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OBSERVATIONS OF SALINITY PATTERNS IN SHALLOW GROUNDWATER AND DRAINAGE WATER FROM AGRICULTURAL LAND IN THE NORTHERN PART OF THE NETHERLANDS[†]

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ABSTRACT

In studies concerning rainwater lenses on a parcel scale in brackish polder areas it is assumed that infiltrated rainwater flows through the rainwater lens and seeps to the watercourses. This freshwater system is supposed to be superimposed on the brackish diffuse upward seepage system. This study investigates the influence of field drainage on the dynamic behaviour of fresh rainwater lenses and the risk of salinization of the root zone. Observations presented in this paper show that shallow water and salt movements in clayey polders are more complex and more dynamic than previously thought.

On 18 parcels 2D geo-electrical resistivity imaging profiles were measured, which give a good spatial and temporal representation of the salinity distribution of the groundwater. It appears that during wet periods upconing of brackish groundwater appears under pipe drains and ditches, which drain a mixture of fresh meteoric water and deep brackish groundwater. Between drainpipes small rainwater lenses develop. During the dry season, when the groundwater table drops below the drainage level, brackish soil moisture stays behind. Transpiration of the crops rooted in the clayey polder soils result in strong capillary rise of salts, which may even reach the root zone in some places. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: groundwater; salinity; field drainage; polder; rainwater lens; electrical resistivity tomography; time lapse monitoring

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RÉSUMÉ

Dans les études concernant les lentilles d’eau de pluie à l’échelle de la parcelle dans des zones saumâtres de polders, on considère que l’eau de pluie infiltrée s’écoule à travers la lentille d’eau de pluie et percole jusqu’aux cours d’eau. Ce système d’eau douce est censé se superposer au système de remontée diffuse d’eau saumâtre. Cette étude examine l’influence du drainage du terrains sur le comportement dynamique des lentilles d’eau douce issues de la pluie, et le risque de salinisation de la zone racinaire. Les observations présentées dans cette communication montrent que le comportement de l’eau et les mouvements de sels dans des polders argileux sont plus complexes et plus dynamiques que ce que l’on pensait précédemment.

Sur 18 parcelles des profils géoélectriques 2D de résistivité ont été relevés, qui fournissent une bonne représentation spatiale et temporelle de la distribution de la salinité dans la nappe. Il s’avère que durant les périodes humides une remontée d’eau saumâtre apparaît sous les tuyaux de drainages et les fossés, qui drainent un mélange d’eau douce provenant des précipitations et d’eau saumâtre profonde et provenant de la nappe de petites lentilles d’eau de pluie se développer entre les tuyaux de drainage. Pendant la saison sèche, lorsque la nappe phréatique descend sous le niveau de drainage, l’humidité persiste dans les sols saumâtres. L’évapotranspiration dans un sol argileux provoque une forte remontée capillaire des sels, qui peut même atteindre la zone racinaire.

Avec le changement climatique, on s’attend à une augmentation du déficit de précipitations. L’élévation du niveau de la mer et l’affaissement du sol entraîne une augmentation des infiltrations d’eau saumâtre. Il convient de s’y adapter, et d’innover pour cela dans les méthodes de drainage et d’irrigation. Les conclusions de cette étude sont d’une utilité pratique pour permettre aux

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[†] Observations de modèles salinité dans souterraines peu profondes et eaux de drainage de terres agricoles dans la partie Nord du Pays-Bas.

agriculteurs d'anticiper ces changements et constituent une contribution à l'élaboration des politiques de gestion des eaux en lien avec le changement climatique.

MOTS CLÉS: eaux souterraines; salinité; drainage des sols; polders; lentilles d'eau de pluie; tomographie de résistivité électrique; suivi temporel

INTRODUCTION

After the Holocene transgression reached the far north of the Netherlands around 6000 BC, clays and sandy clays were deposited in a shallow tidal flat environment (Roeleveld, 1974; Griede and Roeleveld, 1982). Reclamation and protection of land by dykes started only in early medieval times and led to the typical Dutch polders. In the beginning reclaimed land was drained by permanent open watercourses and more shallow dry ditches. In the nineteenth century subsurface tile drainage systems were introduced for better control of groundwater levels. Most of the agricultural land bordering the northern coastline is now used for growing potatoes, wheat, sugar beet and vegetables (Berendsen, 2005). After reclamation, infiltrating rainwater rapidly flushed salt water from the upper soil and shallow rainwater lenses developed, floating on the brackish and saline groundwater, which is never more than a few metres below the surface. Figure 1 shows a map with the depth of the salt–fresh interface in the northern coastal plain of the Netherlands which still reflects the recent Holocene development. Elevation in the coastal plain ranges between 2 m − MSL (mean sea level) in the peat areas and 2.5 m + MSL at the salt marsh cliffs. In general upward diffuse groundwater seepage from deeper formations prevails with rates of less than 0.5 mm day^{-1}, with some local exceptions exceeding 1 mm day^{-1} (Snepvangers and Berendrecht, 2007). The average rainfall is 750–850 mm yr^{-1} and actual evapotranspiration 540–570 mm yr^{-1}, which results in a precipitation surplus of 200–280 mm yr^{-1}. During the dry season large amounts of water (100–250 Mm^3 yr^{-1}) (million cubic metres) from Lake IJssel are released into the polders to control water levels in the watercourses, which lose water by evaporation, discharge of seepage water and water abstractions for irrigation. Also water is needed to flush the watercourses and to a lesser extent for agriculture (De Heer *et al.*, 1996).

The principle of a freshwater lens, floating on salt water, which was recharged through local rainfall, dates back to the first descriptions of freshwater lenses in island and dune systems (Drabbe and Badon Ghijben, 1889; Herzberg, 1901). Much smaller freshwater or rainwater lenses in wetlands and agricultural fields have been studied by Van Immerzeel, Vegter and Schot (1996), Poot and Schot (2000), Van der Wal (2001) and Schot *et al.* (2004). However, these latter studies concern only theoretical simulations and lack detailed measurements of spatial and temporal salinity patterns. They also did not account for the role of field drainage systems like ditches and subsurface pipe drainage.

During the last century field drainage systems and designs were rationalized on the basis of stationary analytical flow models in combination with field measurements of soil parameters (Hooghoudt, 1940; De Zeeuw and Hellinga, 1958; Kraijenhoff van de Leur, 1958; Ernst, 1978). The main design parameters were primarily groundwater levels and drainage discharge. De Vries (1974, 1995) combined the various analytical drainage equations with those of regional flow and demonstrated that the field drainage systems drive shallow groundwater flow systems, which are superposed on more natural regional flow systems according to the theory of Tóth (1963) and Freeze and Whitherspoon (1967).

With respect to this study, all these above-mentioned concepts have inherent shortcomings and cannot adequately explain the highly dynamic behaviour of shallow freshwater lenses in drained agricultural fields, which are furthermore complicated by salt diffusion and density-driven flow.

In this paper we show some spatial and temporal salinity variations of groundwater and surface water at several parcels and try to explain these according to the concept of

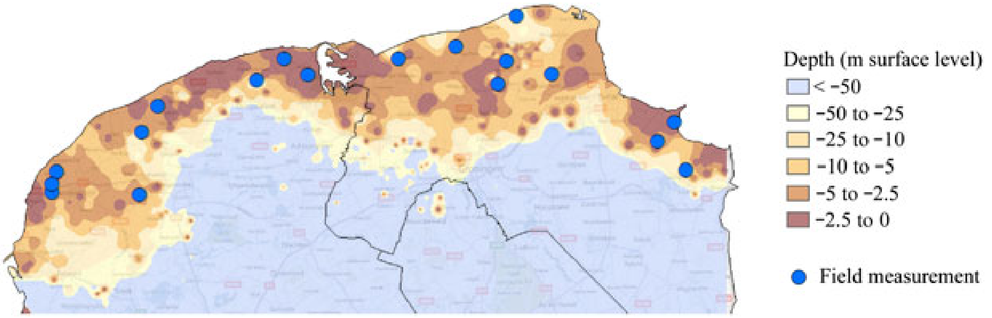

Figure 1. Study area showing depth of freshwater/saltwater interface and locations of field measurements (after van Staveren and Velstra, 2011)

flow systems. For the investigated parcels the following conceptual model is proposed (Figure 2). In the low-lying study area upward seepage of brackish and eutrophic water occurs, which is part of a deep *regional* groundwater system driven by percolation on high-lying areas inland. Near the surface this brackish groundwater mixes with fresh water belonging to superimposed shallow flow systems fed by infiltrating rainwater. Finally all groundwater finds its way to the watercourses and is discharged to the sea. The shallow meteoric flow system again consists of two superimposed systems. Part of the infiltrated rainwater flows directly to the open watercourses bordering the 100–200 m wide parcels. This flow system is designated here as the *parcel* system. The major part of the rainfall, however, discharges first into the densely spaced drains at a depth of about 1 m below the surface, and in the second instance into watercourses. Some parcels are drained only by ditches. The system of drains and ditches is the so-called *drainage* system and is superimposed on the *parcel* system.

This paper presents results of an extensive field investigation to map the distribution of chloride concentrations in groundwater and the spatial and temporal behaviour of the rainwater lens. The field measurements are used to test the concept of flow systems described above. The pipe drainage and ditches play an important role in both the spatial distribution of chloride concentrations in groundwater and may lead to fluctuations over a small timescale of chloride concentrations in surface water. Finally, a qualitative prognosis is made about the expected impact of climate change on saline intrusions in rainwater lenses and the root zone.

METHOD AND DATA ACQUISITION

In the coastal zone 18 parcels were selected representing the various soil types, drainage systems, crops and depth of the freshwater/saltwater interface in this area. The locations are shown in Figure 1. The distance between drains varies from 8 to 12 m. In general the pipe drains have been installed between 100 and 125 cm below the surface, though in the western part (Province of Friesland) they tend to lie at a shallower depth (sometimes < 100 cm), while in the eastern part (Province of Groningen) they are somewhat deeper (in some cases > 125 cm). All parcels contain pipe drainage systems with the exception of the parcel at Anjum that is drained by ditches. The distance of the ditches is 12 m with the bottom level 35 cm below the surface. The soil types vary from sandy clay (8×), silty clay (4×), heavy clay (1×) and sticky clay (5×). Field measurements were carried out from May 2010 to October 2010.

At all locations 2D CVES resistivity profiles (also known as time lapse electrical resistivity tomography or TL-ERT) of the shallow subsurface were measured with the ABEM Lund imaging system and Terrameter SAS 4000 (Dahlin, 1993). A Schlumberger array was used with 64 electrodes with electrode spacing of 0.5 m (inner 2 × 10 m) and 1 m (outer 2 × 10 m) over a length of 40 m. Roll along was applied to obtain profiles with lengths of 50 m. The penetration depth of this layout is about 7 m. RES2DINV software (Loke, 2004) was used to convert the measurements into formation resistivities. For each location a resistivity profile was produced at the end of the rainy season (March/April) and at the end of the dry season (September). In all parcels boreholes were drilled with an Edelman auger to describe the soil profile. A more extensive field monitoring was carried out at two locations, Rottum and Herbaijum. Here five 2D CVES resistivity profiles were measured in the period of March till November of 2010. For verification of the CVES profiles a hand-pushed EC/temperature probe (Van Wirdum, 1991) was used to a maximum depth of 3 m to obtain average soil and water temperatures and electrical formation resistivities at intervals of 10 cm. Several groundwater monitoring pipes were placed in a line perpendicular to the drainpipes. From September till the end of November electrical conductivity of the drain effluent was monitored, using self-recording CTD-divers with sensors for temperature, electrical conductivity and pressure

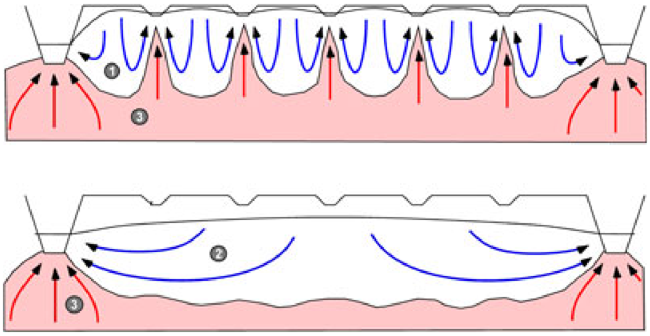

Figure 2. Concept of groundwater flow system in a parcel: (1) drainage system, (2) parcel system and (3) regional system

(Schlumberger, 2010) with 5-min intervals. Precipitation was monitored using a tipping bucket rain gauge with data logger (Eijkelkamp, 2005).

According to the empirical law of Archie, the electrical formation resistivity is proportional to the water resistivity via the formation factor (Archie, 1942). The formation depends on lithology and can be derived from spots where both formation and water resistivity (or electrical conductivity) can be measured. In this case the analyses of the groundwater samples along the CVES profiles have been used. Water resisitivities can be converted to salinities, expressed in mg l^{-1}; of chloride, using the empirical relation by Post *et al*. (2002), based on a large number of water analyses in the Netherlands.

RESULTS AND INTERPRETATION

Given the range of salinities and lithologies, the observed resistivity pattern of the CVES profiles is mainly controlled by the water salinity. The calculated formation factors, based on the analysed water conductivities in the boreholes, range from 2.5 for sandy clay to 5 for sand. With these formation factors and the relation of Post *et al*. (2002), water chlorinity can be calculated from the measured resistivities along the CVES profiles. Because of the statistical nature of the relations these calculated chlorinities have a degree of uncertainty. Therefore we choose to display and discuss the formations resistivities, directly from the CVES profiles. Note that the 7 and 20 Ohmm contours correspond approximately with the 2000 and 500 mg l^{-1}; chlorinity contours. Values lower than 7 Ohmm stand for deep connate brackish groundwater, while values higher than 20 Ohmm relate to meteoric water of the rainwater lenses.

In this paper only those results are presented that best illustrate the processes that are of influence on the form of the rainwater lens and corresponding dynamics of the chloride concentration in the groundwater.

Results from CVES measurements on the parcel at Rottum are given in Figure 3. To a depth of 2 m the soil consists of sandy clay below which the soil develops into fine sand. Drainpipes are located at depths varying

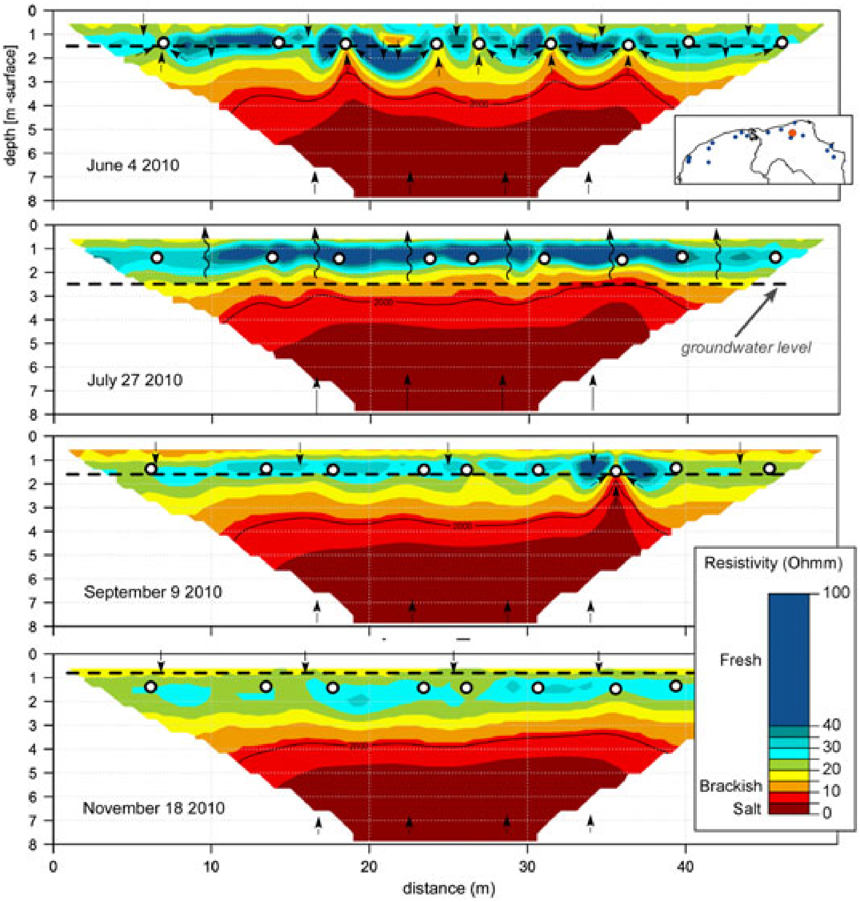

Figure 3. 2-D resistivity CVES profiles at the parcel at Rottum perpendicular to the pipe drains. Arrows indicate direction of flow. A contour line indicates an estimated concentration of 2000 mg Cl l^{-1}. The dashed line indicates the observed groundwater level

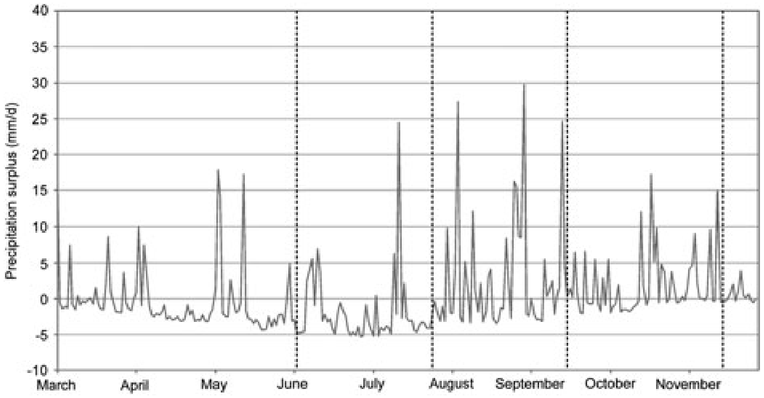

Figure 4. Precipitation surplus in 2010 at the parcel at Rottum. Dashed lines indicate the dates on which CVES measurements were carried out

between 1.4 and 1.6 m below the surface. Drain spacing varies from 3 to 7 m. Upward diffuse seepage flux is less than 0.1 mm day^{-1} according to Snepvangers and Berendrecht (2007). The freshwater lens has a thickness of about 2 m.

A wet period preceded the CVES profile of 4 June. The groundwater table lies above the drainage level and the drainpipes drain water away. The profile clearly shows the influence of the drainpipes. Between drainpipes rainwater lenses develop from which water flows into the drains. At the same time upconing of brackish groundwater takes place from below the drainpipes.

The second profile of 27 July was taken at the end of the dry season when the precipitation deficit reaches values of up to 5 mm day^{-1} (Figure 4), far exceeding diffuse upward seepage flux. As a result the groundwater table dropped to 2.5 m below the surface and the drainpipes are no longer active (Figures 3 and 5). Due to density differences the brackish groundwater cones below the drains have dropped and the salinity distribution becomes horizontal. Noteworthy are the relatively low resistivities in the unsaturated zone above the groundwater table, indicating that brackish soil moisture remained behind, a phenomenon that is observed at other locations as well.

The third profile of 9 September was taken in a period where the precipitation deficit is moving to a precipitation surplus (Figure 4). Figure 5 shows that the groundwater table rises and reaches the lowest of the drainpipes situated 1.60 m below the surface (37 m CVES). This initiates flow towards the drain; a rainwater lens develops as well as upconing of brackish groundwater from below. Later in time the groundwater table also reached the shallower drains. Less clear but already visible is that the same types of flow systems are developing at the shallower drains.

The final profile dates from 18 November and was taken after a prolonged period of precipitation surplus. The groundwater table was situated well above the level of the drains, 0.80 m below the surface level. Because of this rainwater starts dominating the flow system, the rainwater lens becomes thicker and the influence of brackish seepage diminishes.

The drain effluent salinity graph in Figure 6 shows that rainfall events lead to strong fluctuations in salinity and that these fluctuations are superimposed on the seasonal fluctuations. During the dry season with a precipitation deficit the freshwater lens shrinks, groundwater level drops below the drainage level and the drains run dry. During this period diffuse upward groundwater seepage and capillary rise dominate the system. When the rains start again in August and September the groundwater level rises above the level of the drains, which start to produce relatively brackish groundwater. This is because the small freshwater lenses of the preceding wet season have shrunk and brackish groundwater has accumulated near the water table because of the upward rise of deep brackish groundwater. Only by the end of October,

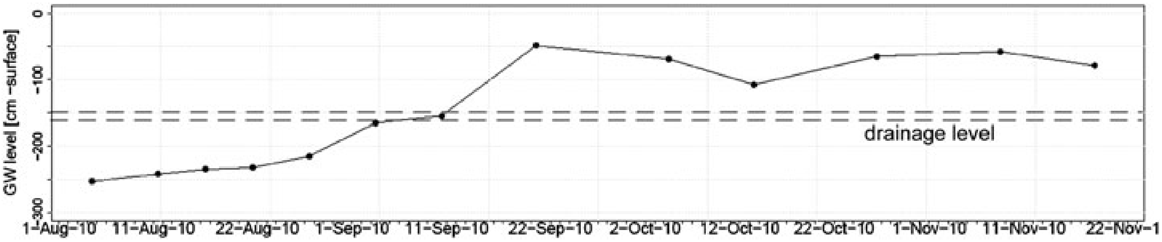

Figure 5. Observed groundwater level at 3 m below surface (at 31 m CVES, Figure 2)

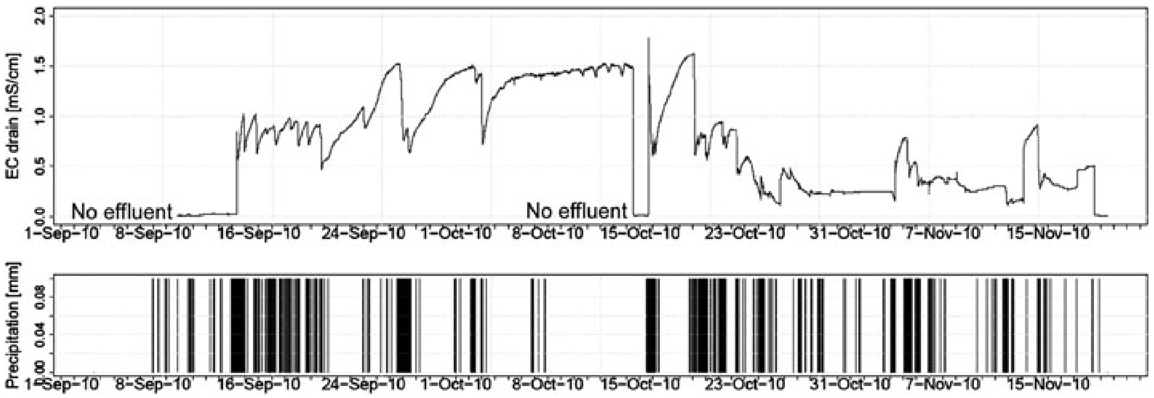

Figure 6. Effluent salinity from a drain (26 m CVES, Figure 2) and observed rainfall

when the rains have built up a new freshwater lens, the salinity of drain water decreases again.

Superimposed on this seasonal pattern are the strong fluctuations caused by individual rainfall events, particularly striking in the period with the brackish base flow in September and October. Each rainfall event causes a sudden decline in effluent salinity, after which it recovers to almost its original values after a few days. Apparently

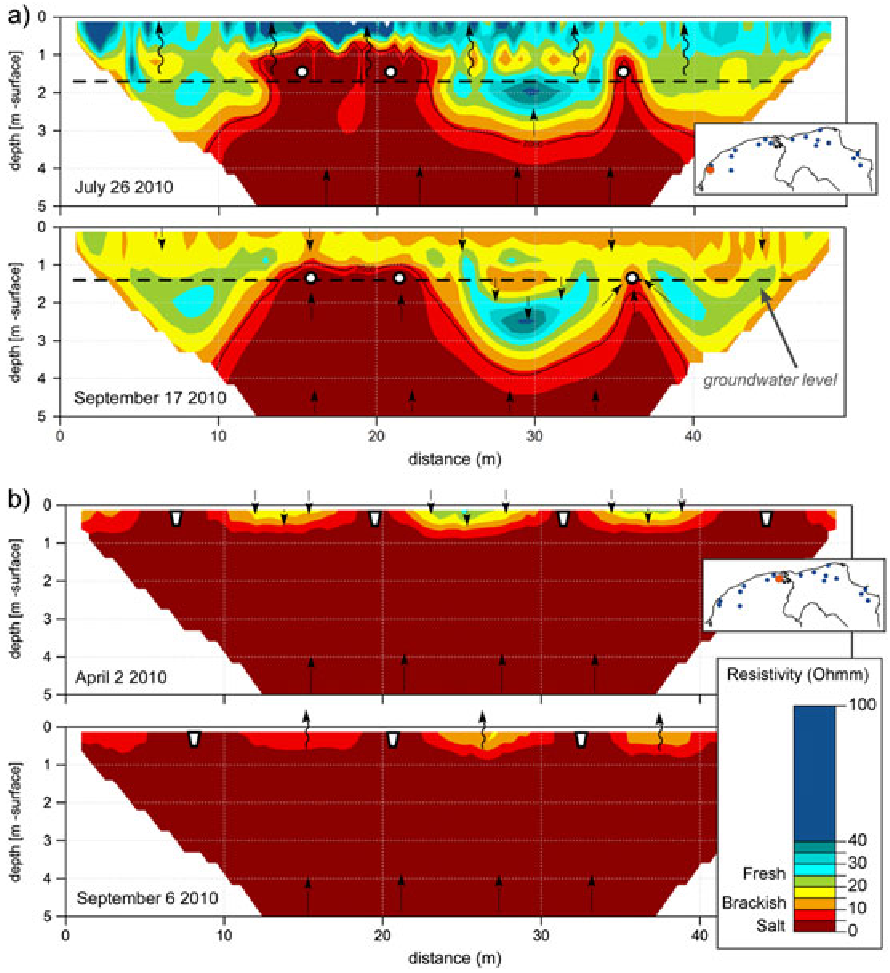

Figure 7. (a) 2-D resistivity CVES profiles at the parcel at Herbaijum perpendicular to the pipe drains. Arrows indicate direction of flow. A contour line indicates an estimated concentration of 2000 mg Cl l^{-1}. The dashed line indicates the observed groundwater level. (b) 2-D resistivity CVES profiles at the parcel at Anjum perpendicular to the ditches. Arrows indicate direction of flow

there exists a very fast-responding flow system superimposed on the systems of the pipe drainage. This may be related to deep cracks in the clayey soils that develop during the dry summer period (Raats, 1984). These cracks act as conduits, which quickly lead excess rainfall to the drains.

Similar results were found in the other parcels. Figure 7 (a) is located at Herbaijum. To a depth of 2 m the soil consists of silty clay below which it develops from fine sand to medium coarse sand. Seepage flux is approximately 0.5 mm day^{-1} (Snepvangers and Berendrecht, 2007). The drain spacing is 12 m. In the profile on the left an old buried watercourse is present in which two drains are located at a distance of 5 m. No differences in the soil profile at the buried watercourse were observed compared to other parts of the parcel. Approximately 12 m to the right another drain is present. Corresponding to the findings so far, a freshwater lens has developed between the drains, which diminishes during the summer. No rainwater lens has developed in the filled-up watercourse. In this parcel the small distance between the drains prevents development of a substantial rainwater lens. Brackish water is flowing upward to the drains. Of interest is the profile of 26 July taken in the summer. It shows the effect of capillary rise and upward movement of saline soil moisture.

The profiles taken at the location at Anjum are shown in Figure 7(b). This parcel is located in a low-lying polder with respect to its surrounding polders. The soil profile consists of sticky clay with some peat to a depth of 4 m, followed by 1 m of peat. Below this the soil consists of medium to coarse sand. Diffuse upward seepage flux is approximately 0.5 mm day^{-1} according to Snepvangers and Berendrecht (2007). However, this parcel is located in a low- lying polder with respect to surrounding polders based on which we expected a somewhat higher diffuse upward seepage flux. The field drainage system consists of shallow ditches with the bottom level 35 cm below the surface. The profile shows shallow developed rainwater lenses between the ditches. The lenses diminish during the summer. Notably these lenses are not connected to the ditches. Apparently each rainwater lens functions as a local flow system. During the rainy season the lens is replenished and due to the effect of evaporation from the soil and plant transpiration in the summer fresh water from the lens is consumed. The ditches only drain away brackish water originating from the groundwater below. It seems that the combination of diffuse upward seepage and the low permeability of the soil prevents the development of a thicker rainwater lens.

DISCUSSION AND CONCLUSIONS

Up till now studies on rainwater lenses (Van Immerzeel *et al*., 1996; Poot and Schot, 2000; Van der Wal, 2001; Schot *et al*., 2004) were mainly theoretical and did not account for the influence of field drainage by pipe drains and ditches on the form and dynamics of a freshwater lens. The results from field measurements at 18 parcels in the northern coastal plain of the Netherlands, however, prove the existence of shallow flow systems of pipe drainage and ditches on top of the parcel-scale systems and regional-scale flow systems of deep brackish groundwater.

The fresh rainwater lenses controlled by the drainpipes and ditches show a seasonal pattern of shrinkage during dry periods and growth during wet ones. It was observed that during wet periods, when the groundwater table is above the base of the field drainage system, upconing of brackish water occurs under drainpipes and ditches.

During the dry season, when the lenses have shrunk and the groundwater table has dropped below the drainage level, it was observed that brackish soil moisture has moved upward more than 10 cm due to capillary rise and can reach the root zone.

Measured time series of rainfall and salinity of the drain effluent show that rainfall events lead to strong fluctuations in chloride concentrations in both groundwater and drain effluent, on the scale of hours to days. These fluctuations are superimposed on seasonal fluctuations of the drainage systems. We suggest that they are related to fast flow through soil cracks (scale of days) and the flushing of brackish soil moisture after the summer period (scale of hours).

The upward movement of salts by capillary rise is well known from irrigation in arid regions (Prathapar *et al*., 1992; Ritzema, 1994; Zhang *et al*., 1999; Kelleners, 2001). It is not known to what extent capillary rise of salts affects growth and rooting depth of crops in the Netherlands. Van Hoorn (1984) believes the effective capillary rise in clayey soils is only a few centimetres, as horizontal cracks formed during the dry season impede the capillary movement.

The shallow water and salt movements in clayey polders are more complex than previously thought. The conceptual models presented here need to be validated further by means of field measurements and mathematical groundwater models, which couple saturated and unsaturated zones and incorporate variable density flow and solute transport.

This is necessary as climate change in the Netherlands will result in larger precipitation deficits during the summer season, while on the other hand, expected sea level rise and land subsidence will cause an increase of diffuse upward seepage fluxes. Based on this field study the authors consequently expect that drainage water and soil moisture, even in the root zone, will increase in salinity in the dry period; or stated differently, periods of salinization may occur more frequently. Obviously this has consequences for crop yields and farming economics and calls for adaptive measures.

One of the measures is to redefine the drainage design criteria, which up till now were solely based on drainage during wet periods. Salinity control and irrigation have to be taken into account as well. This can be realized by applying the new mathematical drainage models mentioned above and already under study by the authors.

CONFLICTS OF INTEREST

None of the authors have any conflicts of interest to declare.

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