Groundwater Recharge Modeling of the Nete Catchment (Belgium) Using the HYDRUS-1D – MODFLOW Package

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Abstract

The HYDRUS-1D and MODFLOW software packages were coupled to produce a groundwater model of the Nete catchment (northern Belgium) that would improve simulations of near-surface hydrological processes, including temporal and spatial variabilities in groundwater recharge rates. The present paper reports the practical implementation of the HYDRUS package for MODFLOW. Several issues are discussed: the choice and design of MODFLOW zones for coupling to one-dimensional HYDRUS profiles; time discretization of the MODFLOW and HYDRUS components, numerical oscillations and related warm-up periods; and the presence of seepage water in zones of shallow groundwater. In this study we delineated MODFLOW zones on the basis of groundwater depths as obtained with a calibrated steady-state version of the model. Transient simulations are then compared with observed groundwater depths derived from a piezometer network. We summarize a number of priorities and issues that need to be addressed in order to improve the model and achieve sound coupling of the two parts at the catchment scale, while keeping computation times reasonable.

1. Introduction

A groundwater model for the Nete catchment (Belgium) was previously developed assuming constant (in space and time) recharge (Gedeon and Wemaere, 2008). The model was calibrated for steady-state conditions using a uniform groundwater recharge rate of 289 mm y^{-1}. One way to introduce more realism in the spatial and temporal characterization of groundwater recharge is to couple the groundwater model to an unsaturated zone model. A review of surface-subsurface coupling methods and models is provided by Furman (2008). Recent examples using MODFLOW (Harbaugh et al., 2000) as the subsurface component include Xu et al. (2012) and Morway et al. (2013). Seo et al. (2007) developed a module that couples HYDRUS-1D (Šimůnek et al., 2008) to MODFLOW-2000, but until now only applications on synthetic cases have been documented (Twarakavi et al., 2008).

This case study documents the implementation of the HYDRUS-MODFLOW package for the Nete catchment in northern Belgium. The groundwater modeling domain for MODFLOW was discretized into cells of 400×400 m each (9644 active cells in the top layer; see Figure 1). The vertical thickness of active layers in the model varied between 0 and 200 m as some layers were wedged out.

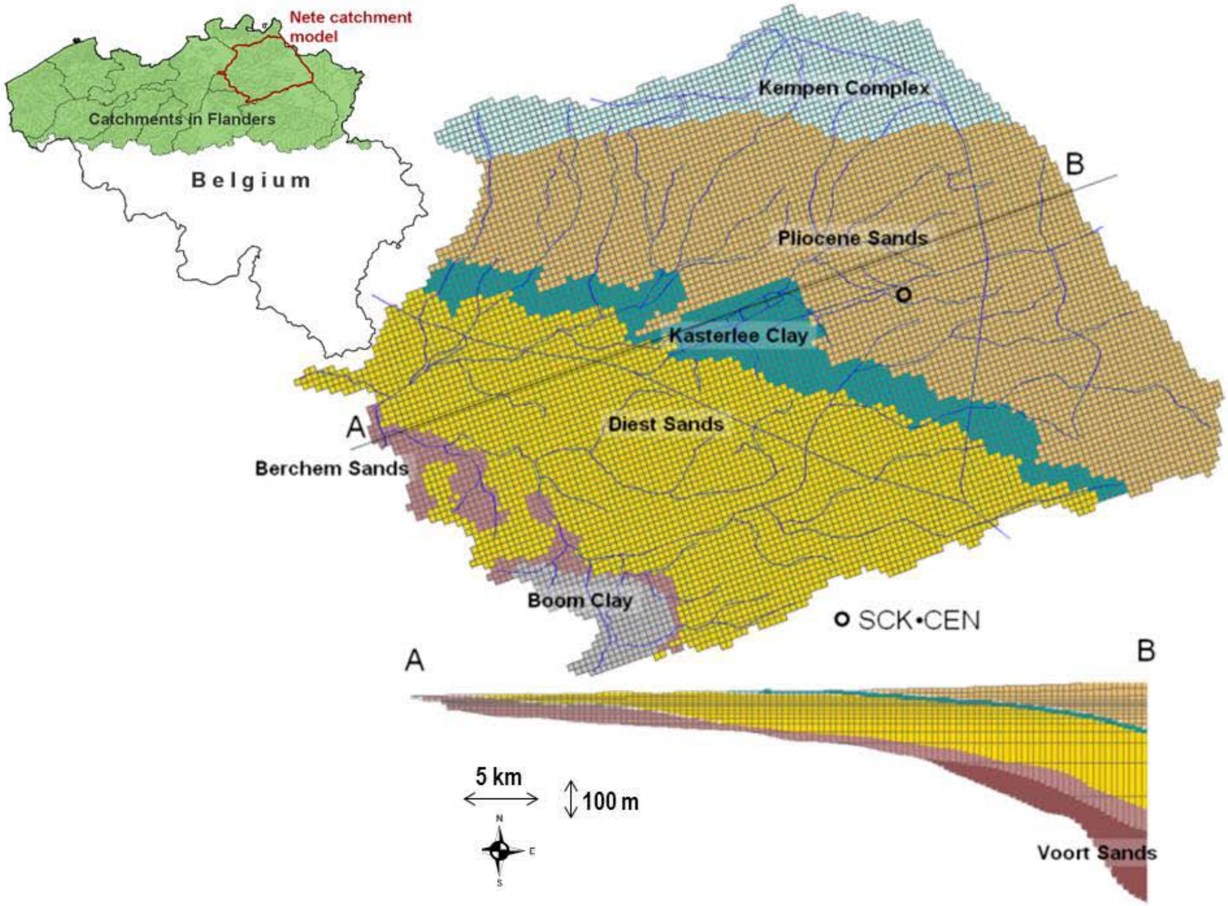

Figure 1. Surface discretization and cross-section of the groundwater model developed using MODFLOW.

2. Implementation of the HYDRUS Package for MODFLOW

2.1. Zone Definition

Zones within the MODFLOW discretization identify cells to which each unsaturated soil profile applies. In theory, the number of zones can vary between 1 and the total number of active cells in the top layer (9644 in the present case). In practice, a compromise is needed between increasing model realism (i.e., including more zones) and keeping reasonable CPU time (i.e., limiting the number of zones). For a given MODFLOW zone, the depth to groundwater in each cell is averaged to determine the hydraulic head at the bottom of the corresponding HYDRUS soil profile (details in Seo et al., 2007). The time-averaged flux at the bottom of the soil profile is applied to each cell in the zone as recharge during the time step. Therefore, the expected depth to groundwater should be taken as the first criterion for defining relatively homogeneous MODFLOW zones, in order to limit precision losses due to averaging between the MODFLOW and HYDRUS models. In our study, the expected groundwater depth was taken from the calibrated steady-state model of Gedeon and Wemaere (2008).

Other logical criteria for defining MODFLOW zones relate to surface processes. For given atmospheric input (i.e., precipitation time series), it is expected that different soil types and vegetation covers will significantly affect the fluxes calculated with HYDRUS, which then are applied to the MODFLOW cells. For this reason we used the soil association map (Maréchal and Tavernier, 1974) as a possible geographical criterion to define MODFLOW zones. Soil hydraulic parameters were taken from the AARDEWERK database (Van Orshoven and Vandenbroucke, 1993). Spatial information of land cover was extracted from a 2001 Landsat image (AGIV, 2011), which we further aggregated to obtain six main classes: surface water (1%), impervious (urban areas; 13%), grass (16%), deciduous trees (7%), coniferous trees (14%), and crop (maize; 49%).

We next developed a pre-processing script in Python that enables one to generate a zone array and HYDRUS soil profiles by specifying criteria of groundwater depth intervals, soil types, and land cover types (vegetation). The resulting number of zones can be easily tuned by changing the selection criteria.

For the work reported here, different simulations were performed using different numbers of zones obtained by changing only the groundwater depth intervals. Soil and land cover types were kept constant, being a typical podzol with a grass cover for the whole study area (except surface waters which were already included in the groundwater model). Despite the reduced complexity, several issues had to be addressed while coupling of the separate HYDRUS and MODFLOW models. These issues are discussed hereafter.

2.2. Seepage Water

A significant part of the study area can be characterized as a relatively shallow aquifer. This is illustrated in Figure 2 where zones 1 and 2 correspond to estimated groundwater depths being less than 2 m (on the basis of the calibrated steady-state model). For zones having shallow groundwater, it became apparent that the average groundwater depth transmitted from MODFLOW to HYDRUS frequently exceeded the soil surface. This may partly be a consequence of the spatial resolution (i.e., averaging of groundwater depths and/or topography), or could reflect a lack of precision of the calibrated groundwater model in certain areas. For example, the calibrated hydraulic conductivity of aquifer layers is closely linked to the imposed steady-state recharge rate.

The HYDRUS package could not properly handle this problem and produced convergence problems. We therefore modified the code to allow the excess water to be removed as seepage from the soil surface. For zones 1 to 3 (which accounted for approximately two thirds of the study area), Figure 3 shows the number of MODFLOW cells in which seepage was simulated during the last time step of the simulation (model with 20 zones). The simulated seepage was found to be very important for zone 1 (shallowest groundwater).

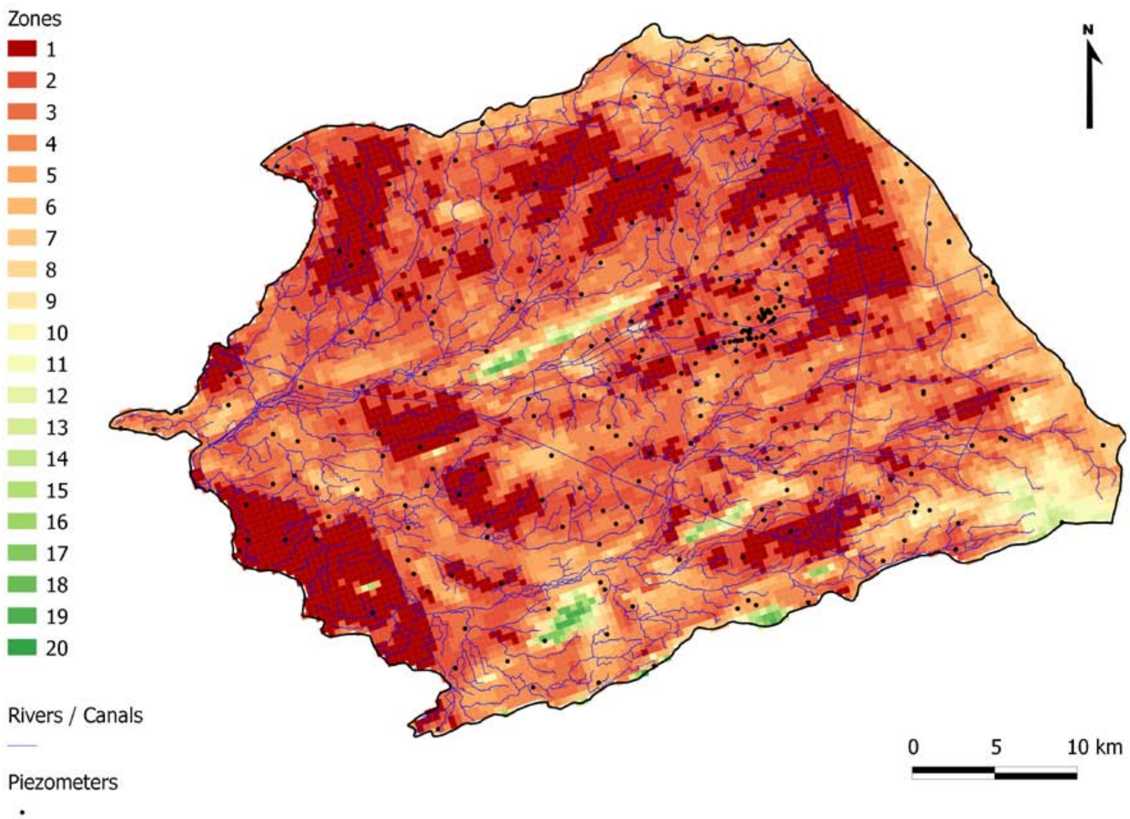

Figure 2. Map of the Nete catchment with 20 MODFLOW zones. Black dots represent locations of the piezometers available for comparison of simulated vs. observed groundwater depth.

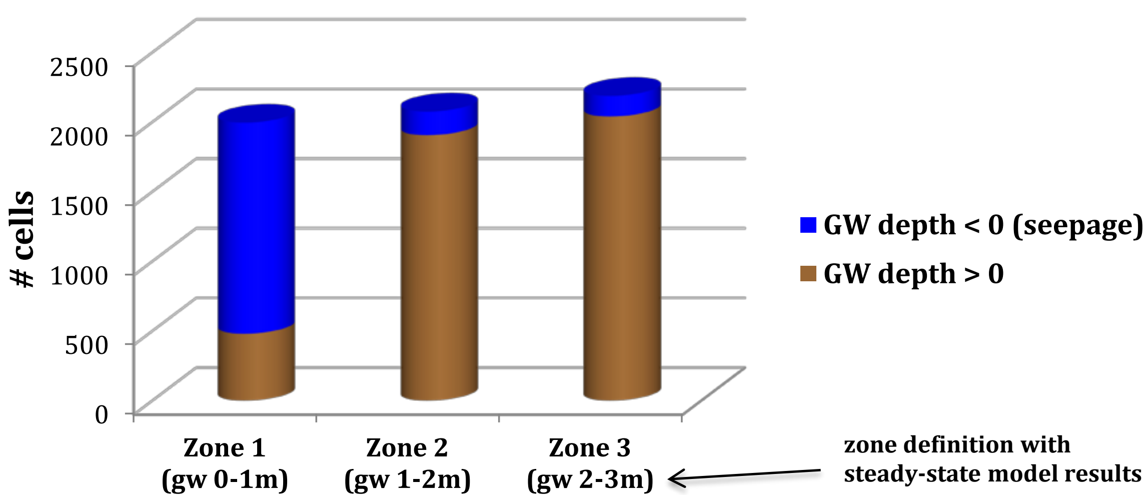

Figure 3. Total number of MODFLOW active cells with or without seepage during the last time step of a 10-year simulation (+10 years warm-up) for the coupled model using 20 zones. Only the first three zones are shown.

2.3. Warm-up Period

For all simulations tested (assuming a different number of zones, and using transient or steady-state atmospheric input), we noted oscillations in the fluxes being exchanged between HYDRUS and MODFLOW during some initial time period of the simulation (Figure 4). While this could be a consequence of the removal of seepage water, the oscillations were not limited to zones having shallow groundwater (e.g., see Figure 4(b)). The oscillations could eventually lead to non-convergence, especially when the number of zones was very low or the number of coupling time steps were insufficient during the early stress periods.

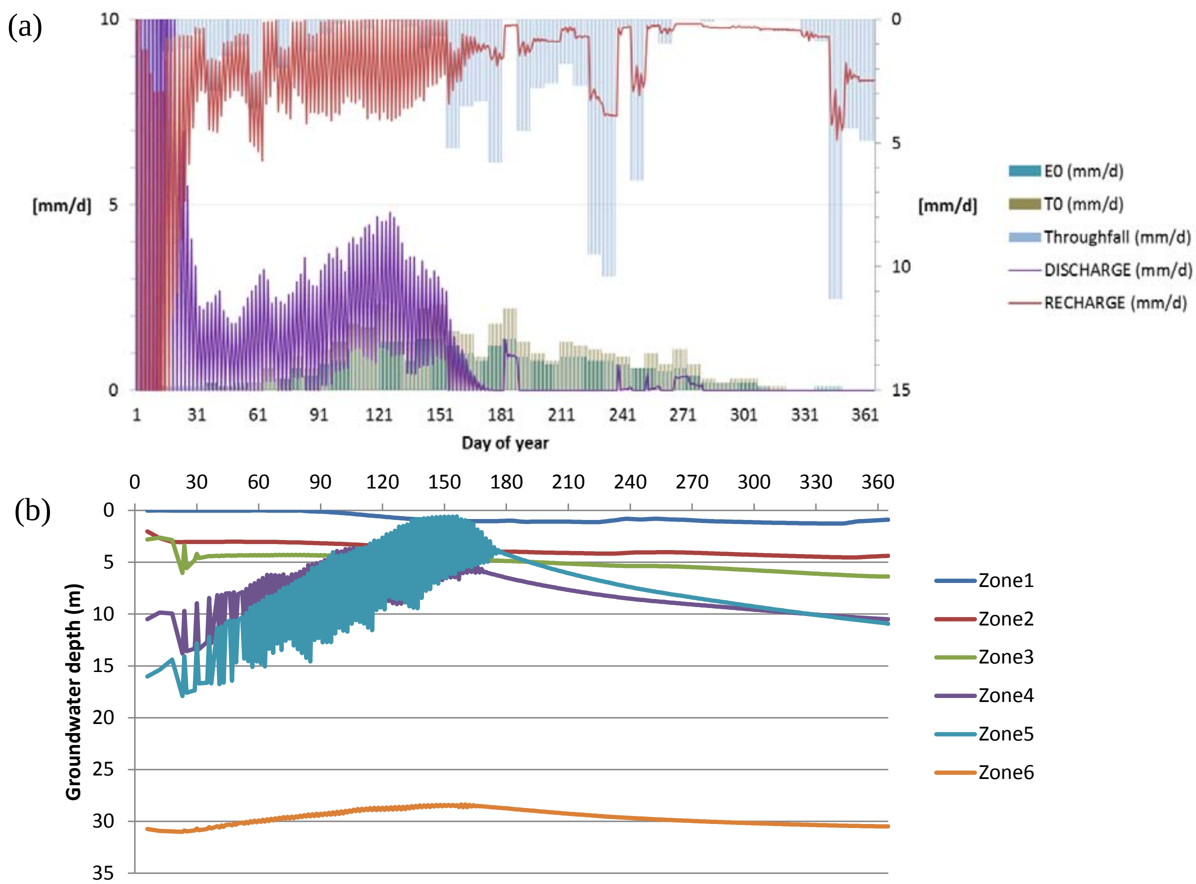

Figure 4. First year of transient simulation with the coupled HYDRUS-MODFLOW package using 6 zones, showing oscillations during approximately the first 180 days in (a) the total discharge rate (left vertical axis) and the potential evaporation (E0), transpiration (T0) and recharge rates (right axis), as well as the exchange flux between the unsaturated and saturated zones (right axis), all in mm d^{-1}, and (b) averaged groundwater depths (m) for each zone.

Even while the numerical solution eventually stabilized, we noted that relatively long warm-up periods were necessary to avoid oscillations (at least several years). This was partly due to the presence of zones with a deep groundwater table, which required several years before atmospheric input migrated through the unsaturated zone. This is illustrated in Figure 5, which compares HYDRUS profile water contents and fluxed at the bottom of the profile for two zones with different groundwater depths. We therefore used a warm-up period of ten years in subsequent simulations (see section 2.4) to ensure results independent of the initial conditions.

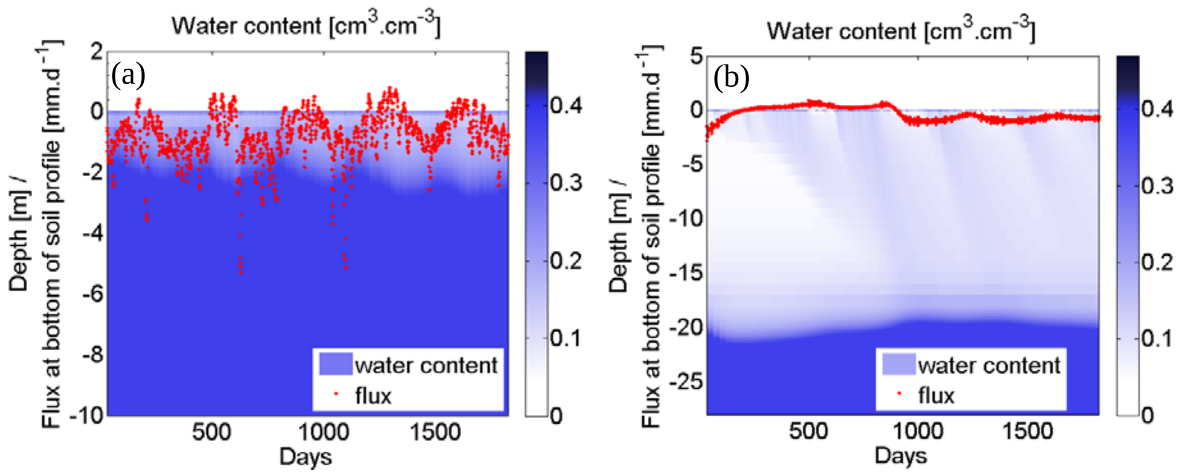

Figure 5. Water contents (blue color scale; $cm^3\ cm^{-3}$) and fluxes (red dots; $mm\ d^{-1}$) at the bottom of the HYDRUS profile during the first 5 years of a simulation with 10 zones. Results are for (a) zone 2 (initial groundwater depth between 2.5 and 5 m) and (b) zone 9 (initial groundwater depth between 20 and 25 m).

2.4. Comparison with Piezometer Data

For a 10-year simulation (plus a 10-year warm-up period) with 20 zones, the recharge rate varied between 226 and 392 mm y^{-1} for the different zones (Figure 6). In the present case, the variability between the zones was due only to variability in the groundwater depth translated to different positions of the bottom boundary condition in the HYDRUS profiles. This because a single combination of soil type, land cover and atmospheric boundary conditions was considered. For the entire Nete catchment, the average simulated recharge rate was 274 mm y^{-1}, and the average seepage rate 32 mm y^{-1} (mainly in zone 1 with initial groundwater table < 1 m). Net simulated recharge was thus 242 mm y^{-1}. Previous estimates of the groundwater recharge rate in the area ranged from 237 to 486 mm y^{-1} (see the review in Hardy et al., 2001).

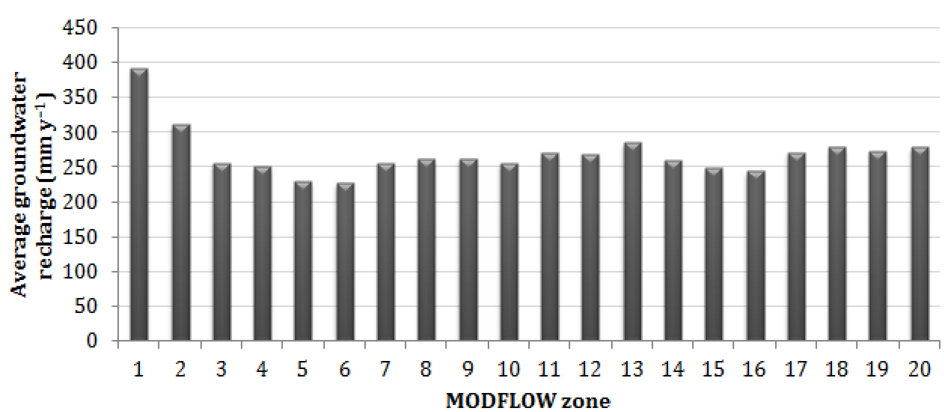

Figure 6. Average annual recharge rate in the period 2000-2009 for the 20 MODFLOW zones.

For each zone, simulated groundwater depths were compared with data available from a network of piezometers in the study area (Figure 2 indicates piezometer locations). This comparison is shown in Figure 7 for zones 1 to 3. Results indicate that the average simulated groundwater depths generally reflect seasonal fluctuations (higher water table at the end of winter). In zone 1, the simulated groundwater depth was close to zero due to seepage in many of the cells (cf. section 2.2), while piezometer data showed groundwater depths in the range 1.5-3.0 m most of the time. In zones 2 and 3, average calculated depths corresponded approximately to the observations.

We emphasize that until now no calibration was attempted with the model (which was previously calibrated for steady-state conditions using a single recharge rate). There are possibilities to improve the simulation by calibrating the number of zones and including more soil types and land covers. Also, the consistency and reliability of the piezometer observations need to be verified since different data sources were combined. Figure 7 shows that piezometric observations do not show an overall increasing groundwater depth from zone 1 to zone 3, contrary to the simulated groundwater depths. This may partly be due to the resolution of the MODFLOW cells and the corresponding DEM (400×400 m), which were too coarse compared to point measurements such as piezometers.

3. Conclusions and Perspectives

This paper presents a case study of coupling surface and subsurface models for the Nete catchment. A few practical issues during implementation of the HYDRUS-MODFLOW package are described. The main issues are related to the use of homogeneous MODFLOW zones (section 2.1), the occurrence of seepage in areas of shallow groundwater (section 2.2), and oscillatory behavior of the model during the initial time steps and the resulting need for a relatively long warm-up period (section 2.3). Results of a simulation with 20 zones were compared to piezometer data (section 2.4).

The main issue to address in the future is probably the treatment of seepage. Currently, this water is not routed to rivers, which makes it impossible to obtain a consistent water balance over the whole catchment. Moreover, currently simulated seepage rates seem too high and do not correspond to rates that have been observed in the catchment. This is probably due to the relatively large area covered by zones 1 and 2, and to assumed hydraulic parameters of the groundwater model. These parameters need to be re-calibrated to allow for more precise recharge drainage rates. The re-calibration will be done using transient groundwater level observations.

In parallel, the sensitivity of the model to the number of zones should be quantified. This would lead to an optimization of the number of zones. Important information for this is the variability in the simulated zone groundwater depth within a zone (cf., red shadowed area in Figure 7). A high standard deviation in a given zone indicates that splitting that zone may improve the results. On the other hand, analysis of HYDRUS sensitivities to groundwater depth prior to coupling could also provide valuable information. For example, having more zones may be beneficial in intervals of groundwater depth where the sensitivity is high (i.e., where actual ET is influenced by groundwater;Maxwell and Kollet, 2008), while having fewer zones may be possible in intervals with deeper groundwater (i.e., where groundwater is disconnected from the surface).

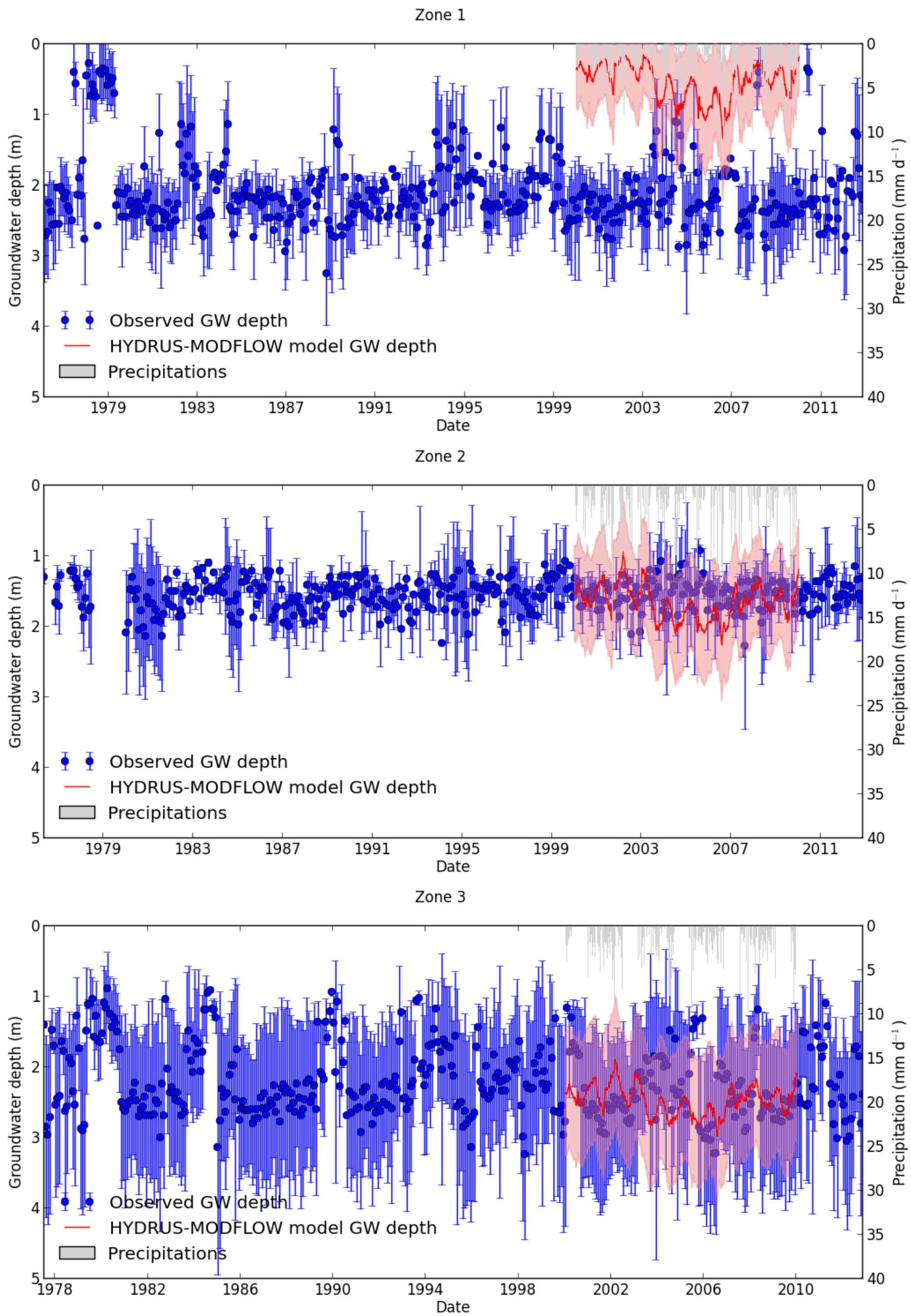

Figure 7. Comparison of observed (blue) and simulated (red) groundwater depths for zones 1 to 3 for a simulation with 20 zones. The shadowed red area is the average calculated depth (± 1 standard deviation) of all cells pertaining to a given zone.

Future simulations are planned, including for more soil types and land cover classes. This should improve model realism (e.g., having very low or no recharge in urbanized areas), but could require a (much) higher number of zones. One major issue here is the relatively long simulation time. The 10-year (plus 10-year warm up) simulation presented here took about 4 h on a standard computer. This is relatively high considering the need of multiple runs for calibration and/or sensitivity analyses. As such, an optimal design of the warm-up period, of MODFLOW stress periods and of the time steps could possibly improve CPU time. We also believe that the model eventually needs to be calibrated against observed piezometer data.

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