Saline seepage in deltaic areas: how small scale processes dominate salinization

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ABSTRACT

In low-lying coastal areas that lie below mean sea level, saline groundwater may reach the surface by upward groundwater flow leading to the salinization of surface waters, shallow groundwater and soil water in the root zone. This process is referred to as 'saline seepage' and was the main subject of a six-year term PhD-research in the Dutch delta. The most important results will be discussed and it will be demonstrated how small scale local processes dominate salinization of regional water systems.

INTRODUCTION

In many coastal areas, groundwater is brackish to saline which may pose problems for the sustainable exploitation of fresh groundwater. Saline seepage, the upward flow of saline groundwater, leads to the salinization of surface waters, shallow groundwater and soil water in the root zone. Climate change and future rise in sea level are expected to increase saline seepage and reduce the availability of both fresh surface water and groundwater. Predicting effects of future changes, defining effective water management strategies for a climate proof sustainable freshwater supply and successful implementation of any measure are only meaningful when all relevant processes involving saline seepage are fully understood. The main objective of my PhD-research was to address the knowledge gap that exists of the understanding and quantification of the dynamic processes involving saline seepage leading to the salinization of surface water, shallow groundwater and soil moisture.

The research focused on (i) the preferential saline seepage through boils leading to surface water salinization and (ii) the interaction between thin rainwater lenses and saline seepage leading to the salinization of shallow groundwater and the root zone. These two processes were identified as important contributors to the salinization of the Dutch delta which was the study area of the research. The results written in this extended abstract are taken from my PhD-thesis (De Louw, 2013) and five published papers (De Louw et al., 2010, 2011[ab], 2013[ab]) of which the thesis is composed.

METHODS

The spatial variability and temporal dynamics of salinization processes involving saline seepage were analysed and quantified based on field campaigns supported by numerical and analytical methods. The study area was the south-western delta of the Netherlands Dutch delta and two deep polders (reclaimed lakes) in the western part of The Netherlands: the Noordplas Polder and the Haarlemmermeer Polder. The field campaigns involved field techniques applied at scales varying from local point (groundwater sampling, temperature and electrical soil conductivity (TEC)-probe measurements, electrical cone penetration tests (ECPT)) to field scale (continuous vertical electrical soundings (CVES), electromagnetic survey with EM31), and even to regional scale using helicopter-borne electromagnetic measurements (HEM). Time varying field data was collected at agricultural fields and polder catchment outlets to monitor the dynamic salinization processes. For a period of 3 years we collected monthly ground and soil water salinity in combination with hourly observations of water table elevation, drain tile discharge and drain water salinity. Numerical modelling was applied to analyse the dynamic behaviour of the salinization processes.

RESULTS AND DISCUSSION

Preferential saline seepage through boils

Based on field observations and measurements, we distinguished three types of seepage in a deep polder which differ in flux and salt concentration (Figure 1): (i) diffuse, background seepage through the low permeability sediments (clay, peat) of the Holocene confining layer (HCL), (ii) preferential seepage through permeable, sandy paleochannel belts in the HCL, and (iii) intense preferential seepage via boils (De Louw et al., 2010). Boils are small conduits in the upper aquitard (HCL) connecting the aquifer with the surface through which water preferentially discharges at high velocities in the order of 10^2 to 10^4 m d^{-1}. The largest seepage fluxes and highest chloride concentrations are found in boils producing an average chloride concentration of 1100 mg L^{-1} for the Noordplas Polder with a recorded maximum of 2850 mg L^{-1}. Boil water salinity is up to 5 to 30 times more saline than the other two forms of seepage. Based on field measurements and numerical modeling we conclude that saltwater upconing is the key mechanism leading to elevated salinities of boil water (De Louw et al., 2013a). Concentrated forms of seepage at higher rates tend to discharge groundwater from deeper strata with more saline groundwater than diffuse forms of seepage at low rates which discharge only fresh groundwater from the aquifer top (Figure 1).

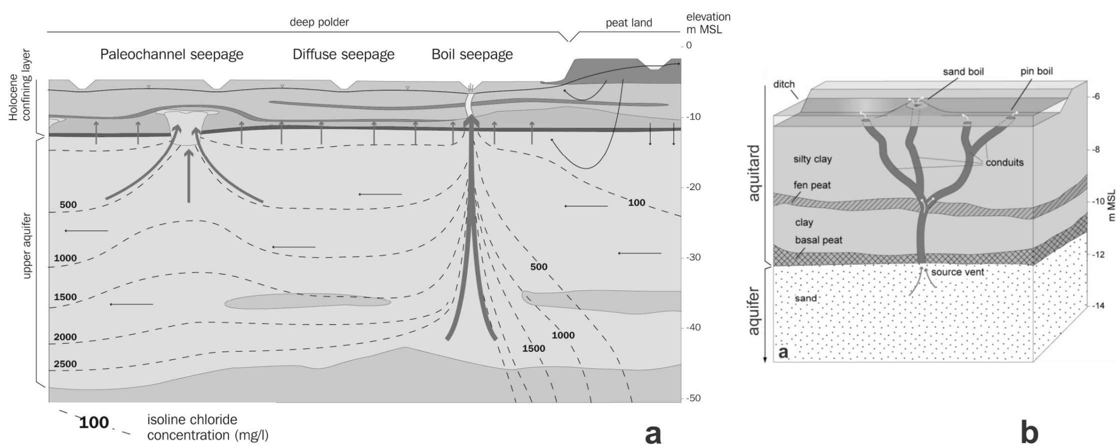

Figure 1. (a) Three seepage types with different fluxes and chloride concentrations: diffuse seepage, paleochannel seepage and boil seepage. (b) Boil with different conduits connecting the aquifer with the surface (adapted from De Louw et al., 2010).

To quantify the water and salt fluxes in a deep polder on a daily time scale, and taking into account the uncertainty of parameters, a probabilistic (GLUE) dynamic water and salt balance model on a daily time scale has been set up and successfully applied to Noordplas Polder (De Louw et al., 2011[a]). The results showed that the far most dominant salinization source in the Noordplas Polder is boil seepage with an average contribution of 66% (± 7.2%) to the total salt loads from only 15% (± 4.7%) of the total water flux. Standard deviations are given between brackets. Regarding the omnipresence of saline boils in Dutch deep polders and the typical salinity distributions found below most deep polders (i.e. fresh above salt groundwater) we presume that boils are the most likely dominant salinization source in most Dutch deep polders.

Thin rainwater lenses in areas with saline seepage

Point measurements (TEC, ECPT) below 30 agricultural fields with saline seepage showed a gradual mixing zone between infiltrated rainwater and upward seeping saline groundwater (De Louw et al., 2011[b]). The centre of this mixing zone (D_{mix}) was found at a median depth of 1.7 m below ground level and almost all mapped lenses lacked truly fresh groundwater. For the purpose of this study the thin rainwater lens in saline seepage areas was defined as the entire groundwater body from the base of the mixing zone (B_{mix}, which is the depth at which the salinity equals the salinity of regional groundwater) to the water table (Figure 2). With this definition, the rainwater lens (further referred to as RW-lens) is not purely a freshwater lens, and salinities within the RW-lens vary both in space and in time. B_{mix} was found at a median depth of 2.8 m and the ECPT measurements showed that below B_{mix} the salinity stayed virtually constant with depth until a depth of at least 25 m below ground level.

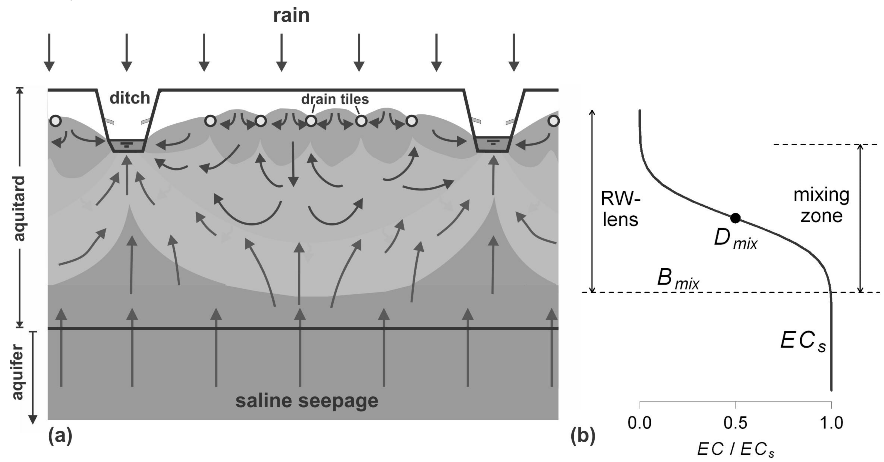

Figure 2. (a) Schematic visualization of a RW-lens in an area with upward seepage of saline groundwater. (b) Vertical profile of the electrical conductivity (EC) of groundwater at an arbitrary point in the RW-lens (adapted from De Louw et al., 2013[b])

The limited size of RW-lenses is primarily caused by the permanent regionally head driven upward groundwater flow from the upper aquifer into the HCL which prevents rainwater from reaching depths below the bottom of the HCL. Unlike RW-lenses in seepage areas, the vertical downward flow of rainwater in the infiltration areas is only limited (in absence of aquitards) by the buoyancy force of the surrounding saline groundwater and its density importantly determines lens thickness according to the Badon Ghyben Herzberg principle. These systems build up much thicker lenses (BGH-lenses), varying from 5-15 m thick lenses in sandy creek ridges to 100 m thick lenses in the dunes. As it was established that lenses in seepage areas are limited to the extent of the upper aquitard (HCL) due to permanent upward seepage, we subsequently examined the mixing mechanisms and flow processes within the aquitard and the factors controlling lens size and mixing zone properties with numerical modeling. We concluded that the transient oscillatory vertical flow regime in the aquitard driven by water table fluctuations is the main mechanism of mixing between infiltrating rainwater and upward saline seepage and determines the position and extent of the mixing zone in the aquitard. Recharge, seepage flux and drainage depth are the controlling factors.

The time varying field data showed that the change of the position of D_{mix} is small (< 0.25 m), and fluctuates at a seasonal time scale (De Louw et al., 2013[b]). The base of the RW-lens (B_{mix}) stayed virtually at the same position. Numerical simulations showed that the small variations in the position of the mixing zone can be explained by the slow transient oscillatory flow regime in the permanent saturated part of the RW-lens, which also controls the mixing between infiltrated rainwater and seepage water. The flow and mixing processes are much faster near the water table, which fluctuates on a daily basis in response to recharge and evapotranspiration, and conditions alternate between saturated to unsaturated. When the water table falls, most of the water with variable dissolved salt concentrations is retained as soil water, which will mix and become diluted with only a small amount of infiltrated rainwater when the soil saturates again. The salinity of the mixture will thus be close to that of the soil water before saturation, which explains the observed absence of very fresh groundwater. Although the mixing processes are fast, the temporary storage of salt in soil water has an important damping effect on groundwater salinity variations when the RW-lens grows due to the recharge by rainwater.

Salt migrates upwards into the root zone by capillary rise of the groundwater at the water table. As the water table falls during the summer, the water rising through the capillaries originates from deeper parts of the RW-lens and is therefore more saline. Salinities of soil water can become significantly higher than in the groundwater due to the unsynchronized effects of capillary rise of saline water during dry periods and the flow of infiltrated rainwater during wet periods being restricted to cracks in the soil. Preferential flow through cracks is thought to play an important role in the rapid response of the drain tile discharge to individual rain events. Groundwater of variable salinity, originating from different parts of the RW-lens, as well as infiltrated rainwater, contributes to the drain tile discharge in proportions that vary on a timescale of hours to days, and this causes the dynamic behaviour of drain water salinity.

CONCLUDING REMARK

The findings of the PhD-research demonstrate that small scale processes dominate salinization of regional water systems. These processes should therefore be taken into account when modelling salinization and predicting effects of climate change, defining effective water management strategies and successful implementation of any measure.

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