselian age (Groen et al, 2000; Geyh, 1989). Moreover, observations of groundwater heads of the deeper aquifers at Nantucket Island (Kohout et al., 1977) and Suriname (Groen, 1998) indicate stagnant conditions or even landward gradients, providing additional evidence that these offshore meteoric groundwater wedges are not related to active flow systems with onshore recharge.

Groen et al (2000) used groundwater flow modelling to study freshening of the pore waters in the shelf at Suriname during the Weichselian regression phase, assuming that the aquifers had become saline during preceding transgressive periods. They found that groundwater movement of the primary flow system (due to the overall shelf gradient) was too slow to reproduce the observed deep flushing of the aquifers. Moreover, this primary flow system could not explain the observed meteoric waters beyond 50 km offshore which was exposed for a period of 10,000 years only during the LGM. Incorporating secondary flow systems in the model associated with deeply incised rivers and gullies in the Weichselian surface (for which there is ample evidence) did provide much improved results (figure 4).

EFFECTS OF THE HOLOCENE TRANSGRESSION

During the Holocene transgression from 15,000 to 6,000 BP, sea level rose some 130 m (Fairbanks, 1989) and in many places the coastline rapidly moved inland with a speed 1 to 2 km/100yr, often over distances of more than 100 km.

Kooi et al (2000) carried out numerical model simulations with the METROPOL code to study the factors which control salinization during transgression of the sea. They found that for sufficiently slow rates of transgression, a quasi-steady evolution results, in which the transition zone can roughly keep up with the migrating shoreline, resulting in a “horizontal style of sea-water intrusion”. However, when a critical transgression rate is exceeded, an inverted density stratification develops which results in a vertical style of salinization. The critical condition separating these styles of intrusion was found to be a predictable function of substrate permeability and topographic gradient. For permeable sediments, vertical salinization occurs relatively fast by fingering (free convection) (figure 5). However, only relatively minor low permeability clay layers suffice to greatly reduce the salinization rates and to preserve low salinity waters far offshore for very long periods of time. Even for sandy substrates, Holocene trangression rates were often sufficently high to cause the transition zone to significantly lag behind coastline migration.

At Suriname thick late Pleistocene and Holocene clays have led to quasi-stagnant offshore and coastal paleowaters that are subjected to salinization by downward and upward diffusive salt transport. Groen et al (2000) carried out diffusion modelling of vertical profiles of chemical and isotopic tracers (^{37}Cl and ^{18}O) in these sediments and found that they are in excellent agreement with the Holocene transgression/regression history of the coastal plain (figure 6). Post et al. (2000) carried out a similar study for data from the southern North Sea.

Important questions remain as to the longevity of offshore paleowaters once they have formed. Answers to these questions reside, apart from diffusion rates, in the driving forces of flow in these bodies. Evidently, far offshore buoyancy forces are of prime importance. For instance, observations of small landward hydraulic gradients in the offshore meteoric wedges at Nantucket (US) (Kohout et al., 1977) and Suriname may be (partly) due to lateral differences in the thickness of the overlying wedge of dense sea water. Meisler et al. (1984) found a landward flow of about 3 m per 100 yr in a sharp-interface simulation of the fresh-water wedge at New Jersey in which buoyancy is the primary driving force. Preliminary (unpublished) modelling experiments with the METROPOL code show that buoyancy-driven lateral flow becomes important for paleowater trapped in shelfs with high-gradient secondary topography of river valleys where sea water intrudes the aquifers along the valleys, while fresh water escapes by submarine discharge at the former water divides. Part of the submarine discharge we observe today may be related to the waning of trapped paleowater bodies. However, this is expected to be mainly small diffuse discharge via sediments with a low permeability; higher discharge rates at large submarine springs would have largely emptied paleowater reservoirs during the 6,000 years since the transgression.

Finally, compaction should be considered as a driving force in paleowater bodies. For instance, in Suriname, artesian groundwater heads have been observed in deep coastal aquifers (Groen, 1998) which are too high to be caused by the inland topography or buoyancy forces. The heads can only be explained by the pressure of the rapidly accumulating Holocene sediments (Amazone sediment) in the coastal and near shore area. In the deep aquifers this pressure is transferred to the pore waters and at present will not have fully dissipated because of the strongly confined conditions. We feel that this process is often overlooked in coastal regions with a rapid sedimentation. Kooi (1999) gives an analytical solution for groundwater hydraulics in areas where groundwater is driven both by gravity and compaction.

CONCLUSIONS AND DISCUSSION

At a number of coasts around the world, vast bodies of fresh and moderately brackish groundwater of meteoric origin have been documented to occur in the offshore. At present, observations are too scarce and too scattered to draw general conclusions about the worldwide occurrence of such waters. However, we reason, based on observations and model experiments, that fresh/brackish waters in the offshore may be the rule rather than the exception. Climate, stratigraphy and shelf morphology determine where fresh groundwater could have formed during the Weichselian regression. The latter two factors also control the preservation of these waters during the Holocene transgression.

As offshore meteoric groundwater has a remarkably low salinity in some places, it may be a viable source for water supply. The Hydrogeology group of the Vrije Universiteit participates in a consortium of oil and water supply companies to investigate this possibility. Though it is essentially a form of mining, recovery of offshore paleowater should not be discarded outright. First of all the resources are vast and could last for hundreds to thousands of years. Secondly, and perhaps more importantly, if not used, these paleowaters would disappear naturally by submarine groundwater discharge or salinization by diffusion.

Clearly, more observations from offshore drilling (isotopic and hydrogeochemical analyses of water samples and geophysical bore hole logs) are needed in order to test the above concepts and hypotheses. Because, drilling is quite costly, exploration of offshore groundwater must rely on predictive mathematical models. These models could determine the probability of offshore meteoric groundwater, given the paleogeography, paleoclimate and stratigraphy of the coastal and offshore region.

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