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Rainwater lens dynamics and mixing between infiltrating rainwater and upward saline groundwater seepage beneath a tile-drained agricultural field

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SUMMARY

Thin rainwater lenses (RW-lenses) near the land surface are often the only source of freshwater in agricultural areas with regionally-extensive brackish to saline groundwater. The seasonal and inter-annual dynamics of these lenses are poorly known. Here this knowledge gap is addressed by investigating the transient flow and mixing processes in RW-lenses beneath two tile-drained agricultural fields in the Netherlands. Evidence of RW-lens dynamics was systematically collected by monthly ground- and soil water sampling, in combination with daily observations of water table elevation, drain tile discharge and drain water salinity. Based on these data, and numerical modeling of the key lens characteristics, a conceptual model of seasonal lens dynamics is presented. It is found that variations in the position of the mixing zone and mixing zone salinities are small and vary on a seasonal timescale, which is attributed to the slow transient oscillatory flow regime in the deepest part of the lens. The flow and mixing processes are faster near the water table, which responds to recharge and evapotranspiration at a timescale less than a day. Variations of drain tile discharge and drain water salinity are also very dynamic as they respond to individual rain events. Salinities of soil water can become significantly higher than in the groundwater. This is attributed to the combined effect of capillary rise of saline groundwater during dry periods and incomplete flushing by infiltrating freshwater due to preferential flow through cracks in the soil. The results of this study are the key to understanding the potential impact of future climate change and to designing effective mitigating measures such as adapting tile-drainage systems to ensure the future availability of freshwater for agriculture.

1. Introduction

In many coastal areas worldwide, groundwater is brackish to saline because of the combined effects of seawater intrusion and marine transgressions (e.g. Post and Abarca, 2010; Werner et al., 2013). In such areas, freshwater lenses recharged by rainwater are often the only water resource available for agriculture and drinking water. The best-known type of freshwater lens is the Badon Ghijben–Herzberg (BGH) lens (Drabbe and Badon Ghijben, 1889; Herzberg, 1901), which develops in areas with saline groundwater where recharge creates an elevated water table in areas like dune belts along the coast (e.g. Stuyfzand, 1993; Vandenbohede et al., 2008), below islands (e.g. Chidley and Lloyd, 1977; Underwood et al., 1992), and even in inland desert areas (e.g. Kwarteng et al., 2000).

Another type of a rainwater-fed lens forms in areas where saline groundwater migrates to the surface by upward groundwater flow (referred to here as seepage), such as the coastal area of the Netherlands (De Louw et al., 2011; Velstra et al., 2011) and Belgium (Vandenbohede et al., 2010) and the Po-delta, Italy (Antonellini et al., 2008). They differ from BGH-lenses in that the upward moving saline groundwater limits the penetration depth of rainwater, and thus the volume of the freshwater lens (De Louw et al., 2011; Eeman et al., 2011). Field measurements by De Louw et al. (2011) in the south-western delta of the Netherlands showed that the transition zone between infiltrated rainwater and upward seeping saline groundwater occurs within 2 m below ground level (BGL) and that nearly all mapped lenses lacked truly fresh groundwater (chloride concentration <0.3 g L^{-1}). These lenses are the object of the current study, and are referred to as RW-lenses. For the purpose of this study, the vertical extent of the RW-lens is bounded by the water table and the depth below which no rainwater penetrates (B_{mix}, which is the depth at which the salinity equals

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the salinity of regional groundwater, Fig. 1). With this definition, the RW-lens is not purely a freshwater lens, and salinities within the RW-lens vary both in space and in time.

The dynamic behavior of salinities within RW-lenses and the soil moisture in the unsaturated zone above them is of great importance from an agricultural perspective. It is expected that lens thickness and mixing zone properties are not steady state and will respond to temporal recharge variations at intra- and inter-annual timescales, as well as to seepage variations on a longer timescale. Due to their limited size and vicinity to the land surface, RW-lenses are vulnerable to changing precipitation and evapotranspiration (which control recharge) patterns. During dry periods, saline groundwater can reach the root zone via capillary rise, affecting crop growth (Katerji et al., 2003; Rozema and Flowers, 2008). Besides recharge and seepage, another important factor that controls the size of the RW-lens is tile drainage (De Louw et al., 2011; Velstra et al., 2011). Adapting drainage systems has been proposed as an effective water management strategy to mitigate the predicted adverse consequences of increased drought and sea level rise (e.g. Poulter et al., 2008). The latter may enhance upward seepage rates (Maas, 2007; De Louw et al., 2011; Eeman et al., 2011, 2012), thus negatively impacting the freshwater volume stored in RW-lenses.

Successful implementation of any measure to make the RW-lenses more resilient to future climate change requires knowledge of their dynamic behavior. So far, research into lens dynamics has mainly been focused on BGH-freshwater lenses (e.g. Drabbe and Badon Ghijben, 1889; Herzberg, 1901; Meinardi, 1983; Underwood et al., 1992; Collins and Easley, 1999; Bakker, 2000; Stoeckl and Houben, 2012). Stoeckl and Houben (2012) examined the development and flow dynamics of freshwater lenses by physical experiments on laboratory scale. Underwood et al. (1992) examined the dynamic behavior of the mixing zone of a BGH-lens of a generalized atoll groundwater system and found that mixing is controlled by oscillating vertical flow due to tidal fluctuation, while recharge determines lens thickness. On Jeju Island (Korea), measurements showed small tidally-induced variations, but no long-term seasonal variation of the fresh–salt water interface (Kim et al., 2006). In BGH-lenses the response to recharge variations is in the order of decades (e.g. Vaeret et al., 2011; Oude Essink, 1996). Rotzoll et al. (2010) observed thinning rates of 0.5 to 1.0 m y^{-1} in thick freshwater lenses in Hawaii due to long term groundwater withdrawal and reduced recharge.

In the absence of long-term field data for RW-lenses, their response at intra-annual and inter-annual timescales remains poorly characterized and understood. De Louw et al. (2011) reported that, since temporal variations were not measured, they could not conclusively determine if the noted absence of fresh groundwater was a transient or a permanent feature of the RW lens. Velstra et al. (2011) used DC resistivity measurements to delineate RW-lenses in the northern coastal area of the Netherlands and found seasonal variations in lens-thickness. However, the use of geophysics to monitor temporal variations of shallow subsurface resistivities is difficult due to the limited resolution, impact of unsaturated zone conditions and non-unique interpretation of the measurement data (Goes et al., 2009). Recently, Eeman et al. (2012) developed a theoretical relation between lens thickness variations and sinusoidal recharge variations. Their study showed how temporal thickness variations of a RW-lens increased with increasing recharge amplitude and with decreasing recharge frequency including damping and delay in the response of the lens, but the model was not corroborated with measured data. To understand the complex RW-lens field behavior, direct measurements of groundwater and soil water salinities are much needed.

The intent of the present study was to address the knowledge gap that exists on the temporal dynamics of RW-lenses. To this end, a comprehensive set of data was collected at two tile-drained agricultural fields in the Netherlands. The data consisted of groundwater and soil water salinities, groundwater levels, drain tile discharge and drain water salinity, precipitation and evapotranspiration. The main objectives were (i) to obtain direct, field-based evidence of RW-lens dynamics, and (ii) to quantify the temporal variations of the flow and mixing processes within the RW-lens. The main focus was on the control of recharge and tile drainage. A numerical flow and transport model was used to complement the collected field data and to support the development of a conceptual model of RW-lens dynamics.

2. Study area

Two of the 27 agricultural sites examined by De Louw et al. (2011) were selected to monitor the RW-lens dynamics and mixing behavior between March 2009 and January 2011. These sites were referred to as sites 11 and 26 in De Louw et al. (2011) but here as site A and B, respectively. These sites were selected primarily because of their representative hydrogeological conditions and rainwater lens characteristics, which are typical for the saline seepage areas of the south-western part of the Netherlands (De Louw et al., 2011). Practical considerations, such as accessibility of the sites and a nearby electricity supply, also played a role. Monitoring sites

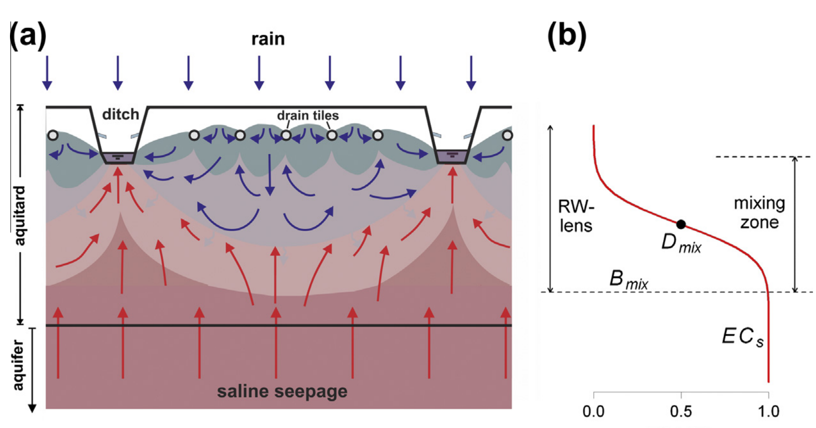

Fig. 1. (a) Schematic cross-section visualizing the conceptual model of a RW-lens in an area with upward seepage of saline groundwater. (b) Vertical profile of the electrical conductivity (EC) of groundwater at an arbitrary point in the RW-lens. The vertical extent of the RW-lens at any point is from the base of mixing zone (B_{mix}) to the water table. The depth of the center of the mixing zone (D_{mix}) is at the point where the EC is 50% of the seepage water salinity (EC_s).