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Improved representation of groundwater-dominated catchment using SWAT+gwflow and modifications to the gwflow module

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Abstract.

Recent water availability and scarcity problems have highlighted the importance of surface water-groundwater interactions. Thus, groundwater models such as Modular ground-water Flow (MODFLOW) were coupled to the Soil and Water Assessment Tool (SWAT (+)). However, this solution is complex, needing code modifications, complex coupling, and high computation time. Lately, a new groundwater module (gwflow) was developed directly inside the SWAT+ code to tackle those issues. This research assesses gwflow's capabilities in representing surface – groundwater systems interactions in the Dijle catchment, Belgium. A hydrological model was set up using the standalone SWAT+ and SWAT+gwflow. In addition, the interaction between the soil and the groundwater is not represented in the new module, hence, it was modified to account for such exchanges. Finally, pumping is also included in the module to enable the modeling of transient state conditions. Model comparison is made using Nash-Sutcliffe efficiency (NSE) for the calibration period (1986 to 1996) and two validation periods (1975 to 1983 and 1997 to 2002).

It is found that the SWAT+gwflow model is better representative (NSE of 0.6) than the standalone SWAT+ (NSE of 0.4). This is signified during two validation periods where the standalone scored negative NSE while the new model's NSE was 0.7 and 0.5. This shows that, in a highly groundwater-driven catchment of this type, the simplistic representation of groundwater systems by the standalone SWAT+ model has pitfalls. In addition, the modification we made on the gwflow module has improved the model performance as groundwater-soil interaction is inevitable whenever the water table reaches the soil profile. In conclusion, groundwater-surface water processes need to be appropriately designated in hydrological models; hence, the modification we made to the gwflow module (groundwater–soil interaction) is found to be critical. This novel modification can also have an implication for other distributed hydrological models to consider such exchanges in their modeling scheme. This paves a road towards refining coupled ground-surface water hydrogeological models. Finally, the modified SWAT+gwflow model is more appropriate for assessing the Dijle catchment hydrology than the standalone model.

1 Introduction

SWAT+ is an entirely revised version of the Soil and Water Assessment Tool (Arnold et al. 1998) which has been under continuous development since the early 1990s (Bieger et al. 2017). It is open-source software developed to solve water resources management issues (Arnold et al. 2018). The model is a continuous, semi-distributed, physically-based model that divides the watershed into subbasins which are identified based on a topography map. Each subbasin can be further subdivided into Landscape Units (LSUs) which is one of the principal improvements in the development of SWAT+ from SWAT (Bieger et al. 2019). This option facilitates the inclusion of riparian and flood plain components and improves the runoff-routing capabilities within the landscape. Other adjustments are the flow and pollutant routing throughout the landscape.

These LSUs are further separated into unique combinations of land use, soil, and slope called Hydrologic Response Units (HRUs). At this level, most SWAT+ processes take place (i.e., hydrology, erosion, nutrient cycling, pesticide dynamics, and agricultural management). Flow at the HRU level is summed at the LSU level and then routed to other spatial objects such as an LSU, channel, wetland, pond, reservoir, or aquifer.

As precipitation reaches the soil surface, it may infiltrate and percolate through it while evaporation losses occur simultaneously. Part of the water will percolate into the soil and become recharge for the shallow aquifer, further contributing to streamflow. When the water seeps deeper, it becomes recharge for the deep aquifer and is assumed to contribute to streams outside the watershed. Different methods were implemented in SWAT+ to calculate these fluxes (Neitsch et al. 2011). Flow from the shallow aquifer that ends up in streams is referred to as groundwater flow, baseflow, or return flow.

As described, SWAT+ can account for the groundwater component of the hydrological system within the aquifer module but with important limitations. Like other processes in SWAT+, the groundwater head is calculated at the HRU level, wherefore the water table is not spatially distributed. Hydraulic conductivity and specific yield do not vary spatially as each aquifer system is assumed to be homogenous. Therefore SWAT+ is not suited to simulate spatio-temporal variation of groundwater variables. Another limitation is that the groundwater head only changes with recharge and return flow, whereas many other groundwater flows exist (e.g., groundwater extraction through pumping). In addition, return flow is calculated only for steady-state conditions. This component only occurs when groundwater storage surpasses a certain threshold, while in reality, this is determined by hydraulic gradients. Also, seepage caused by hydraulic gradients is not simulated (Kim et al. 2008; Putthividhya and Laonamsai, 2017; Bailey et al. 2020a). Due to these reasons, there has been utmost effort to replace this simplistic representation of groundwater hydrology in SWAT+.

Moreover, surface water and groundwater bodies have been treated as separate structures in the hydrological system for a long time. As new challenges arise regarding water quantity and quality, together with many other water management practices, a more holistic approach towards hydrological modeling is obliged (Woessner, 2000; Oxtobee and Novakowski, 2002; Kalbus et al. 2006; Chapman et al. 2007; Fleckenstein et al. 2010; Levy and Xu, 2012). For example, to make accurate forecasts

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regarding the effect of drought, water resources should be quantified by holistic models, including both GW and SW processes, instead of modeling them separately (Perkins and Sophocleous, 1999). Therefore, researchers began to investigate relations between both groundwater (GW) and surface water (SW) processes. This resulted in modeling concepts where additional modules were implemented in existing code to include GW-SW exchange processes. The number of models that have both GW and SW modeling schemes increased over the past 20 years. This coupling of surface water and groundwater is often challenging because of the high spatial and temporal variability between the resulting exchange fluxes (Fleckenstein et al. 2010; Bailey et al. 2016a). An example of a coupled GW-SW flow model is the GSFLOW model by Markstrom et al. (2008). This integrated hydrological model links the Precipitation Runoff Modelling System (PRMS), as the surface water model with Modular ground-water Flow (MODFLOW-2005), as a model for the subsurface processes.

Several coupling techniques have been applied to integrate SWAT and MODFLOW (Perkins and Sophocleous, 1999; Sophocleous and Perkins, 2000; Kim et al. 2008; Galbiati et al. 2006; Guzman et al. 2015; Bailey et al. 2016a). The coupled SWAT-MODFLOW framework combines the SWAT software modeling tool with MODFLOW (Harbaugh, 2005), where the latter is embedded as a subroutine, replacing the groundwater module in SWAT. Recently, Bailey et al. (2016a) investigated the coupling of SWAT+ with MODFLOW to model the flow patterns of groundwater discharge to a river system in a semi-arid region by quantifying the interaction between groundwater and surface water for this particular river system through space and time. This model operates by a mutual exchange between SWAT+ and MODFLOW. More specifically, MODFLOW uses recharge and stream stage from SWAT+ as input for the recharge and river packages, respectively. SWAT+ then uses groundwater head, groundwater flow rate, and SW-GW exchange rates from MODFLOW for its stream channels and stream routing.

The main issue with integrating SWAT+ and MODFLOW is the complex model code modification and large computation time requirement. Due to this, Bailey et al. (2020a) recently developed a new physically based groundwater flow module (gwflow) as part of the SWAT+ modeling code. The module is based on the Dupuit-Forchheimer assumption of horizontal flow in unconfined aquifers. Therefore, this module should be used in cases with unconfined aquifers that are hydraulically connected to streams. Hence, this module could replace the current SWAT+ aquifer module for unconfined aquifers and allow for spatially distributed groundwater simulations such as groundwater head (i.e., water table elevation), groundwater storage, groundwater discharge to streams, etc.

However, one critical limitation to the gwflow module is that groundwater-soil interactions are not represented, leading to incorrect water balance at the HRU level. This is vital interaction whenever the water table is higher than the bottom of the soil profile. Hence, in this paper, this limitation/research gap is assessed and modified the gwflow module to account for such exchanges. This is the primary novel side of this research article. Furthermore, since the groundwater component of the standalone SWAT model had already been seen as being limited for applications on groundwater-dominated catchments (Peterson and Hamlett, 1998; Spruill et al. 2000; Srivastava et al., 2006; Gassman et al. 2007; Deb et al. 2019), we aim to apply the coupled model (SWAT+gwflow) to a groundwater-influenced catchment located in a temperate climate. Subsequently, a model output comparison will be made between the standalone SWAT+ and the one modified with the gwflow module. Finally, we included pumping to account for transient state modeling in the module.

2 Study area and data

Located in the center of Belgium, the Dijle catchment (Figure 1) has a length of 86 km on average. It is a part of the larger Scheldt basin (21,863 km^2) situated in Belgium, France, and the Netherlands. The Dijle River springs near Houtain-Le-Val in Wallonia and flows towards the North-East. In Court-Saint-Etienne, Thyle and Orne's rivers are added to its river flow. In addition, the Train river originating from Wallonia ends up in the Dijle. At the border between Flanders and Wallonia, the Dijle has an average flow rate of 4.5 m^3/s.

The most important tributaries of the Dijle river are the Laan, the Ijse and the Voer joining the Dijle in Sint-Agatha-Rode, Neerijse and Leuven respectively. Situated in Rotselaar, the Demer river merges into the Dijle and is categorized as navigable from this point onwards. Upstream from Mechelen, a weir is used to attenuate the flow rate of the Upper Dijle while feeding the inner Dijle in Mechelen to preserve its navigability. Further downstream, several streams are debouching into the Dijle including, the Weesbeek, Barebeek, Vrouwvliet and the Zenne. The Dijle River meets the Nete and becomes the Rupel near Rumst, Belgium.

In general, the catchment is homogeneous regarding soil type, whereas more than 90% is covered by silt-textured luvisols (Van Oost et al. 2012). Substantial soil textures that can be found in the Dijle catchment are silt, sandy loam and loamy sand. The area is known to have a spatial transition in texture from North-West to South-East, giving a pattern of sand and sandy loam in the Northern part and silt regions in the southwestern part. The sandy aquifer (traditionally known as "Brussels sand") is dominant with lower impermeable layer called Kortrijk (Figure 2). The Dijle catchment has a mean elevation of 40 meters and an average slope of 2% (Batelaan and De Smedt, 2007). Sectors extracting water from the Dijle catchment are households, industry, agriculture, etc. In addition, the provision of water and drinking water is managed by five different drinking water companies and is entirely derived from groundwater extractions. Already in Leuven, an amount of 10^3 million m^3 of phreatic groundwater is exploited annually (Sumaqua, 2020).

The weather data is obtained from Royal Meteorological Institute of Belgium (RMI) for variables such as precipitation (mm), relative humidity (decimal fraction), solar radiation (MJ/m^2), temperature (°C), and wind speed (m/s) from 1970 until 2011 at the Uccle gauging station. Although this weather station is not situated inside the catchment area, the weather data can be used in Belgium, especially Flanders, with small elevation variations. Hence, the weather variation is not considerable. The other inputs for developing the SWAT+ model are soil and land use maps obtained from the Food and Agriculture Organization (FAO) and the European Space Agency (ESA), respectively. Finally, the Digital Elevation Model (DEM) of 50m by 50m was

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reassembled from 90m by 90m DEM acquired from USGS (https://earthexplorer.usgs.gov/) and is used to delineate the catchment.

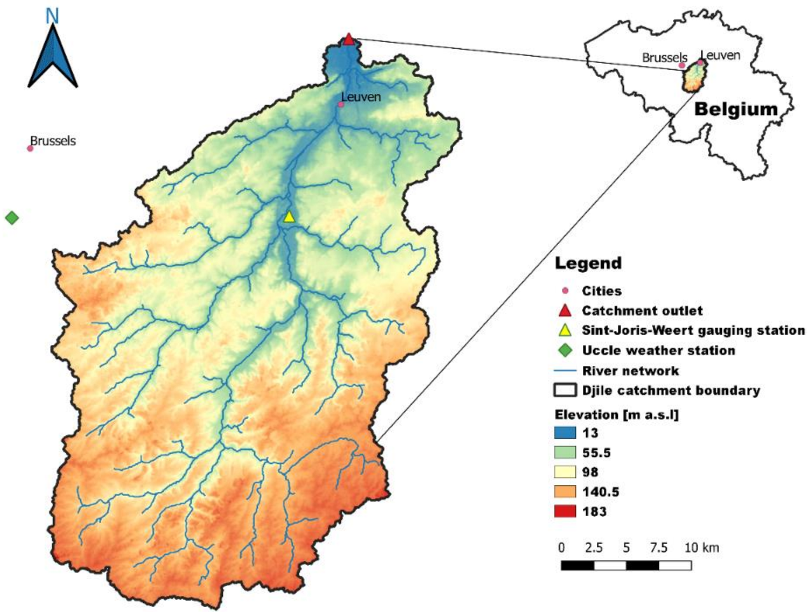

Figure 1: Study area map where the catchment outlet is located at Wielsele. The catchment is low land in the northern part and higher in the southern region.

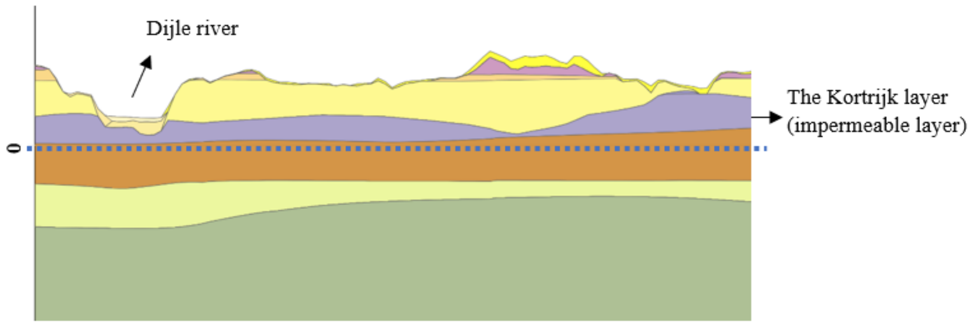

Figure 2: The elevation of the impermeable layer base, which is taken as a reference for the unconfined aquifer. It was accessed on September 30th, 2021, from https://www.dov.vlaanderen.be/portaal/. The plot is not into scales.

3 Methodology

The methodology comprises two main parts: the first is modeling the catchment with the standard SWAT+ model, and the second is to use the new "gwflow" module as a replacement for the simplistic representation of the groundwater module in the

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SWAT+ model. This will enable us to assess the potential of the new module (gwflow) to simulate the groundwater hydrology of the Dijle catchment better than the standalone model.

3.1 SWAT+ model setup

As aforementioned, the groundwater system in SWAT+ can be divided into shallow and deep aquifers. Recharge results from percolation moving through the vadose zone towards the shallow and/or deep aquifer. An exponential decay weighting function accounts for the time delay caused by the time needed for the water to leave the soil profile and penetrate the shallow or deep aquifer. The recharge on a specific day can be estimated with:

$$w_{rchrg,i} = \left[1 - exp\left(\frac{-1}{\delta_{gw}}\right)\right] * w_{seep} + exp\left(\frac{-1}{\delta_{gw}}\right) * w_{rchrg,i-1} \tag{1}$$

where $w_{rchrg,i}$ is the recharge volume moving into the aquifer on day i, δ_{gw} is the delay time (days), w_{seep} is the total volume of water leaving the soil profile on day i, and $w_{rchrg,i-1}$ is the recharge volume entering the aquifer on day $i-1$. It's not possible to directly measure δ_{gw} and therefore should be calibrated. The fraction of water recharging the deep aquifer on a specific day is calculated by:

$$w_{deep,i} = \beta_{deep} * w_{rchrg,i} \tag{2}$$

where w_{deep} is the volume of water flowing to the deep aquifer on day i, β_{deep} is the aquifer percolation coefficient, and w_{rchrg} is the recharge volume entering the shallow and deep aquifer on day i.

The relation used to estimate the baseflow is a function of recharge and the baseflow recession constant α_{gw} which is a direct index of groundwater flow response to changes in recharge. Values between 0.1-0.3 indicate a slow response, while 0.9-1.0 characterize a fast response. Baseflow can only enter the stream if a threshold of water present in the shallow aquifer is exceeded, and this threshold is user-defined (Neitsch et al. 2011). Another flow, R_{evap}, moves from the shallow aquifer towards the covering unsaturated layer in dry periods. In such periods, water from the capillary fringe will evaporate and be replaced by the water from the underlying aquifer. R_{evap} can only occur at baseflow when the water present in the shallow aquifer exceeds a user-defined threshold (Neitsch et al. 2011).

The SWAT+ model setup starts by delineating the catchment where the Wilsele gauging station is taken as the catchment outlet, and this resulted in a total catchment area of 892.54 km² with 1496 HRUs, 21 subbasins, and 162 channels. The streamflow data at Wilsele is downloaded from Waterinfo (https://www.waterinfo.be/) for the same time window as the other weather inputs. The Penman-Monteith was chosen as the potential evapotranspiration (PET) calculation method, whereas the Muskingum method was selected for flow routing. We used SWAT+ version 60.5.2 for modeling work using the model setup.

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3.2 SWAT+ model with the gwflow module setup

The gwflow module simulates groundwater fluxes, including lateral flow within the aquifer, recharge for HRUs, evapotranspiration (ET) from shallow groundwater, pumping, interactions between groundwater and surface water through the streambed (i.e., groundwater discharge to streams and seepage to the aquifer), and excess saturation flow. To use this gwflow module, the model domain is discretized horizontally in square grid cells (for this research we used 200m by 200m). The module calculates a water balance equation for each grid cell through a control volume method based on mass conservation. For each simulation time step, the equation is solved for groundwater volume and correlated groundwater head. These values are calculated explicitly, based on head values of neighboring grid cells and flows from sources and sinks at the preceding time step only.

The inputs for the standalone SWAT+ model are also inputs for the gwflow model setup. For the SWAT+gwflow module, the SWAT+ version 60.5.2 is coupled with the gwflow module. In addition, an aquifer thickness raster (vertical distance from ground surface to bedrock, i.e., the thickness of unconsolidated sediments) was downloaded from https://data.isric.org/ (Shangguan et al. 2017). To check the validity of the global dataset, the depth to the impermeable layer, called the Kortrijk layer (Figure 2), was also taken from a previous study made by Wossenyeleh, (2021). Permeability of the aquifer material was obtained from https://dataverse.scholarsportal.info/ (Huscroft et al. 2018). This will help classify the aquifer into distinct zones where each zone will have corresponding hydraulic conductivity (K_{aqu}) and specific yield (S_y) values.

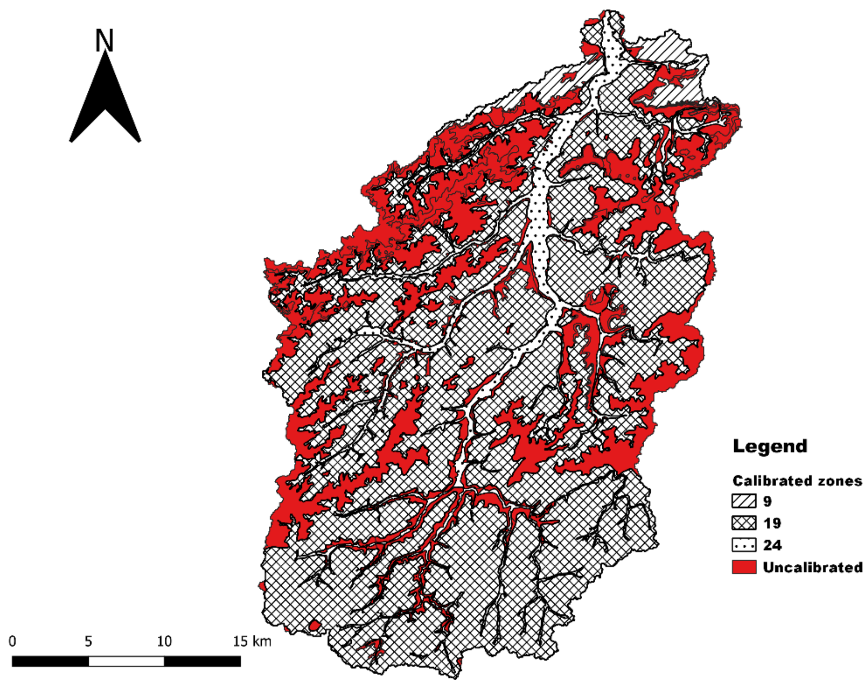

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Figure 3: The different hydraulic conductivity zones according to the GLHYMS dataset. Originally there were 24 zones which has 3 dominant zones.

It is worth noting that the global datasets that we used to prepare the gwflow inputs have a mismatch with the locally available data. Hence, we have made simplifications that ease the sensitivity and calibration process. For instance, the number of different hydraulic conductivity zones according to the global dataset is 24; however, previous studies on this catchment (Wossenyeleh, 2021) have shown the dominance of one zone (called "Brussels sand"), and we also have noticed from the global dataset that the hydraulic conductivity values for most zones were similar. Hence, accordingly, we calibrated only the dominant zones (Figure 3). If we take the 24 zones as independent zones, we will need to perform sensitivity analysis for 24 zones (a total of 48 parameters which is 24 for hydraulic conductivity and 24 for specific yield). Note that this number does not account for the other model parameters. This will increase computation time, create difficulty while calibrating the model at the latter stages, and may lead to overfitting. This simplification, however, will not reduce model performance, and this is checked at later stages in the result section. This type of simplification are well known in hydrological modeling as parsimonious representation.

3.2.1 Modifications to the gwflow module

In the water balance equation of the gwflow module, interaction between groundwater and soil profile is not considered. Specifically, in Bailey et al. (2020a), the water table does not interact with the soil profile. In our study, the GWFLOW module is modified to transfer groundwater to the soil profile for grid cells where the water table rises into the soil profile. This is evident for groundwater-dominated catchments where the water table is shallow.

In addition, we have also modified the module to include municipal pumping, which is added as another sink term in the water balance equation. The starting and ending date of pumping and the daily pumping rate are inputs for wells located inside any case study area. The water balance is solved for each grid cell using an explicit scheme for each time step of the simulation.

$$\frac{\Delta V}{\Delta t} = \left(Q_{rech} + Q_{sw \rightarrow gw}\right) - \left(Q_{gwet} + Q_{gw \rightarrow sw} + Q_{gw \rightarrow soil} + Q_{satex} + Q_{pump}\right) \pm Q_{north} \pm Q_{south} \pm Q_{west} \pm Q_{east} \quad (3)$$

Where Q_{rech} (1) is recharge, $Q_{sw \rightarrow gw}$ (2) is flow from surface water to groundwater, Q_{gwet} (3) is evapotranspiration from the shallow groundwater, $Q_{gw \rightarrow sw}$ (4) is flow from the groundwater to the surface water, $Q_{gw \rightarrow soil}$ (5) is water reaching from the groundwater to the soil profile, Q_{satex} (6) saturated excess flow, Q_{pump} is pumping (7) and Q_{north},Q_{south},Q_{east} and Q_{west} are incoming or outgoing flow from the boundary cells (Figure 4).

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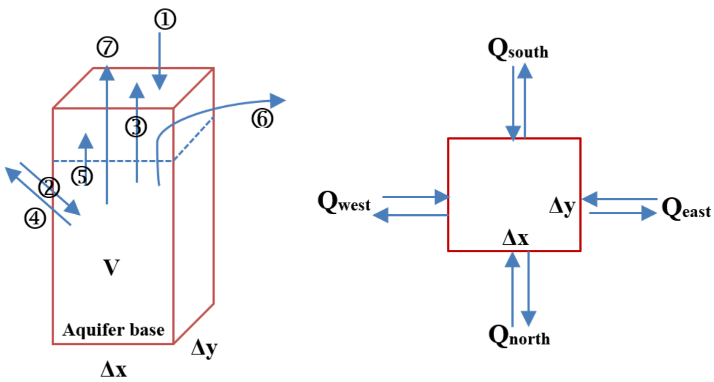

Figure 4: The schematic representation of the hydrologic fluxes entering and leaving a cell in the gwflow module. Fluxes labeled 5 and 7 are the main modifications we have made to the module.

3.3 Sensitivity, calibration, and water balance analysis

The sensitivity and calibration analysis for the SWAT+gwflow model setup is made using the Parameter Estimation Tool, PEST (Doherty, 2010). For the standalone SWAT+ modeling work, sensitivity and calibration analysis were done based on two approaches. One uses the SWAT+ toolbox developed by Celray James Chawanda (https://swat.tamu.edu/software/plus/). This tool uses the variance-based Sobol method with an estimator described by Saltelli and Annoni, (2010). Two, the standalone SWAT+ model was also calibrated with the PEST tool to compare the two model setups based on a similar calibration methodology. The time window from 1983 till 1996 is taken as a calibration period, where the first three years are taken as warming up period. The rest of the data is divided into two validation periods where from this point onwards, 1975 to 1982 is called "validation 1" and 1997 to 2002 as "validation 2". Sensitivity and calibration are done using monthly streamflow data at the outlet of the catchment.

Comparison is made between the daily and monthly simulated and measured streamflow data at the catchment outlet. In addition, the calibrated model is tested using another gauging station streamflow data at the Sint-Joris-Weert (SJW), located around 14 km upstream of the catchment outlet. Although sensitivity and calibration go in parallel while using PEST, we preferred to use fewer parameters to guarantee comparability with the standalone SWAT+ model.

The soil water balance for the standalone SWAT+ model output was calculated using the precipitation (P), surface runoff (Surq), lateral discharge (Latq), percolation (Pr), and evapotranspiration (ET). As for the SWAT+gwflow, similar variables were considered, but additional components such as saturated excess flow (Satexq) and groundwater discharge (Gwtranq) are accounted.

$$\text{Water balance}_{\text{SWAT+}} = \text{P} - \text{Surq} - \text{Pr} - \text{Latq} - \text{ET} \quad (4)$$

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$$\text{Water balance}_{\text{SWAT+gwflow}} = \text{P} + \text{Gwtranq} - \text{Surq} - \text{Latq} - \text{Pr} - \text{ET} - \text{Satexq} \quad (5)$$

The groundwater balance is calculated for the SWAT+gwflow using recharge (rech), groundwater evapotranspiration (gwet), groundwater flow towards the streams (gwsw), surface water towards the groundwater (swgw), saturated excess flow (Satexq), groundwater transferred to the soil (gwsoil) and flow from the boundary of the catchment (bound).

$$\text{GW balance} = \text{rech} - \text{gwet} - \text{gwsw} + \text{swgw} - \text{satex} - \text{gwsoil} + \text{bound} \quad (6)$$

The sum of *GW balance* at the daily time step is compared with the difference in the volume of groundwater before and after each day.

While using the SWAT+ toolbox, (NSE) Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) was used as an objective function. On the other hand, PEST tries to reduce the sum of squared residuals (SSR). The conventional statistics, the Nash-Sutcliffe efficiency (NSE) and the (PBIAS) Percent Bias (Gupta et al. 1999), were used to assess the performance of the models on simulating the streamflow at the catchment outlet and SJW gauging station. Furthermore, the water balance closure was also checked. The closer the NSE and PBIAS are to 1 and 0, respectively, the better the model simulation.

$$\text{NSE} = 1 - \frac{\sum_{t=1}^{T}(Q_m^t - Q_o^t)^2}{\sum_{t=1}^{T}(Q_o^t - \overline{Q_o})^2} \quad (7)$$

$$\text{PBIAS} = \frac{\sum_{t=1}^{T}(Q_o^t - Q_m^t) \times 100}{\sum_{t=1}^{T} Q_o^t} \quad (8)$$

Where Q_m^t is the simulated streamflow at time t, and Q_o^t the observed stream discharge at time t while $\overline{Q_o}$ is the mean of observed streamflow.

3 Result and discussion

3.1 Sensitivity analysis

The sensitivity analysis based on both the SWAT+ toolbox and PEST revealed that the curve number, usually the most sensitive parameter in the SWAT+ model, is not sensitive. Instead, the percolation coefficient (perco), which is a coefficient that adjusts the soil moisture for percolation to take place, is the most sensitive one. This is evident as the catchment is more groundwater-driven. The sensitivity analysis hides the importance of the other parameters due to the super-sensitive nature of perco. However, when the other parameters except perco are compared, it is found that the other groundwater-related parameters also play a role that indicates the importance of appropriate representation of the groundwater hydrology to simulate the general hydrological processes in highly groundwater-dominated catchments.

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The sensitivity analysis has a similar result as Wossenyeleh, et.al (2021) where the hydraulic conductivity of the "Brussels sand" (K_{aqu19}) is very sensitive parameter. Nevertheless, according to their result, river conductance, which is equivalent to streambed conductivity (bed_k) in SWAT+gwflow is not sensitive, contrary to the result of our sensitivity analysis. However, the study made by Wossenyeleh, et.al (2021) is only a tiny part of the catchment (only the Doode Bemde wetland area), while our study area encompasses the whole catchment.

3.2 Calibration, validation, and water balance

The calibrated model parameters values closely match with the finding of Wossenyeleh, et.al (2021), where according to SWAT+gwflow, "Brussels sand (zone 19)" hydraulic conductivity is 9.6 m/day while they estimated it to be 8 m/day. The values are in-between the range of values suggested by Possemiers et al. (2012) and Vandersteen et al. (2014). In addition, the hydraulic conductivity of the river valley represented as zone 24 is 3.1 m/day, while Wossenyeleh, et.al (2021) estimated it to be 3m/day. As for the specific yield, the result indicated that the "Brussels sand" has a specific yield of 0.4, which has a difference of 0.25 compared with Wossenyeleh, et.al (2021). In addition, for the quaternary formation (the river valley), the specific yield is 0.026 and 0.03, according to SWAT+gwflow and Wossenyeleh, et.al (2021), respectively. Here, it is vital to mention that in Wossenyeleh, et.al (2021), the model setup was using MODFLOW forced with recharge obtained from another hydrological model (WetSpaSS). However, for SWAT+gwflow model setup, the recharge is directly transferred from the soil profile, which does not require setup, calibration, and validation of other hydrological models to get recharge values. This is one added value of the new coupled model compared to independently developed models.

The calibration has resulted in an NSE of 0.4 and 0.6 for the standalone SWAT+ and the SWAT+gwflow, respectively (Figure 5). The SWAT+gwflow simulation result corresponds to satisfactory, according to Moriasi et al. (2007). This is a considerable improvement, and it is in line with our starting objective, where a simplistic representation of the SWAT+ model reduces the effectiveness of hydrological modeling in groundwater-dominated catchments. The daily streamflow simulation using SWAT+gwflow has also resulted in high NSE (0.5) during the calibration period (Figure 5).

The result of the first validation period (1975 to 1982) suggested that the standalone SWAT+ has a lower NSE (less than zero) while the SWAT+gwflow simulation managed to show a higher similarity between measured and simulated streamflow data with an NSE of 0.7 (Table 1), which is good according to Moriasi et al. (2007). The SWAT+gwflow is also successfully applied to research conducted by Bailey et al. (2020a) and Bailey et al. (2022). The result indicated that the SWAT+ model could not fully represent the Dijle catchment while the SWAT+gwflow has improved the hydrological simulation. It is to be noted that the calibration using PEST for the standalone resulted in negative NSE while the global optimization tool (SWAT+ toolbox) resulted in 0.4. However, SWAT+gwflow was able to produce good NSE (0.6) using PEST, and hence, if a global optimization tool is made available in the future for this model setup, the model can improve considerably.

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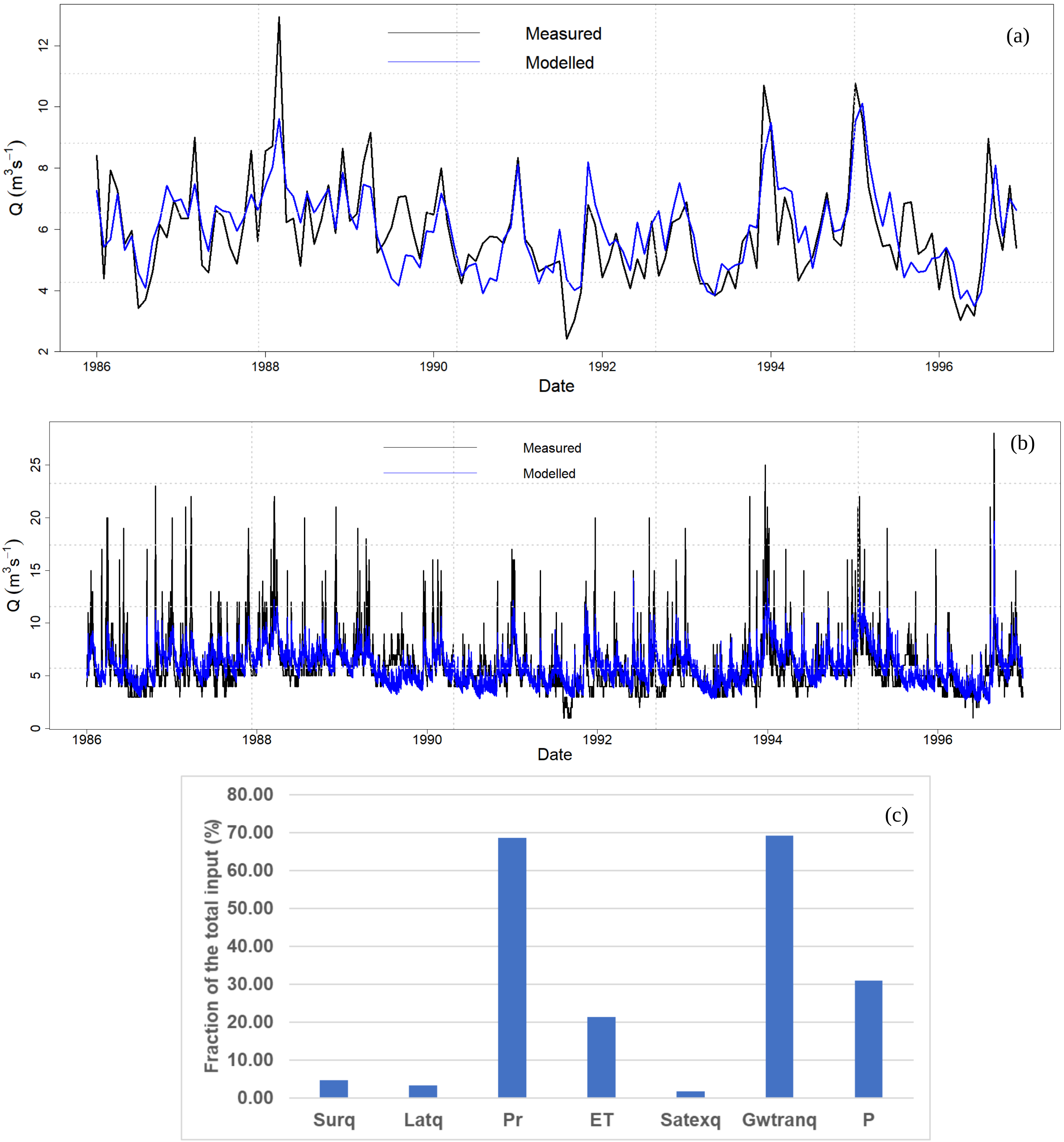

Figure 5: The comparison between measured and simulated monthly (a) and daily (b) streamflow and watershed water balance components (c) at the calibration period (1986 to 1996). The notations in the plot (c) are as described in section 3.3.

The modeled streamflow at the SJW gauging stations mimics the measured monthly mean streamflow where the NSE is 0.5, 0.7, and 0.4 for the calibration period, the first and second validation periods, respectively. Hence, the calibrated model managed to accurately estimate streamflow in another location (inside the catchment).

The water balance closes for both the watershed as a whole and the groundwater. It closes with less than 5.6% error for both SWAT+ and SWAT+gwflow during calibration and validation periods. It is also evident from the watershed water balance assessment that nearly 69% of the water is transferred from the groundwater system to the soil profile (Fig. 5). Moreover, the amount of percolation (Pr) is almost equivalent to the groundwater discharge (Gwtranq). This is also shown in the groundwater balance, where the recharge amount has similar magnitude and variations as the groundwater-soil flux (Fig. 6). Precipitation (P) and evapotranspiration also play a significant role, but the other catchment water balance components are relatively low (surface runoff - Surq, lateral flow – Latq, and saturated excess flow-Satexq).

Table 1: The NSE, PBIAS, and water balance closure measures for the standalone SWAT+ and SWAT+gwflow modeling setups.

	SWAT+/SWAT+gwflow			SWAT+/SWAT+gwflow	SWAT+gwflow
	Time step	NSE	PBIAS	Watershed soil water balance	Groundwater balance error (mm)
Calibration	Daily	-0.9/0.5	2.3/-0.9	0.6%/0.17%	-1.12
	Monthly	0.4/0.6	2.4/-1.0		
Validation 1	Daily	-1.7/0.5	29.9/-11	0.7%/0.21%	1.72
	Monthly	-0.5/0.7	29.9/-10.9		
Validation 2	Daily	-2.0/0.4	38.6/6.4	5.6%/0.17%	1.22
	Monthly	-1.0/0.5	31.5/4.9		

4.3 Groundwater model outputs

The module's spatially distributed nature helps assess groundwater variables that vary in space. For example, groundwater recharge, groundwater hydraulic head, groundwater-soil flux, etc., are the main outputs of the module. As depicted in Figure 6, the groundwater balance mainly comprises the recharge and groundwater-soil interaction fluxes. Both have yearly and seasonal variations where if one gets into peaks/low conditions, the other also follows the same trend. Due to the groundwater-soil interactions, the soil becomes wet in most years, also attributed to the recharge, a dominant feature in playing the groundwater balance.

Furthermore, the groundwater volume which is calculated per grid cell, can be summed up to estimate the amount of groundwater available in a given catchment. For the calibration period, the groundwater volume peaks in the late 1980s while it decreases considerably in the early 1990s. This is vital information for managing sustainable aquifer systems and applying necessary mitigation measures to curb decreasing groundwater volume trends.

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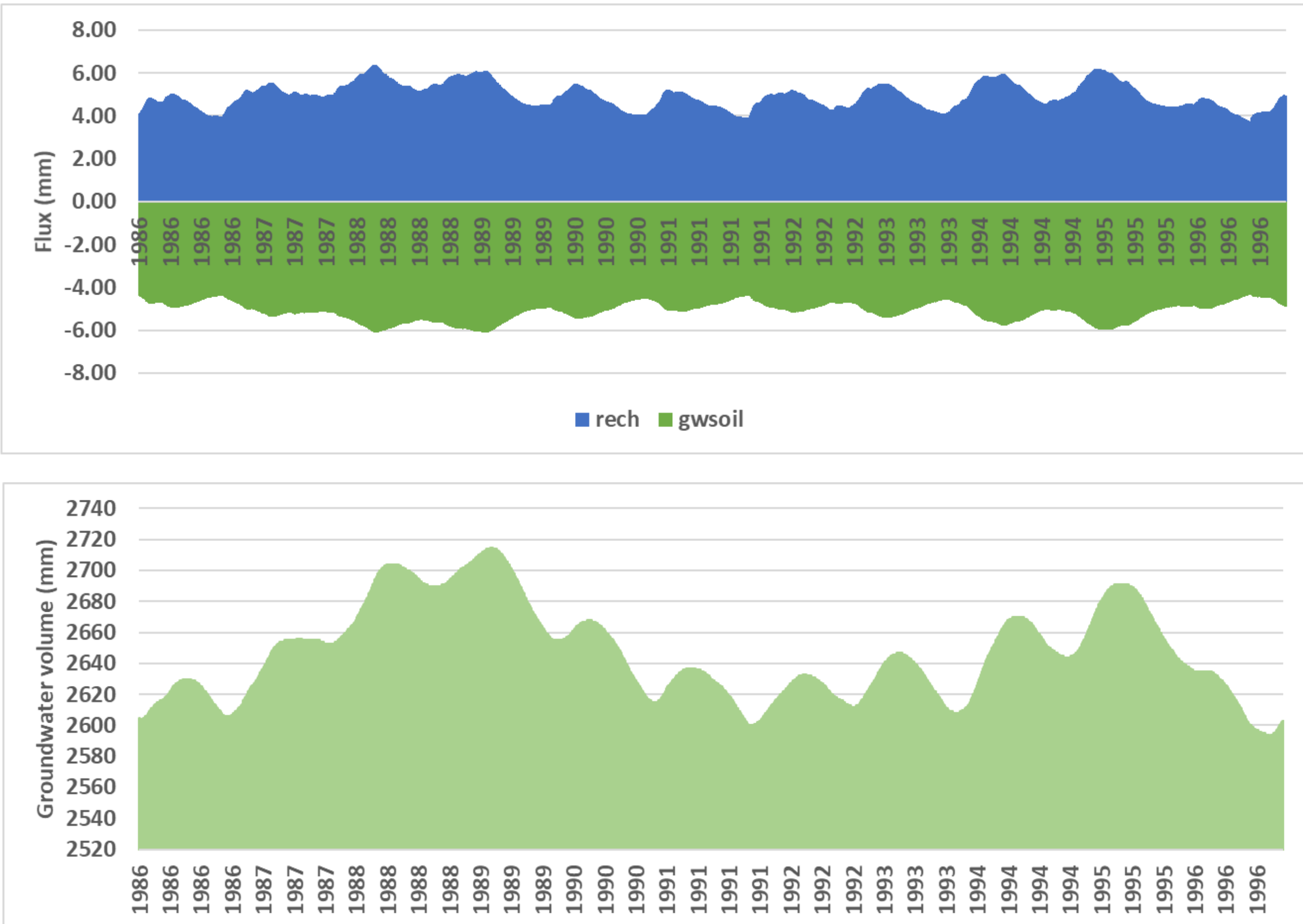

Figure 6: Major groundwater balance components (top figure: recharge (rech) and groundwater-soil interactions (gwsoil)) and groundwater volume time series (bottom figure) for the calibration period.

The delayed groundwater recharge is high at the southern end of the catchment, leading to higher groundwater heads in those regions (Figure 7). The groundwater reaching the soil profile whenever the water table is above the soil profile is dominant in this catchment (Figure 7), with annual average values reaching up to 146 mm's in 2003. Due to the gwsoil higher flux, saturation of the soil profile can take place leading to a quick flow routing towards the streams via surface runoff and/or lateral flow.

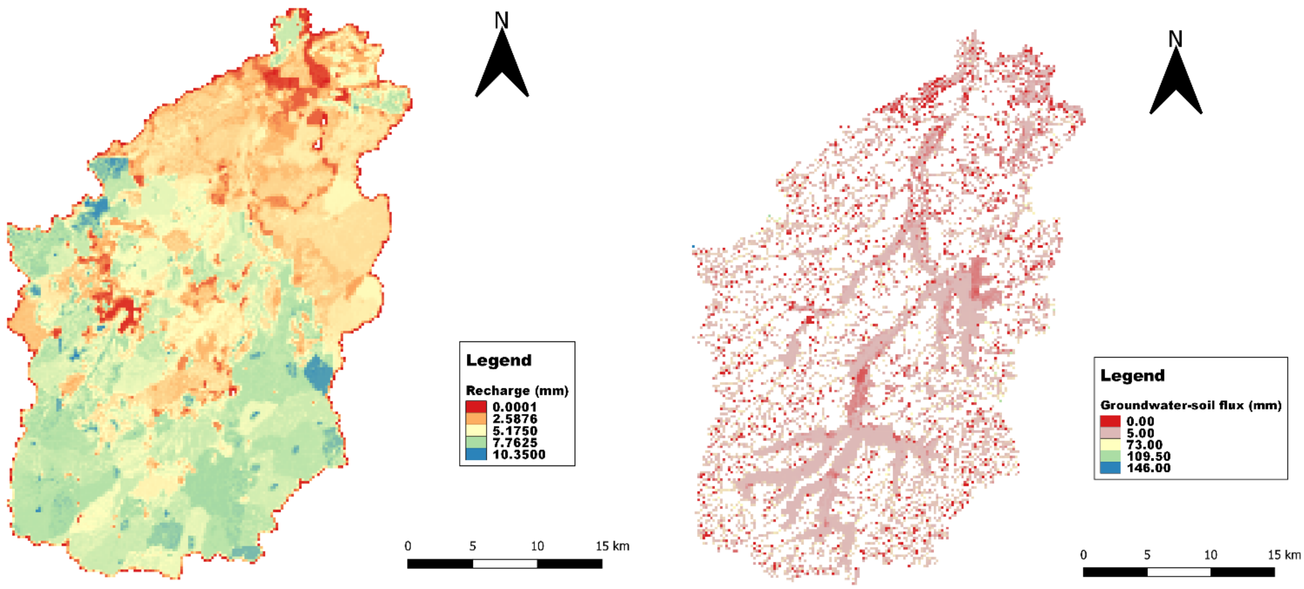

Figure 7: Annual average groundwater recharge (left) and groundwater flux to the soil profile (right) for the year 2003.

4 Conclusion

This paper aimed to assess whether a groundwater-driven catchment (Dijle) can be better represented with either the "standard" SWAT+ model or the newly developed SWAT+gwflow model. In addition, modifications to the gwflow module is made to account for groundwater-soil interactions and pumping. Calibration is done using Parameter Estimation Tool (PEST) for both model setups. In addition, since PEST is a local optimization tool, the standalone SWAT+ model is also calibrated using the SWAT+ toolbox.

First, we modeled the catchment using the standalone SWAT+ model, and during the calibration period (1983 to 1996), the NSE is 0.4, while this decreased considerably (less than zero) during the two validation periods (1975 to 1982 and 1997 to 2002). From this, it is apparent that the standalone model could not fully represent the hydrology accurately. This is attributed to the simplistic representation of the groundwater component of the SWAT+ model.

Contrary to this, the simulation improved considerably when we modeled the catchment using SWAT+gwflow. For instance, the NSE has increased to 0.6, 0.7, and 0.5 during the calibration, the first and second validation period, respectively. Furthermore, we compared the streamflow model output at another gauging station (Sint-Joris-Weert), and it was captured with an NSE of 0.5, 0.7, and 0.4 during the calibration and the first and second validation periods, respectively. The water balance analysis also revealed the importance of including groundwater-soil interaction in the hydrological modeling, signifying the importance of the modification we made to the gwflow module.

On top of these, our results were compared with a previous study that used MDOFLOW to model a small part of the catchment, and nearly similar results were obtained. Nevertheless, to build the MODFLOW model, an additional hydrological model was required to generate recharge. This, however, is not required for the SWAT+gwflow model setup where recharge is directly passed from the hydrological response units (HRUs) to the water table.

In general, the new groundwater module (gwflow) has an advantage over the standalone SWAT+ groundwater module. This is important for a highly groundwater-driven catchment. Hence, an appropriate representation of such catchment type in modeling work has importance for proper aquifer management in an integrated (coupled) scheme. However, further research is required to represent wetlands in SWAT+gwflow and identify and assess tile drain units. We believe that the latter may play a significant role in improving models on groundwater-dominated catchments where groundwater is likely to enter near the root zone, driving the application of tile drains.

Data availability. The data that support the findings of this study are available from the corresponding author upon request.

Author contributions. Conceptualization, E.A.Y.; methodology, E.A.Y, R.T.B, L.L.P, J.N and A.V.G.; software, E.A.Y and R.T.B.; validation, E.A.Y, R.T.B, L.L.P, J.N and A.V.G; formal analysis, E.A.Y.; investigation, E.A.Y, R.T.B, L.L.P, J.N and A.V.G; resources, E.A.Y and R.T.B; data curation, E.A.Y and L.L.P.; writing—original draft preparation E.A.Y; writing—review and editing, E.A.Y, R.T.B, L.L.P, J.N and A.V.G; visualization, E.A.Y.; supervision, R.T.B, J.N and A.V.G; project administration, J.N and A.V.G All authors have read and agreed to the published version of the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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