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Fast calculation of groundwater exfiltration salinity in a lowland catchment using a lumped celerity/velocity approach

Joost R. Delsman [a, *], Perry G.B. de Louw [a], Willem J. de Lange [a], Gualbert H.P. Oude Essink [a, b]

[a] Deltares, Unit Subsurface and Groundwater Systems, The Netherlands
[b] Utrecht University, Department of Physical Geography, The Netherlands

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ABSTRACT

To support operational water management of freshwater resources in coastal lowlands, a need exists for a rapid, well-identifiable model to simulate salinity dynamics of exfiltrating groundwater. This paper presents the lumped Rapid Saline Groundwater Exfiltration Model (RSGEM). RSGEM simulates groundwater exfiltration salinity dynamics as governed by the interplay between water velocity, gradually adjusting the subsurface salinity distribution, and pressure wave celerity, resulting in a fast flow path response to groundwater level changes. RSGEM was applied to a field site in the coastal region of the Netherlands, parameter estimation and uncertainty analysis were performed using generalized likelihood uncertainty estimation. The model showed good correspondence to measured groundwater levels, exfiltration rates and salinity response. Moreover, RSGEM results were very similar to a detailed, complex groundwater flow and transport model previously applied to this field site.

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Software availability section

Developed software: RSGEM (Rapid Saline Groundwater Exfiltration Model)
Developer: Joost R. Delsman, Unit Subsurface and Groundwater Systems, Deltares, Utrecht, The Netherlands, P.O. Box 85467, 3508 AL, Utrecht, the Netherlands (joost.delsman@deltares.nl)
First year available: 2015, regular Windows pc, requires python 2.7. Software is freeware, and available from the developer. Program (script) size is 10 kB

1. Introduction

In coastal lowlands, shallow groundwater is often saline as a result of sea water intrusion, past marine transgressions, storm surges or tsunamis, or infiltration from estuarine surface water (McLeod et al., 2010; Post et al., 2013; Werner et al., 2013). The exfiltration of shallow saline groundwater to surface water adversely affects surface water quality and threatens the cultivation of freshwater-dependent crops, drinking water production, industrial use and aquatic ecosystems (Jury and Vaux, 2005). Projected global change foresees a larger demand for freshwater, while the availability decreases due to increasing evapotranspiration, decreasing river runoff, and increasing salinization of groundwater reserves (Ferguson and Gleeson, 2012; Forzieri et al., 2014; IPCC, 2013; Oude Essink et al., 2010; Wada et al., 2013). The increased mismatch between freshwater supply and demand calls for new ways to manage freshwater resources in coastal lowland areas. Successful strategic and operational management of freshwater resources in turn requires improved understanding and modeling of the temporal and spatial dynamics of saline groundwater exfiltration causing surface water salinization.

Where shallow saline groundwater flows upwards, driven by a regional hydraulic gradient, thin rainwater-fed freshwater lenses are often present on top of the saline groundwater (Antonellini et al., 2008; De Louw et al., 2013, 2011a; Delsman et al., 2014b; Vandenbohede et al., 2014; Velstra et al., 2011). A predominantly two-dimensional flow field exists between successive tile drains or ditches (De Louw et al., 2013; Eeman et al., 2011; Maas, 2007). Variations in the thickness of freshwater lenses were shown to be only minor, driven by seasonal variations in precipitation and

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* Corresponding author. Unit Subsurface and Groundwater Systems, Deltares, P.O. Box 85467, 3508 AL, Utrecht, The Netherlands.
E-mail address: joost.delsman@deltares.nl (J.R. Delsman).

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evapotranspiration (De Louw et al., 2013; Eeman et al., 2012), whereas the salinity of groundwater exfiltrating to surface water is highly dynamic and varies on the event scale (De Louw et al., 2013; Delsman et al., 2014b; Velstra et al., 2011). Previous work showed these event-scale salinity dynamics to mainly depend on: (1) clear separation between saline groundwater originating from regional groundwater flow and overlying shallow fresh groundwater of meteoric origin, (2) a fast response of vertical groundwater flux distribution to head variations (pressure wave celerity, cf (McDonnell and Beven, 2014).), resulting in changing contributions of groundwater from different depths and of different salinities, (3) a slower response of groundwater salinity distribution, driven by the low velocity of water droplets, and (4) the possibility of infiltration and subsequent exfiltration of surface water (Delsman et al., 2016, 2014b). Note that buoyancy effects, induced by the density difference between fresh and saline groundwater, appeared negligible compared to occurring hydraulic gradients in a comparable densely-drained lowland catchment (De Louw et al., 2013).

While groundwater flow models have tended to become increasingly complex to represent the heterogeneity in hydrological behavior found on different scales and across catchments (Voss, 2011), the limitations of observational data to adequately identify more complicated model structures and parameters have also become increasingly apparent (Beven, 2006; Delsman et al., 2016; Wagener et al., 2001). Modeling approaches should therefore balance the need for process complexity with the level of complexity supported by the available observational data (Haasnoot et al., 2014; van Turnhout et al., 2016; Wagener et al., 2001). Existing models that simulate the salinity of groundwater exfiltration and resulting surface water salinity encompass a wide range of process complexity. Detailed, spatially distributed (unsaturated) groundwater flow and transport models solve the three-dimensional groundwater flow and advection-dispersion equations, and can represent detailed spatial heterogeneity (Costa et al., 2016; Langevin et al., 2008; Quinn et al., 2004; Therrien et al., 2010). Applications of 2D and 3D distributed models to simulate groundwater exfiltration salinity have been described by (Alaghmand et al., 2016; De Louw et al., 2013; Delsman et al., 2016; Devos et al., 2002). However, these models generally require the estimation of more parameters than can be justified from the available observational data, leaving the inverse problem ill-posed. Furthermore, long run times of such models limit thorough evaluation of model uncertainty (Zhou et al., 2014), and preclude application in operational freshwater management. On the other end of the complexity scale, lumped models as the Sobek-RR model (available from: http://www.deltares.nl/nl/software/108282/sobek-suite) have been used to model exfiltration of salts to surface water (Verhoeven et al., 2013), but the employed fully-mixed conceptualization of the subsurface does not match system understanding (De Louw et al., 2013; Delsman et al., 2016) and will lead to overly smoothed exfiltration salinity dynamics. Recent work on understanding and somehow generalizing the exfiltration of different sources of water within a catchment that together drive solute dynamics, has focused on using (dynamic) travel time distributions as a catchment property (Benettin et al., 2013; Botter et al., 2010; Van der Velde et al., 2012, 2010). However, these approaches only consider solute inputs at the ground surface, and solute dynamics are mainly related to varying inputs driven by recharge variations.

A need therefore still exists for a fast and simple, well-identifiable model structure, that adequately accounts for the main processes governing the salinity dynamics of exfiltrating groundwater. This paper presents Rapid Saline Groundwater Exfiltration Model (RSGEM), a lumped water balance model that simulates groundwater exfiltration salinities based on a celerity/velocity approach. The model aims to include the dominant processes underlying the temporal dynamics of groundwater exfiltration salinity in coastal lowlands. We test the model concept on an agricultural field in the coastal region of the Netherlands, a site where both elaborate field measurements and more detailed modeling approaches are available (Delsman et al., 2016, 2014b). We acknowledge equifinality in model results due to uncertainty in model structure, parameters and observational data (Beven, 2006), and apply the generalized likelihood uncertainty estimation (GLUE) methodology (Beven and Binley, 2013, 1992) to condition model parameters and investigate uncertainty in our model results.

2. Study area and previous modeling

We instrumented a 35 m slice of an agricultural field (Schermerpolder, the Netherlands, 52.599° lat, 4.782° lon) to physically separate and measure different flow routes of water and solute fluxes (Fig. 1). A full description of the field site, measurement setup and measurement results has been presented in (Delsman et al., 2014b), we include only a brief summary here. The subsoil of the instrumented field consists of a consistent 0.2–0.4 m thick tillaged clay layer on top of at least 17 m of fairly homogeneous loamy sand. A system of tile drains (every 5 m, 1 m depth) and ditches drain the average annual precipitation surplus of 290 mm, limiting groundwater level variation to within 0.6 and 1.6 m below ground surface (BGS) (Delsman et al., 2014b). The regional groundwater gradient (De Lange et al., 2014) ensures the upward flow and exfiltration of brackish to saline groundwater (around 5 g/l Cl), originating from marine transgressions around 5000 y. BC (Delsman et al., 2014a; Post et al., 2003). A rainwater lens (De Louw et al., 2011a) overlies the upward flowing brackish groundwater, enabling the cultivation of freshwater-dependent crops on the field.

We separately recorded flow rate and electrical conductivity (EC25) of discharge from tile drains and ditch at 15 min intervals. In- and exfiltration to and from the ditch could not be separately measured, but was calculated using a combined water, salinity and heat balance approach (Delsman et al., 2014b). A station at the agricultural field recorded meteorological information. Groundwater level and EC25 were measured in nine dual piezometers (screened at 0.8–1.0 and 1.8–2.0 m BGS) in a transect perpendicular to the ditch, an additional piezometer screened at 2.8–3.0 m depth was placed in the center of the ditch. We installed soil moisture sensors at different depths both at and between tile drains, and eight temperature sensor arrays in transects both perpendicular and parallel to the ditch-field interface. The groundwater salinity distribution was inferred from geophysical surveys (CVES and EM) before and after the measurement period.

Data was collected during two measurement periods (30 May – 1 Dec 2012 and 15 Apr to – 1 Oct 2013), the field was cultivated and the measurement setup partly dismantled in the intermediate period. Potatoes (planted April 21, 2012, harvested August 20, 2012) were grown on the field in the first period of study, lettuce (planted June 1, 2013, harvested August 9, 2013) was grown in the second. Crop growth was monitored by weekly visual inspection. Actual evapotranspiration was calculated using the FAO Penman-Monteith dual crop-coefficient method (Allen et al., 1998), accounting for the different crops grown (crop factors from Allen et al. (1998)), crop development stages and soil moisture conditions (Delsman et al., 2014b).

Delsman et al. (2016) describe a detailed, distributed, variable-density groundwater flow and transport model of the Schermer field site (Fig. 1c). The model applies SEAWAT (Langevin et al., 2008) and MT3D (Zheng and Wang, 1999; Zheng, 2009) to model temperature-corrected electrical conductivity (EC25) and groundwater temperature respectively for a subsection of the field site, extending from a tile drain to the nearest midpoint between two

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