Journal of Hydrology 551 (2017) 756–767

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Groundwater salinity patterns along the coast of the Western Netherlands and the application of cone penetration tests

P.S. Pauw [a,*], J. Groen [b], M.M.A. Groen [b], K.J. van der Made [c], P.J. Stuyfzand [d,e], V.E.A. Post [f]

[a] Deltares, Unit Subsurface and Groundwater Systems, PO Box 85467, 3508 AL Utrecht, The Netherlands
[b] Acacia Water, Van Hogendorpplein 4, 2805 BM Gouda, The Netherlands
[c] Wiertsema en Partners, Feithspark 6, 9356 BZ Tolbert, The Netherlands
[d] TU Delft, Faculty of Civil Engineering and Geosciences, Stevinweg 1, PO Box 5048, 2628 CN Delft/2600 GA Delft, The Netherlands
[e] KWR, KWR Watercycle Research Institute, PO Box 1072, 3430 BB Nieuwegein, The Netherlands
[f] BGR, Federal Institute for Geosciences and Natural Resources (BGR), Stilleweg 2, 30655 Hannover, Germany

ARTICLE INFO

Article history:
Available online 12 April 2017

Keywords:
Saltwater intrusion
Submarine groundwater discharge
Offshore fresh groundwater
Cone penetration tests

ABSTRACT

Submarine groundwater discharge is an important part of the hydrological cycle, but remains under-investigated for confined aquifers with no surface outcrop at the beach. This paper considers the offshore directed flow of fresh groundwater in the unconfined and confined aquifers along the coast of the Western Netherlands. Salinity patterns based on hydrological, geological, and geophysical field data are presented in five shore-normal hydrogeological cross-sections, extending from the beach to 4 km inland. The offshore continuation of the fresh groundwater is discussed using analytical models and cone penetration tests (CPTs) performed at the beach. All CPTs taken around the low water line of the intertidal zone reveal that changes from saline to fresh groundwater are always associated with a low-permeable layer. Such a low-permeable layer, which can be as thin as a few decimetres, may form the confining layer between the unconfined and confined aquifers, or can occur within of the unconfined aquifer. Due to its high vertical resolution, a CPT is an effective method to detect these variations in salinity and lithology. At each of the investigated locations, freshwater was present in the confined aquifer. Assuming that this fresh groundwater is part of an active flow system, the submarine freshwater tongue is estimated to extend at least a few hundred meters offshore, based on analytical model calculations. Hydrochemical data from an old offshore borehole, however, suggest this may be an underestimate and that the submarine freshwater tongue originates from former times when the coastline was located further westward than nowadays.

1. Introduction

Aquifers in coastal areas contain freshwater reserves that are vital to sustain human populations and ecosystems. Understanding the salinity distribution and groundwater flow patterns at the coast is important when investigating saltwater intrusion (Custodio and Bruggeman, 1987; Bear et al., 1999), as well as submarine groundwater discharge (Taniguchi et al., 2002; Moore, 2010). Moreover, this understanding is also crucial when adopting boundary conditions of mathematical groundwater models (Bakker and Schaars, 2006), which are widely used for the management of coastal freshwater resources (Bear et al., 1999; Werner et al., 2013).

Most of the submarine groundwater discharge studies published to date focus on shallow, unconfined aquifers and have yielded valuable insights on a number of well-characterised study sites, including De Panne, Belgium (Lebbe, 1983; Vandenbohede and Lebbe, 2005), Waquoit Bay, USA (Michael et al., 2005; Mulligan and Charette, 2006; Abarca et al., 2013), and Queensland, Australia (Robinson et al., 2007). Based on field measurements and numerical modelling, these investigations demonstrated the existence of a brackish-saline groundwater circulation cell below the beach. This circulation cell is primarily driven by the infiltration of seawater during rising tide and the discharge of groundwater (seepage) during falling tide. Inland-derived fresh groundwater may flow below this circulation cell, mix with the infiltrated seawater, and discharge at the lower part of the beach. Factors that influence the flow patterns and salinity variations include the mor-

---

* Corresponding author.

E-mail addresses: pieter.pauw@deltares.nl (P.S. Pauw), koos.groen@acaciawater.com (J. Groen), michel.groen@acaciawater.com (M.M.A. Groen), c.made@wiertsema.nl (K.J. van der Made), p.j.stuijfzand@tudelft.nl, pieter.stuyfzand@kwrwater.nl (P.J. Stuyfzand), vincent.post@bgr.de (V.E.A. Post).

http://dx.doi.org/10.1016/j.jhydrol.2017.04.021
0022-1694/© 2017 Elsevier B.V. All rights reserved.

phology of the beach, the tidal regime, wave action, and the flux of fresh groundwater that discharges offshore (Michael et al., 2005; Robinson et al., 2007; Abarca et al., 2013; Greskowiak, 2014).

In contrast to superficial, unconfined aquifers, considerably fewer studies of submarine groundwater discharge have focused on confined aquifers. Confined aquifers that extend offshore fundamentally differ from unconfined aquifers in that fresh groundwater continues to flow below the seabed instead of terminating near the shore, giving rise to an offshore tongue of fresh groundwater. This tongue can extend many kilometres below the seabed, and its length depends on the freshwater flux, the permeability of the confined aquifer and the confining layer, and the horizontal extent of the confining layer (Kooi and Groen, 2001; Bakker, 2006).

Because direct observation in the offshore region is more difficult, more expensive and has traditionally been considered less relevant than onshore investigations, very few observations exist in aquifers below the seabed. A geophysical study in Indian River Bay, USA, showed that freshwater occurs up to 1 km offshore where layers of silt and peat prevent seawater from intruding into a sandy aquifer (Krantz et al., 2004). The significance of palaeochannels was demonstrated by Mulligan et al. (2007) who used field data and numerical modelling at a field site in North Carolina, USA, to show that where these channels breach an offshore confining layer, seawater can intrude along the channel axis, while brackish groundwater discharges along the channel margins. Heterogeneity can also influence the offshore flow of fresh groundwater on a local scale, as was shown by Andersen et al. (2007) in their study near the coast of Esbjerg, Denmark. These studies have highlighted the important role of the lithological variability on groundwater flow and salinity patterns, and the need of detailed field studies to understand these interactions.

The objective of this paper is to provide enhanced understanding of offshore and nearshore salinity patterns in layered unconfined-confined aquifer systems. To this end, salinity patterns were analysed in shore-normal hydrogeological cross-sections along the western coast of the Netherlands, extending from the beach to 4 km inland. The coastal dune belt is of critical importance to the potable water supply in the Netherlands. While a wealth of onshore data is available with data from as early as 1900, flow conditions on the seaward side remain poorly understood due to a lack of observations offshore or close to the shoreline. Existing data were therefore complemented by conducting cone penetration tests (CPTs) at the beach. The CPTs penetrated into the unconfined, as well as into the confined aquifer. The CPT measurements provide information about the variation of the lithology and resistivity, which is a proxy for groundwater salinity, at a vertical resolution of 2 cm (Lunne et al., 1997). By analysing the relationship between small-scale heterogeneity and salinity at this scale, it is demonstrated how this technique can be useful in future studies of coastal (beach) hydrology. While the collected data also provide information about the unconfined aquifer, they are not sufficient to unambiguously delineate the saline circulation cell that has been identified in the aforementioned studies of SGD in unconfined aquifers. The analysis presented in this article therefore focuses primarily on the confined aquifer.

2. Material and methods

2.1. Study area

Fig. 1 shows a representative schematic shore normal cross-section of the fresh dune groundwater flow system of the Western Netherlands, where the width of the dune area varies between 1 and 8 km. The climate is of the maritime temperate type according to the Köppen climate classification system. The natural recharge rate in the dune area ranges between 210 and 620 mm yr^{-1} and is strongly related to vegetation type (Stuyfzand, 1993). Groundwater flows towards the North Sea in the west and to the low lying polder area in the east (Stuyfzand, 1993).

The current groundwater salinity distribution below and in the vicinity of the dune area is the result of a sequence of historical processes. Between 3800 BCE and 1000 CE, a system of barrier islands developed along the coast of the Western Netherlands. Below individual small-scale dune systems on these islands (the "Old Dunes"), shallow freshwater lenses developed in the brackish/saline subsurface. From around 1000 CE, marine erosion resulted in an eastward shift of the coastline, and dissected the low-lying Old Dunes landscape. A new generation of dunes (the "Young Dunes") formed from this time onward, and covered most of the Old Dune remnants, leading to a much wider and higher coastal dune belt. As the width of the coastal dune belt expanded, so did the freshwater lens below it.

Between approximately 1000 CE and 1200 CE man started to exploit and drain the wetlands and salt marshes landward of the dune area. Later, from 1550 CE till the end of the 19th century several large lakes inland of the dune belt were reclaimed. These processes led to widespread land subsidence and a concomitant lowering of surface water levels and water tables, which reached several meters in some areas and is ongoing. Consequently, much of the groundwater flow in the freshwater lens below the dunes was deflected eastward, and intrusion of North Sea water was induced via deep flow paths underneath the freshwater lens (Stuyfzand, 2016).

In 1853 surface water and groundwater exploitation began in the dune area. Until the beginning of 20th century, groundwater exploitation took place in the upper, unconfined aquifer. From 1903 onward also the confined aquifer was exploited. The exploitation led to severe saltwater intrusion and a decline of the thickness of the freshwater lens up to several tens of meters locally (Stuyfzand, 1993). From 1955 artificial recharge projects were started in the dunes. First, river water was infiltrated using spreading basins. Since 1990, deep well injection was applied in the confined aquifers. Presently, the artificial recharge has nearly restored the original volume of the freshwater lens.

The focus in the study area is on five shore-normal hydrogeological cross-sections (Fig. 2). The cross-sections are indicated by a number (e.g., '42', the numbers are correspond to marker poles on the beach). They are 4 km wide and extend from inland in the dune area (east) to the beach (west). In Fig. 3, the aquifers and aquitards, topography, and groundwater salinity distribution at each of the five cross-sections are shown. The hydrogeological units in Fig. 3 are adopted from extensive studies by Stuyfzand (1985, 1987a,b, 1993), and Stuyfzand et al. (1993), and were constructed based geophysical data, hydrochemical analysis of the groundwater, and on manual interpolation between boreholes. The deepest part of the freshwater lens varies between −50 m and −110 m NAP among the transects. The upper 150 m of the subsurface below the dunes consists of unconsolidated eolian, fluvial, marine, glacial, and periglacial deposits of Quaternary age. Three sandy aquifers are generally distinguished, which are separated by confining layers composed of peat, clay, loam, or glacial till. The continuity and thickness of these confining units varies, which results in different degrees of connectivity between the aquifers.

The average tidal amplitude is about 0.8 m. During spring and neap tide, the tidal amplitude is about 0.2 m higher and 0.1 m lower, respectively. Storms can elevate the sea level by up to a few meters. The average slope of the intertidal area (i.e., the beach area between the lowest and highest astronomical tide mark) varies between 0.025 and 0.04.