Hydrology and Earth System Sciences Discussions

Interactive comment on "Shallow rainwater lenses in deltaic areas with saline seepage" *by* P. G. B. de Louw et al.

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We thank referee #2 for the constructive comments. Below we respond (indicated by R) to each of the comments (indicated by C) raised by the referee.

C: This paper presents novel and valuable data on, and modelling of, a hydrological system that has hardly been investigated to date: rainwater-fed lenses which form on top of saline groundwater in ditch- and pipe-drained areas where overall upward flow of the saline groundwater occurs. These lenses are important to agriculture and natural vegetation. Improving understanding of these lenses through observations and modelling is relevant both from a scientific and practical perspective. The use of different observational methods in this paper to characterize the lenses over a wide range of

horizontal scales and with different resolution is impressive. Methods appear generally sound, but are not always sufficiently detailed. Quality and clarity of presentation (textual) can/should be enhanced significantly. R: We will describe the methods in more detail where appropriate. We will improve the quality and clarity of the text according to the specific comments / suggestions made by the referee (see below).

Specific comments C: This is basically a site-specific investigation. The impact of the work would be higher if the generic implications for other parts of The Netherlands and deltaic areas in general would be clarified more explicitly. R: In the revised version (introduction and conclusions) we will describe in more detail the conditions for the studied system to make the findings more generic and applicable for other deltas.

C: It would be good to elucidate existing concepts/ideas of shallow groundwater flow on agricultural fields a bit more extensively, for instance in section 2. The typical Dutch situation may not clear to all readers. Moreover, results/findings could refer to these ideas. For instance, fields with and without tile drainage are studied. Fig 1 is at odds with the findings that apart from the ditches also the drains attract 'seepage' water. R: In the revised version (section 2) we will give some more details about the typical Dutch polder water system. We agree that the effect of subsurface drains should be incorporated in Fig. 1.

C: Information on when the various measurements were done is lacking. These appear to be momentary observations rather than results of lengthy monitoring. This is important to understand the role of the season in which data were obtained and time separation of different types of data. R: The geophysical measurements are momentary observations whereas the measurements carried out on the agricultural fields site 11 and 26 are the results of hourly to monthly monitoring for a period of 2 years (groundwater sampling and head observations). The data of this 2-year monitoring campaign will be analyzed and described in another paper. According to the suggestion of the referee we will give more details on the frequency and dates of the different measurements in the revised version (section 3 and presentation of the data).

C: The results of HEM measurements suggest very high vertical resolution. It should be explained to what extent this is truly the case. That is, what is the role of calibration/constraining and handling of equivalence. R: The resistivity-depth models consist of 15 model layers. All resistivities and the thickness of the top layer are derived by the inversion procedure; the other thicknesses are fixed but increase slightly with depth. The best degree of smoothing was manually tested for the data of the entire survey area. We searched the lowest value that was able to suppress oscillation in resistivity of the (thin) model layers. Lower smoothing values would lead to oscillating layer resistivities as the data is always biased (due to noise, drift, calibrations errors etc.). These data errors were rather small due to a thorough processing of the data and the use of flights over sea water for checking the calibration of the system. Higher smoothing values would just reduce the increase or decrease of the resistivities from layer to layer. In the revised version we will describe this briefly.

C: Isn't Dmix from HEM sensitive to unsaturated zone thickness and is this sufficiently constrained? R: The HEM models do not resolve a very thin unsaturated zone. We derived Dmix with respect to the strongest resistivity gradient within a resistivity zone being characteristic for the fresh-saltwater transition zone (2-5 âĐẹm); it doesn't matter whether the overburden consists of a fully saturated, an unsaturated zone or a mixture of both.

C: Fresh-water heads are not appropriate to characterize vertical flow components. The authors are aware of this because they do not use fresh-water heads to track FLTP. However, they do use fresh-water heads to interpret field observations. This choice and its implications should be clarified. R: As concluded by the referee, we are aware that analyzing fresh-water heads to characterize vertical flow in variable-density ground water systems is normally not sufficient. To determine vertical flow direction and /or fluxes, the buoyancy term must be added to the head gradient (this is well explained in Post et al., 2007; buoyancy term is defined as '(a- f)/ fÂň' where a is the average density of the ground water between the screens and fÂň is density of

fresh water). As the measured vertical fresh-water head gradients are large, at least larger than the buoyancy term, the measured fresh water head gradients give a right indication for vertical flow direction. This is illustrated in the next example with data from the study area. The measured fresh-water head differences between 4.0 m and 1.5 m depth are in the order of 0.1 m or more (see Fig. 7) which result in fresh-water head gradients of at least 0.04 m. The largest possible density difference for the area (which is seawater versus fresh water) leads to a maximum buoyancy term of 0.025 which is smaller than the head gradient. Adding (in the case of downward flow) or subtracting (in case of upward flow) the buoyancy term to the fresh water head gradient will not have any consequences for vertical flow direction derived from the measured fresh water head gradients. In

Model specifics: R: We realize that the given information about the build-up of the numerical models is concise and sometimes insufficient to fully understand the exact model schematization. In the revised version we will add more details where appropriate, mainly following the raised points by the referee below.

C: - How is the top system, notably ditches represented/treated in the models? R: Fig. 5 clearly shows the top system for the 2D-model with ditches and subsurface drains. Drains and ditches were also applied for the 3D-model in the same way as for the 2D-model. However, as the 3D-model represent a real case, we determined the exact locations of the ditches and drains in the field and implemented in the model.

C: - Side boundary and boundary conditions? R: Side boundary conditions for the 3D-model are fresh water heads taken from the regional Zeeland-model (Van Baaren et al., 2011). The boundaries are taken far enough to have no influence for the area of interest. The 2D-model has no-flow side boundaries at the location of the ditches: we assume that all the incoming fluxes by recharge and seepage between the ditches are discharged by the drains and ditches.

C: - Water table tracking: deactivation of dry cells in both SEAWAT and MOCDENS3D?

R: For tracking the groundwater level, as presented in Fig. 12, we used the calculated head in the first active model layer.

C: - The recharge applied in the 2D models should be shown. At present the reader does not have a clue regarding magnitudes and seasonality for the 'representative' year 2005. R: We will give a brief description of the applied recharge characteristics.

C: The authors elaborate much on the competition between free convection and forced convection ? Why this is relevant? R: We want to explain and emphasize the difference in developing mechanism of rainwater fed lenses in seepage areas and in infiltration areas like dunes and fossil sandy creek ridges. The size of lenses in seepage areas is limited by upward flow from the upper aquifer into the confining layer and the dynamic behavior of the shallow intensively drained top system creating large head gradients within the confining layer whereas the much larger so-called BGH-lenses in the dunes and at fossil creek ridges are mainly controlled by the buoyancy force of the surrounding saline groundwater. It is relevant to understand the mechanism of rainwater-fed lens development in saline groundwater under different conditions in order to define appropriate measures / possibilities to enlarge the lens to increase fresh water availability. In the revised version we describe the relevance in more detail.

C: Conductivities and salinities from analyses are freely compared throughout this article (like in Fig 10). The patterns indeed do correspond, but what about the real values. Why are conductivities not converted to salinities using Archies law mentioned in the introduction? R: The formation factor is always an uncertain parameter, even when the lithology of the subsoil is known in great detail. A small error in the formation factor will lead to large absolute errors in the derived 'real' salinities. Because the salinity contrasts and gradients in the study area are very large (they range from fresh to almost sea water) the soil conductivity patterns and gradients obtained by the electrical and electro-magnetic measurements are mainly determined by groundwater salinity. This is nicely illustrated by the ECPT-results in Fig. 7: the salinity pattern of the mixing zone is clearly visible from the measured soil conductivities, the superposed oscilla-

tions are the result of differences in lithology (formation factor). We therefore chose not to convert soil conductivities or resistivities into 'real' salinities when comparing the results of the geophysical measurements with each other (e.g. Fig. 7, Fig. 11) or with the model results (Fig. 10). Please note that we compared real salinities (from groundwater sampling) with the model results as well (Figure 10c).

C: Further comments regarding presentation

C: The objective of the study: 'aim to gain a thorough understanding of' is not very satisfactory for lack of specificity. R: We will formulate our objective more specifically in the revised version.

C: I find 'seepage' to refer to upward flow at depth confusing. Seepage water would typically be the water exiting from the groundwater system, for instance in ditches or drains. R: In the revised version we will define seepage and infiltration to avoid confusion. We use seepage to refer to upward groundwater flow from the upper aquifer into the confining layer. This seepage water (groundwater coming from the upper aquifer) will eventually exit the groundwater system by either drainage or evapotranspiration. The term groundwater discharge is often used to indicate the process of water (seepage water, rainwater or combination) exiting the groundwater system (by drainage or evapotranspiration). In various studies the term seepage is used to indicate the process of upward groundwater flow from deeper aquifer(s) into the (confining) top layer which will eventually exit the groundwater system. A list of references is given below: *)Van Rees Vellinga, E., Toussaint, C.G., Wit, K.E., 1981. Water Quality and hydrology in a coastal region of The Netherlands. Journal of Hydrology, 50, 105-0127; *)Wesseling, J., 1980. Saline seepage in The Netherlands: occurrence and magnitude. Research on possible changes in the distribution of saline seepage in The Netherlands 26, 17–33. Committee for Hydrological Research (CHO-TNO), Proc. and Informations; *)De Louw, P.G.B., G. H. P. Oude Essink, P. J. Stuyfzand, and Van der Zee, S. E. A. T. M, 2010.: Upward groundwater flow in boils as the dominant mechanism of salinization in deep polders, The Netherlands. Journal of Hydrology, 394, pp. 494–506,. *)Cirkel,

D.G., Witte, J.P.M., Van der Zee, S.E.A.T.M., 2010: Estimating seepage intensities from groundwater level time series by inverse modelling: A sensitivity analysis on wet meadow scenarios. Journal of Hydrology, 385, pp. 132-142. *)Oude Essink, G.H.P., Baaren, E.S., De Louw, P.G.B.,2010: Effects of climate change on coastal groundwater systems: A modeling study in the Netherlands. Water Resources Research, 46, W00F04, 2010.

C: The term 'S-shaped mixing zone' has no meaning without elucidation (abstract). Apparently it refers to the shape of a chloride-depth graph. Moreover, even so, 'S' does not seem very fitting for the actual curve shape. R: We agree and we will look for a better term to characterize the typical and smooth form of the mixing zone. Any suggestions are welcome.

C: It is unclear what is meant by 'a sequence of alternating vertical flow directions'. R: We mean the sequence of changing flow directions for a certain depth. For example, at a depth of 1 m below ground level the vertical flow direction will change over time, i.e. part of the year it is downward and part of the year it is upward, depending on the position of the FLTP. In the revised version we will explain this in more detail.

C: Be consistent in use of elevation/depth units and signs. -2.5 m b.m.s.l. is above mean sea level? R: We will be in the revised version.

C: The word 'manifest' is used improperly in several instances. It seems the authors want to say 'show up' or 'occur'. R: We comply.

C: Refering to Dmix as rainwater lens thickness is a bit awkward as unsaturated zone is included. R: We agree that the unsaturated zone is incorporated when using Dmix to indicate rainwater lens thickness. At first, it is a practical choice because for most of the area (e.g. the HEM-area) the thickness of the unsaturated zone is unknown and it fluctuates throughout the year. Because the unsaturated zone contains rainwater, it can be added to the rainwater fed lens. This is for example also assumed in Eeman et al (2011)

C: p. 7659: C: 'areas at large geohydrological gradients'? What does this mean and what is the relation with saline groundwater reaching the surface? R: We will delete this because it is confusing and needs more explanation. C: focussed _ focused, R: We comply. C: 'We suspect ….. as shown by Maas (2007)? If shown by Maas, why uncertain? R: We will delete 'we suspect'. C:'Unlike rainwater lenses in seepage areas, BGH-lenses . . .' This is nonsense. The feature you study here also develops in response to infiltration of rainwater into a saline groundwater body. R: We agree and will delete this sentence.

C: p. 7661 'Shrinkage of peat and clay . . .' It seems odd that in Roman times large peat cutting and dewatering led to subsidence. This area was hardly inhabited at that time. Peat cutting started much later to supply fuel and salt to the urban centres in the Late Middle ages. Peat cutting is again mentioned for the period after 1000 AD, but the paloegeographic maps at that time hardly show peat deposits (Fig 2). Please check if this is consistent with Vos and Zeiler (2008), which publication is not accessible for English speaking readership. R: Vos and Zeiler write about 'considerable Roman peat mining (and dewatering of the peat) at large scale with catastrophic consequences, enhancing flooding and marine erosion'. The peat was used for industrial purposes, including as fuel to cook seawater to obtain salt (page 89, Vos and Zeiler, 2008). The peat deposits are not on the paloegeographic map of 1000 AD because by that time most of the area was supra-tidal flats and a thin layer of marine clay was deposited on top of the peat. During the Late Middle ages, this peat was cut (by removing the clay first) and used for 'selnering'. Selnering is a Dutch word to indicate the process of gaining salt out the peat (page 91, Vos and Zeiler, 2008).

C: p. 7662: C: 'lithological content is heterogeneous'? R: the lithology is heterogeneous C: is divided from _ is separated from R: We comply. C: 'from field to island scale'? What is field scale here? R: Field scale is an agricultural field of about 0.05 km2

C: p. 7663 "Ex situ" CVES what does this mean ? HEM, CVES and EM31 are all

surface geophysical methods. R: We agree that 'ex situ' and 'in situ' is a confusing term and we will remove this throughout the paper.

C: p. 7664: what is depth of screen when screen has a finite length? I miss a description of the TEC probe and the measurement principle"79 groundwater samples". From this study ? R: We took the bottom of the small screen (0.15 cm long) to indicate the depth of the screen. We will add a description of the TEC-probe and the measurement principles of the 79 groundwater samples which are in fact the results of this study.

C: p. 7665: C: described in Goes et al. _ described by Goes et al. R: We comply. Average apparent resistivity. It is not an average bulk resistivity over 6 m. The upper layers contribute more than the lower ones. R: We agree and will add this information.

C: p. 7666, par 3.1.6. The ECPT's do not provide salinity but electrical conductivity profiles. The TEC probe does not measure the apparent conductivity (as with EM31) but the real resistivity of the layered subsurface. R: We will change this in the revised version.

C: p. 7667: 'reproduce the field measurements' Which field measurements do you mean? 'model fresh-saline processes'? R: We will be more specific about the measurements.

C: p. 7668: 'the head difference was relatively constant throughout the year' Explain what this is based on, since no extensive monitoring seems to have been conducted for this particular project. The phreatic water level fluctuates by about 1 m according to the model (Fig 12). Given the fixed heads in the watercourses, piezometric levels will fluctuate much less. We see in fig 9 a very small difference in water level between piezometric and phreatic heads. So the head difference is likely to vary throughout the year. Would a fixed head boundary in the deep aquifer not be a better boundary condition ? R: We will revise the formulation to be more clear and add information on the monitoring of heads, which has been carried out on an hourly basis for 2 years (see also reply to comment no. 4). We experimented with different boundary conditions at

the lower boundary of the model from which we concluded that a fixed (seepage) flux was the best choice. At first, the head in the upper aquifer fluctuates from day to day and this should be incorporated in the model as well. Applying the head measurements from site 11 and 26 as fixed heads would force us to calibrate the conceptual model for the specific field situation and the corresponding monitoring period. On top of that, the calibrated model would not be useable for the sensitivity analysis, i.e. simulate different cases. Namely, a fixed head as lower boundary condition leads in some (sensitivity) cases to relatively large (unrealistic) head differences which cause unrealistic seepage fluxes (e.g. > 2 to 10 mm/d). A fixed flux as lower boundary conditions is much less rigid. Additionally, we wanted to simulate conceptual cases and to have control about the seepage flux in the different cases.

C: "Very low permeable layer" _ "A layer with a very low permeability" R: We comply.

C: p. 7669: 'representative for annual precipitation surplus'? Is the annual (average) precipitation surplus for 2005 representative/typical? Or is the seasonality typical? R: The annual (average) precipitation surplus is representative. C: The precise form _ The form (precise has no meaning here) a clearly S-shaped mixing zone _ a distinct S-shaped mixing zone. R: We comply.

C: p. 7672: C: salinity profiles (Fig. 8) _ salinity profiles (Fig. 9) R: in the latter case the word 'profiles' should be deleted. C: 'permanently higher'? Probably meaning head is always higher in observations. At left ditch in Fig. 9. head info suggest downward flow. Is legend correct?? R: Legend is NOT correct and we will change this. C: Because we deal with seasonal effects apparently, please indicate the time of measurement of the piezometric heads in fig 9. Do that for all measurements for that matter. R: We will do that in the revised version.

C: p. 7673: 'suitable for testing the numerical concepts and parameters' Which concepts and parameters?? 'of the average, modelled, chloride concentration'. Averaged in what sense? Temporal? Spatial? Explain. R: We will explain this in more detail.

C: p. 7675 Lateral variation in conductivity profile is quite large at site 11. Given the footprint of the HEM of 150 m, the correspondence with point measurments by TEC is remarkable (Fig 7). Explain a bit about this foot print. R: To define the footprint exactly is not easy as it depends on system parameters (frequency, bird altitude) and the conductivity distribution of the subsurface. We suppose that the actual footprint at site 11 is much smaller than 150 m due to the low bird altitude (30m) and the highly conductive subsurface. Please note that the distance between the ECPT and HEM results in Fig. 7 are only about 10m for ECPTs 31, 12, 13, 4 and about 40 m for ECPT 2 and 32.

C: Have the HEM and CVES measurements been inverted automatically or have field data been used for optimization. How was this done. What are the degrees of freedom in inversion. Generally inversions for these kind of geophysical measurements suffer from equivalence. Belongs to Material and methods, I think. R: HEM data were inverted automatically and independently at each site, but the degree of smoothing was controlled by taking into account the ECPTs. The details about the used single-site Marquardt-Levenberg inversion procedure (page 7666, line 12-15) are given by Siemon et al., 2009).

C: p. 7677: 'Thus we have established that the vertical flow direction within the confining layer plays a major role in determining the depth the centre of the mixing zone'. What is meant by THE FLOW DIRECTION here? Fresh water is going down, salt water is going up. It is only shown that there is a strong CORRELATION between Dmix and FLTP. And that is not surprising is it? Dmix is deeper when the fresh water flow extends to greater depth. R: Apparently our formulation has not been clear enough and we will improve this. The essence of our message here should be that both fresh and saline water alternate in flow direction, depending on the (rather variable) FLTP. Please note that the FLTP fluctuates from day to day which cause a water particle to move upward at one moment and downward at another moment regardless its salinity. The dynamics of these changing vertical flow directions are caused by the dynamics

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of the phreatic groundwater level triggered by the daily change of recharge. The yearly average position of the FLTP determines the depth of Dmix, i.e. the deeper the yearly average position of the FLTP (comparing different cases / field situations), the deeper Dmix. The bottom of the mixing zone, Bmix, is determined by the maximum depth of the FLTP which occur during the year. Additionally, we think that our results show that these changing vertical flow directions are the main mechanism of mixing between rainwater and seepage water.

C: 'The calculated average flow velocity of the downward flow component' What is average here? Over a depth range and in time? At one depth and in time? R: The calculated average flow velocity of the downward flow component is the average of all downward flow velocities that occur in the confining layer (0-3m) during a time period of 1 year.

C: p. 7679: C: incoming recharge _ recharge R: We comply. C: A sea level rise would cause an increase of the hydraulic head ... Say that this only applies up to some finite distance from the coast. R: That's correct, we will add it.

C: p. 7680: 'salinity of the upward-seeping groundwater does not have a significant influence on lens characteristics' On what is this conclusion based? And what does significant mean? R: The conclusion is based on the sensitivity analysis where we used 4 different salinities for the seepage water in the range from fresh to seawater. The results show no significant differences in lens characteristics. Significant means a larger change in lens characteristics (Dmix, Bmix, Wmix) than 10 cm compared to the reference case.

C: p. 7681: Conclusions section should be shortened. Present conclusions rather than a summary of the previous and make sure the key findings stand out better. What are the key findings and what is their significance? Distinguish better what is based on observations and what on modelling as well as site-specific versus generic. R: We agree and will shorten the conclusion.

C: p. 7683: C: 'incoming fluxes' _ dominant role of the relative magnitudes of upward saline and downward fresh-water flow R: We comply C: 'very vulnerable' What is very here? R: We will delete very or be more specific. effects agriculture _ affects agriculture R: We comply.

Figures: C: Many of the figures are too small to read properly in print. Pleasant if orientation cross sections Fig. 9 and Fig. 10 c,d,e were similar. Caption Fig. 14: line 9 _ Fig. 9 R: We will enlargen the figures where possible.