Received: 22 December 2021 | Revised: 27 April 2022 | Accepted: 3 May 2022
DOI: 10.1002/hyp.14589

RESEARCH ARTICLE

Representation of hydrological processes in a rural lowland catchment in Northern Germany using SWAT and SWAT+

Paul D. Wagner[1] | **Katrin Bieger**[2] | **Jeffrey G. Arnold**[3] | **Nicola Fohrer**[1]

[1]Department of Hydrology and Water Resources Management, Institute for Natural Resource Conservation, Kiel University, Kiel, Germany

[2]Department of Ecoscience - Catchment Science and Environmental Management, Aarhus University, Aarhus, Denmark

[3]Grassland, Soil and Water Research Laboratory, USDA-ARS, Temple, Texas, USA

Correspondence
Paul D. Wagner, Department of Hydrology and Water Resources Management, Institute for Natural Resource Conservation, Kiel University, Kiel, Germany.
Email: pwagner@hydrology.uni-kiel.de

Abstract

The latest version of the Soil and Water Assessment Tool (SWAT+) features several improvements compared with previous versions of the model, for example, the definition of landscape units that allow for a better representation of spatio-temporal dynamics. To evaluate the new model capabilities in lowland catchments characterized by near-surface groundwater tables and extensive tile drainage, we assess the performance of two SWAT+ model setups in comparison to a setup based on a previous SWAT model version ($SWAT_{3S}$ with a modified three groundwater storage model) in the Kielstau catchment in Northern Germany. The Kielstau catchment has an area of about 50 km^2, is dominated by agricultural land use, and has been thoroughly monitored since 2005. In both SWAT+ setups, the catchment is divided into upland areas and floodplains, but in the first SWAT+ model setup, runoff from the hydrologic response units is summed up at landscape unit level and added directly to the stream. In the second SWAT+ model setup, runoff is routed across the landscape before it reaches the streams. Model results are compared with regard to (i) model performance for stream flow at the outlet of the catchment and (ii) aggregated as well as temporally and spatially distributed water balance components. All three model setups show a very good performance at the catchment outlet. In comparison to a previous version of the SWAT model that produced more groundwater flow, the SWAT+ model produced more tile drainage flow and surface runoff. Results from the new SWAT+ model confirm that the representation of routing processes from uplands to floodplains in the model further improved the representation of hydrological processes. Particularly, the stronger spatial heterogeneity that can be related to characteristics of the landscape, is very promising for a better understanding and model representation of hydrological fluxes in lowland areas. The outcomes of this study are expected to further prove the applicability of SWAT+ and provide useful information for future model development.

KEYWORDS
lowland hydrology, model comparison, SWAT+

1 | INTRODUCTION

It is important to accurately represent lowland landscape features and hydrological processes when applying hydrologic models in lowland areas. Rural lowland catchments in Northern Germany are characterized by a flat topography, low flow velocities, and near-surface groundwater tables (Krause et al., 2007). Melioration measures like tile drainage are extensively used to improve conditions for crop production (Hesse et al., 2008). Fast subsurface flow through the tile drains alters the natural hydrology by accelerating runoff from the catchment, affecting water balance components as well as water quality (Schmalz, Bieger, & Fohrer, 2008; Zajíček et al., 2011). Schmalz, Tavares, and Fohrer (2008) highlighted the necessity to represent these specific lowland conditions in models to achieve a good agreement between modelled and measured discharge.

Several attempts have been made to adequately represent lowland features in the hydrologic model SWAT (Soil and Water Assessment Tool, Arnold et al., 1998), for example, with a focus on the floodplain (Sun et al., 2016), tile drainage (Kiesel et al., 2010; Koch et al., 2013), and groundwater (Pfannerstill et al., 2014). SWAT has undergone more than two decades of continuous model development. Its most recent model improvement (SWAT+, Bieger et al., 2017) probably constitutes one of the most pronounced model changes as it involves a revision of the model structure. Several new and enhanced model capabilities provide opportunities for improved modelling of lowland hydrology. The most important one is the definition of different elements of the landscape as spatial objects. The interactions between different spatial objects can be defined using so-called connect files, which give the user more flexibility to represent hydrologic connectivity and hydrologic processes within a catchment as realistically as possible (Bieger et al., 2017, 2019).

So far, only a few applications of SWAT+, primarily in catchments in the United States and Africa, have been reported in the literature. Bieger et al. (2017) introduced the main enhancements of the model and briefly demonstrated its applicability in the Little River Experimental Watershed (LREW) in Georgia by comparing SWAT+ model performance measures for streamflow simulations with those of earlier SWAT models reported in the literature. A handful of publications explored the new capabilities of SWAT+ to represent processes and interactions within a catchment, which can also be used to improve the representation of lowland hydrology in the model. Bieger et al. (2019) tested different representations of the connectivity between upland areas, floodplains, and streams in SWAT+, again using the LREW as an example. Arnold et al. (2021) discussed the feasibility of a SWAT+ model for the contiguous US that will downscale processes to individual fields and first-order channels and van Tol et al. (2021) used hydro-pedological interpretations of soils to define the connectivity of different parts of the landscape in South Africa. Bailey, Bieger, et al. (2020) and Bailey, Park, et al. (2020) enhanced the representation of groundwater processes in SWAT+ by adding a new physically based and spatially distributed groundwater flow module to the model and tested its applicability in the LREW. The new groundwater flow module was extended by Bailey et al. (2022) by adding routines to simulate the removal of groundwater by subsurface drains and testing them in the South Fork Watershed in Iowa.

Further studies in the US include insights into the use of decision tables for simulating complex land and reservoir management operations in SWAT+ by Arnold et al. (2018). The Middle Bosque River Watershed in Texas served as a case study for the first application of IPEAT+, an automatic calibration tool for SWAT+ (Yen et al., 2019). Wu et al. (2020) applied SWAT+ to 123 catchments in the US to analyse the impact of reservoir parameters on the simulation of hydrologic processes and propose calibration guidelines for catchments with reservoirs.

SWAT+ applications in Africa focused on improving model performance through hydrological mass balance calibration and better representation of reservoir and irrigation management in Southern Africa (Chawanda, Arnold, et al., 2020), on introducing a user-friendly software for generating reproducible SWAT+ model setups using the Upper Blue Nile as an example (Chawanda, George, et al., 2020), on an improved representation of seasonal land use dynamics in Tanzania (Nkwasa et al., 2020), and on using high resolution gridded data to analyse the surface runoff response to land use and climate change in Kenya (Kiprotich et al., 2021). In Europe, Senent-Aparicio et al. (2021) developed a post-processing tool for calculating environmental flows that is included in the QGIS interface of SWAT+ and tested it in the Eo River basin in Spain.

Except for an analysis of SWAT and SWAT+ predictions of sub-daily urban runoff in a small catchment in Austin (Texas) by Her and Jeong (2018), no detailed comparisons of SWAT and SWAT+ simulations of hydrological processes have been published to date. By comparing the new SWAT+ to a previous model version, we investigated how the new capabilities of SWAT+ can be used to represent hydrological processes in lowland catchments. Our hypothesis is that the landscape model version of SWAT+ will best represent the hydrological processes in the catchment. To this end, we compared three model configurations: (1) a SWAT2012 model version that was specifically developed to represent lowland hydrology ($SWAT_{3S}$), (2) a SWAT+ model without landscape routing, and (3) a SWAT+ model with landscape routing.

2 | MATERIALS AND METHODS

2.1 | Study area

The Kielstau catchment is a typical rural lowland catchment in Northern Germany. It has a catchment area of about 50 km^2 and is part of the Treene catchment (Wagner et al., 2018). It is characterized by agricultural land uses with ~63% cropland and ~20% pasture and grassland (Lei et al., 2019). The study area experiences a temperate climate with an annual mean temperature of 8.2°C and an average annual precipitation sum of 918.9 mm (weather station Flensburg, reference period 1961–1990, DWD, 2021). Various hydrologic measurement campaigns have been carried out in the catchment since 2005, and a continuous water quality monitoring at the catchment outlet was established in 2006 (Wagner et al., 2018). In 2010, the Kielstau catchment was designated as a UNESCO demonstration site for ecohydrology (Fohrer & Schmalz, 2012; UNESCO, 2011). The Kielstau catchment has been modelled with different SWAT versions, focusing on the integration of tile-drained areas (Fohrer et al., 2007), challenges in lowland hydrology (Schmalz, Tavares, & Fohrer, 2008), nitrate loads (Schmalz, Bieger, & Fohrer, 2008), sediment transport (Kiesel et al., 2010), the environmental fate of herbicides (Fohrer et al., 2014), representation of shallow groundwater layers (Pfannerstill et al., 2014), and enhancing SWAT with in-stream process equations from other models (Femeena et al., 2020).

2.2 | Hydrologic models

Three model setups were compared in the Kielstau catchment. The first, $SWAT_{3S}$ (Pfannerstill et al., 2014), is based on SWAT 2012 Rev. 582. Fast and slow responding groundwater layers were implemented in $SWAT_{3S}$ by Pfannerstill et al. (2014) to adjust SWAT to the lowland conditions in the Kielstau catchment. Even though more recent versions of SWAT are also capable of a three-storage groundwater representation, we chose $SWAT_{3S}$ as it has been specifically developed for this catchment and its lowland hydrology. Therefore, we are confident that $SWAT_{3S}$ performs at least as good as the usual SWAT model in the Kielstau catchment. The spatial setup of the two SWAT+ model applications is the same. In both model setups, the subbasins were divided into upland areas and floodplains before the HRUs were defined, taking advantage of the new capability of SWAT+ to define landscape units. Each landscape unit has its own HRUs and the predicted amounts of the water balance components at HRU level are summed at landscape unit level as opposed to subbasin level in $SWAT_{3S}$. However, in one of the two SWAT+ model configurations, $SWAT+_{HRU}$, the flow generated in each landscape unit is added directly to the stream, similar to the flow generated in each subbasin in $SWAT_{3S}$. In the other SWAT+ model configuration, $SWAT+_{LSU}$, groundwater flow is routed from upland aquifers to floodplain aquifers, which are connected to the stream. A fraction of surface runoff, which depends on the ratios of upland area and corresponding floodplain, is also routed to the floodplain, where it is simulated as an additional input of water that is available for evapotranspiration, infiltration, and runoff. The SWAT+ model applications were run with Revision 60.5.3.

2.3 | Model input data and setup

The same input data was used for all three model setups: a DEM derived from LiDAR data with a spatial resolution of 5 m (LVermA, 2006), a soil map with a scale of 1:200 000 (BGR, 1999), and a land use map that was mapped during field surveys in April 2016 (Lei et al., 2019; Ulrich et al., 2021). Weather data from DWD weather stations outside the catchment (DWD, 2017) was used for deriving the inputs minimum and maximum temperatures, solar radiation, relative humidity, and wind speed. Precipitation data was recorded by a rainfall gauge within the catchment at the tributary Moorau (Figure 1) since October 2010. Data gaps in the precipitation record (1 day in 2012, 85 days in 2013, 64 days in 2015, 70 days in 2016) have been filled using a regression approach and data from the nearby DWD weather station Glücksburg-Meierwik (Wagner et al., 2018).

In all model setups, the catchment was divided into 20 subbasins applying a threshold of 100 ha for the delineation of streams. Potential evapotranspiration was calculated using the Penman–Monteith equation and river routing is based on the variable storage routing method. Similar to Pfannerstill et al. (2014), three slope classes were considered (<2.6%, 2.6%–4.6%, and >4.6%). Land management including crop rotation, fertilization, and tillage is based on Fohrer et al. (2014). The crop rotations implemented in the models are: rape - winter wheat - winter barley, rye - winter barley - rape, spring wheat - corn - corn, spring barley - corn - corn, and continuous corn silage. Plant parameters are based on the SWAT plant data base and heat units were adjusted to represent local plant growth. The simulated leaf area index shows a reasonable development during the vegetation period for all land use classes.

Tile drains are represented in the models based on the spatial distribution of tile-drained areas estimated by Fohrer et al. (2007) as 38% of the agricultural area. The tile drain parameter values for the depth to the subsurface tile drain (800 mm), the time to drain soil (24 h), and the drain tile lag time (48 h) were taken from Kiesel et al. (2010). For all other tile drain parameters the default SWAT values were used. All models were set up with three aquifers: a fast and a slow shallow aquifer as well as a deep aquifer that does not contribute to stream flow. The partitioning of the shallow aquifer in a fast and a slow shallow aquifer in $SWAT_{3S}$ was implemented in the code by Pfannerstill et al. (2014). In SWAT+, the partitioning was achieved by doubling the number of shallow aquifer objects defined in the aquifer input files and using the aquifer connect files (Bieger et al., 2017) to route water from the fast to the slow shallow aquifer.

There are several small farm ponds and one lake (Lake Winderatt) in the Kielstau catchment, which were represented by HRUs with the land use water in $SWAT_{3S}$. In SWAT+, Lake Winderatt and the ponds were implemented as separate spatial objects. The ponds were aggregated at landscape unit level, so that the setup resulted in one pond per landscape unit with a surface area equal to the sum of all individual ponds in that landscape unit. Lake Winderatt was implemented as a reservoir and a SWAT+ decision table (corps_med_res, Arnold et al., 2018) was used to define outflow rules that were geared towards approximating the average residence time of 30 days reported for Lake Winderatt by the MELUND (2021).

There are six wastewater treatment plants in the Kielstau catchment that were integrated as point sources in the model applications. They were parameterized using observed monthly discharge (WWTP Freienwill), observed annual discharge (WWTP Ausacker), and estimated discharge based on unit per capita loading for the other four WWTPs.

The model setups resulted in 2755 HRUs in the $SWAT_{3s}$ model setup and 3295 HRUs in the SWAT+ model setups. The larger number of HRUs in the SWAT+ model setups is due to the delineation of

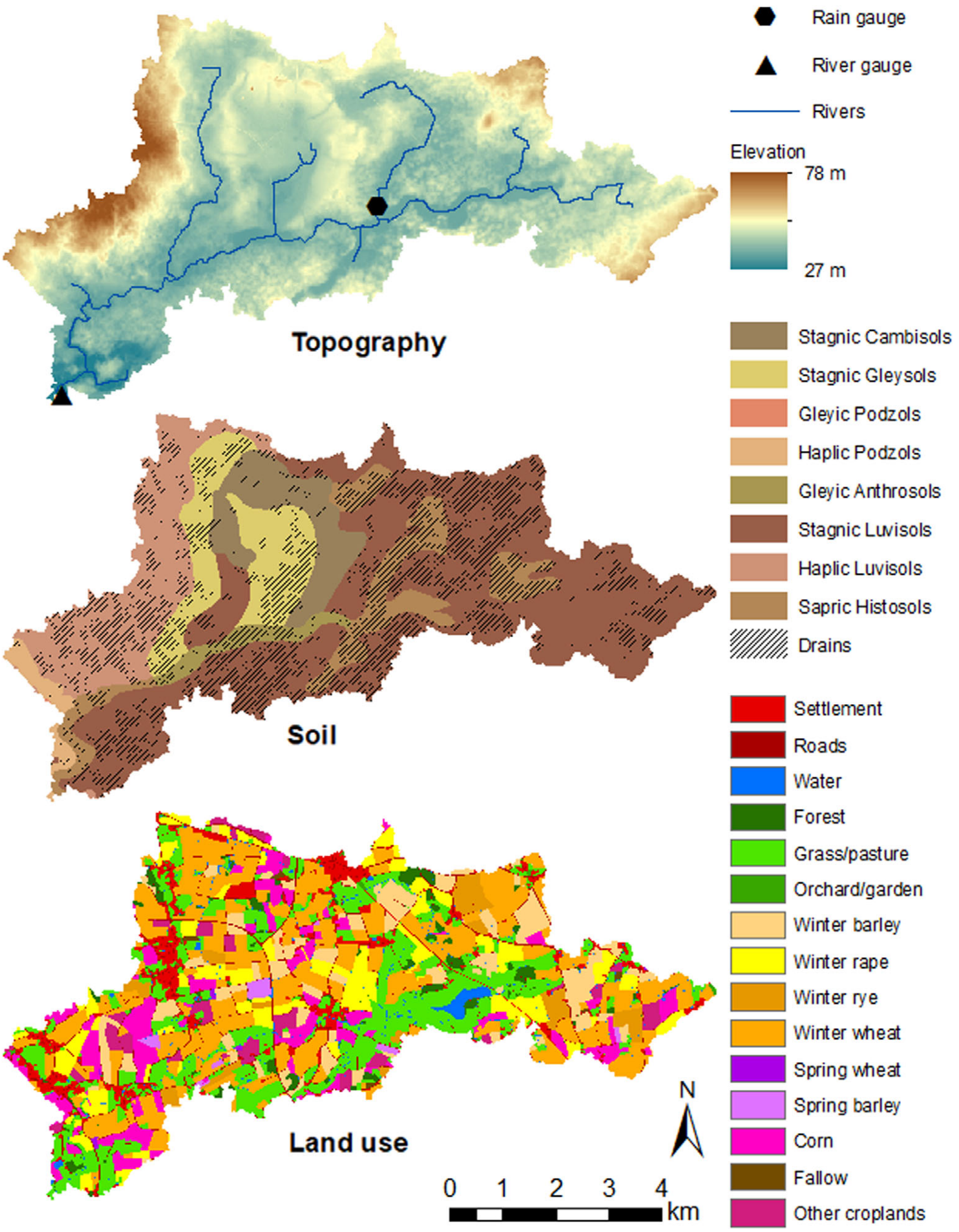

FIGURE 1 Topography (LVermA, 2006), soil map (BGR, 1999) with drained areas (Fohrer et al., 2007), and land use map from 2016 (Lei et al., 2019; Ulrich et al., 2021) of the Kielstau catchment as well as the river network, river gauge, and rain gauge used for modelling.

landscape units that add another property to the HRUs. We did not exclude any combinations of land use, soil, and slope classes during HRU definition.

2.4 | Model parameterization, calibration, and validation

We used the values reported by Pfannerstill et al. (2014) for the initial parameterization of the delay time for aquifer recharge (GW_DELAY), aquifer percolation coefficient (RCHRG_DP), baseflow recession constant aquifer (ALPHA_BF) for the fast and slow shallow aquifers in the SWAT$_{3S}$ model application, and calibrated the parameters given in Table 1. For SWAT+ we used the default groundwater parameterization of the model and calibrated the parameters given in Table 2. The SWAT parameter GW_DELAY is not available in SWAT+.

The parameter PERCO (percolation coefficient) in SWAT+ has replaced the SWAT parameter DEP_IMP (depth to impervious layer in soil profile). It controls percolation from the bottom soil layer and can be used to limit percolation if an impermeable layer or high water table is present. The parameters CN3_SWF and LATQ_CO are new parameters that were added during the development of SWAT+. CN3_SWF gives the user control over the level of saturation of the soil that has to be reached before the model switches from using the Curve Number for moisture condition II to moisture condition III. Thus, it can be used to delay the onset of surface runoff after dry periods. LATQ_CO is a linear coefficient applied to the hillslope storage equation that is used to calculate lateral flow for each soil layer.

TABLE 1 Calibration parameters and the upper and lower boundaries used for calibration of the $SWAT_{3S}$ model setup

Parameter	Description	Min	Max	Change	Final value/adjustment
CN2	Condition II curve number	−15	+5	abschg[a]	−14.772
SURLAG	Surface runoff lag coefficient	0.2	1	absval[b]	0.253
ESCO	Soil evaporation compensation coefficient	0.6	0.8	absval	0.636
EPCO	Plant uptake compensation factor	0.7	1	absval	0.843
SOL_AWC	Available water capacity of the soil layer (mm H_2O/mm soil)	+0.04	+0.2	abschg	+0.142
GW_DELAY	Delay time for fast aquifer recharge (days)	1	15	absval	2.101
RCHRG_DP	Aquifer percolation coefficient fast to slow aquifer	0.3	0.5	absval	0.439
ALPHA_BF	Baseflow recession constant fast aquifer	0.2	1	absval	0.237
ALPHA_BF2	Baseflow recession constant slow aquifer	0.001	0.04	absval	0.005

Note: The last column lists the final calibrated values and adjustments for the absval and abschg change types, respectively.

[a] abschg adds an absolute value to the initial parameter value.

[b] absval replaces the initial parameter value with an absolute value.

TABLE 2 Calibration parameters and the upper and lower boundaries used for calibration of the SWAT+ model setups

Parameter	Description	Min	Max	Change	Final value/adjustment $SWAT+_{HRU}$	Final value/adjustment $SWAT+_{LSU}$
CN2	Curve number condition II	−15	+5	abschg[a]	−1.073	−3.352
SURLAG	Surface runoff lag coefficient	0.2	0.5	absval[b]	0.225	0.323
ESCO	Soil evaporation compensation coefficient	0.05	1	absval	0.095	0.054
EPCO	Plant uptake compensation factor	0.05	0.5	absval	0.072	0.077
LATQ_CO	Lateral flow coefficient	−20	+20	pctchg[c]	−19.641	+19.190
SOL_AWC	Available water capacity of the soil layer (mm H_2O/mm soil)	+0.04	+0.2	abschg	+0.190	+0.170
RCHRG_DP	Aquifer percolation coefficient fast to slow aquifer	0.03	0.17	absval	0.045	0.040
ALPHA_BF	Baseflow recession constant fast aquifer	0.5	1	absval	0.670	0.673
ALPHA_BF2	Baseflow recession constant slow aquifer	0.01	0.02	absval	0.031	0.034
PERCO	Percolation coefficient	−20	+5	pctchg	−18.309	−10.390
CN3_SWF	Soil water factor for curve number condition III	−20	+20	pctchg	−8.850	−14.388

Note: The last two columns list the final calibrated values and adjustments for the absval and abschg change types, respectively.

[a] abschg adds an absolute value to the initial parameter value.

[b] absval replaces the initial parameter value with an absolute value.

[c] pctchg increases or decreases of the initial parameter value by the given percentage of the value.

The three parameters combined can be used to define the soil runoff and leaching potentials at HRU level based on the Soil Vulnerability Index proposed by Thompson et al. (2020). In the two SWAT+ setups for the Kielstau catchment, PERCO, CN3_SWF, and LATQ_CO were parameterized by assigning each HRU a high, moderate, or low leaching and runoff potential based on the Hydrologic Soil Group and the HRU slope. Tile-drained areas were assigned low runoff and leaching potentials regardless of their Hydrologic Soil Group and slope.

The discharge data at the catchment outlet at gauge Soltfeld (LKN, 2021) from October 2010 to September 2017 was split in two periods for model calibration (1 October 2010 to 30 September 2014) and validation (1 October 2014 to 30 September 2017). The model warm-up period was set to 4.75 years (1 January 2006 to 30 September 2010). For calibration, 5000 parameter sets were generated by Latin Hypercube Sampling (Soetaert & Petzoldt, 2010) using the parameter ranges given in Tables 1 and 2. The two SWAT+ model configurations were evaluated for the same 5000 parameter sets whereas the parameter sets for the $SWAT_{3S}$ model application were different (due to different parameters and parameter ranges). For each parameter set a model run was performed and the final parameter set was selected based on the best Kling–Gupta efficiency (KGE, Gupta et al., 2009), so that the KGE is used as objective function in this approach. The model was evaluated with this parameter set for the validation period. Calibration and validation were carried out in R using the packages FME for Latin Hypercube Sampling (Soetaert &

Petzoldt, 2010), hydroGOF for model evaluation (Zambrano-Bigiarini, 2020), and the packages zoo (Zeileis & Grothendieck, 2005) and xts (Ryan & Ulrich, 2020) for data processing.

3 | RESULTS

3.1 | Performance at the outlet

All model setups performed very well during both the calibration and the validation period (Table 3) according to the model performance rating based on NSE, PBIAS, and RSR by Moriasi et al. (2007). It should be noted that the model performance here is based on daily values, but still fulfil the criteria by Moriasi et al. (2007) that refer to a monthly time scale. As temporal aggregation might balance model errors, it is usually harder to achieve a good performance at a higher temporal resolution. In addition, the KGE values between 0.905 and 0.945 underline the very good performance in all model applications. The negative PBIAS indicates a slight underestimation of the measured values in all model applications. In comparison to previous SWAT modelling studies in the Kielstau catchment, which used different input data and time spans, all three model setups performed similarly or better according to goodness-of-fit indicators for the validation period (SWAT$_{3S}$ model by Pfannerstill et al., 2014: NSE = 0.72, PBIAS = −4.4; SWAT 2012 model by Femeena et al., 2020: NSE = 0.78, RSR = 0.46; SWAT 2009 model by Fohrer et al., 2014: NSE = 0.76; SWAT 2005 model by Kiesel et al., 2010: NSE = 0.78; SWAT 2005 model by Schmalz, Tavares, & Fohrer, 2008: NSE = 0.63; SWAT 2005 model by Fohrer et al., 2007: NSE = 0.71). The slightly better performance of the models during the validation period suggests that the parameter set from the drier calibration period (851 mm mean annual precipitation) is similarly or even better suitable for the wetter validation period (963 mm mean annual precipitation).

The SWAT+ model setups perform better than the SWAT$_{3s}$ model setup with regard to NSE, PBIAS, KGE, and RSR. The RSR values for the very high segment of the flow duration curve indicate that very high flows were better simulated in the SWAT+ model applications (Table 3). The SWAT$_{3s}$ model application shows a better performance than the SWAT+ model applications in simulating low and very low flows (best performance during validation period, best or second best during calibration period, Table 3). These differences are also illustrated by the hydrographs in Figures 2 and 3 and the flow duration curves in Figure 4. While all model applications represent the timing of the runoff peaks well, the SWAT$_{3S}$ model application tends to overestimate peak flows (e.g. in December 2014 and December 2015). The new parameter CN3_SWF in SWAT+ gives the user control over how saturated the soils need to be before the model switches from using CN2 to using CN3 and can be used to allow the landscape to wet up before surface runoff occurs after dry periods. The effects of this parameter are clearly recognizable in the hydrographs simulated in the SWAT+ model applications after long periods of baseflow (e.g. in 2011 and 2015). Among the SWAT+ model applications SWAT+$_{LSU}$ usually predicts lower peak flow values (e.g. in January 2015, Figure 3). After most streamflow peaks, the recession simulated in the SWAT+ model applications is slower and fits the observed recession better than the recession simulated in the SWAT$_{3S}$ application (e.g. in February and March 2015). The flow duration curve of measured streamflow is generally well represented in all model applications, but the log scale in Figure 4 depicts small differences in the low and very low flow segment. The poor fit between the measured and modelled hydrographs for all model applications in July and August 2016 in Figure 2 can be explained by a gap in the precipitation records from the Moorau precipitation gauge, for which the gap filling approach with data from outside the catchment was obviously not able to depict precipitation in the Kielstau catchment accurately due to convective precipitation events in summer and the associated high spatial heterogeneity.

TABLE 3 Comparison of goodness-of-fit indicators: Nash–Sutcliffe efficiency (NSE), percentage bias (PBIAS), Kling–Gupta efficiency (KGE), and ratio of the root mean square error (RMSE) between simulated and observed values to the standard deviation of the observations (RSR)

	Calibration			Validation		
	SWAT$_{3S}$	SWAT+$_{HRU}$	SWAT+$_{LSU}$	SWAT$_{3S}$	SWAT+$_{HRU}$	SWAT+$_{LSU}$
NSE	0.799	0.822	0.836	0.850	0.882	0.890
PBIAS	−4.2%	−1.9%	−3.7%	−3.1%	+2.0%	−0.7%
KGE	0.891	0.905	0.911	0.917	0.925	0.945
RSR	0.448	0.422	0.405	0.387	0.343	0.331
RSR very high	0.536	0.283	0.135	0.476	0.269	0.292
RSR high	0.145	0.182	0.228	0.206	0.311	0.193
RSR mid	0.333	0.152	0.193	0.171	0.184	0.172
RSR low	0.397	0.440	1.018	0.356	0.568	1.064
RSR very low	2.126	0.914	2.238	1.485	2.427	3.870

Note: The RSR is used to evaluate the fit of the hydrograph and for five segments of the flow duration curve: RSR very high (<5% days of exceedance), RSR high (≥5% and <20%), RSR mid (≥20% and <70%), RSR low (≥70% and <95%), RSR very low (≥95%). A grey scale is used to visualize the ranking of the model applications. Dark grey indicates the best and light grey the worst model fit to observed data.

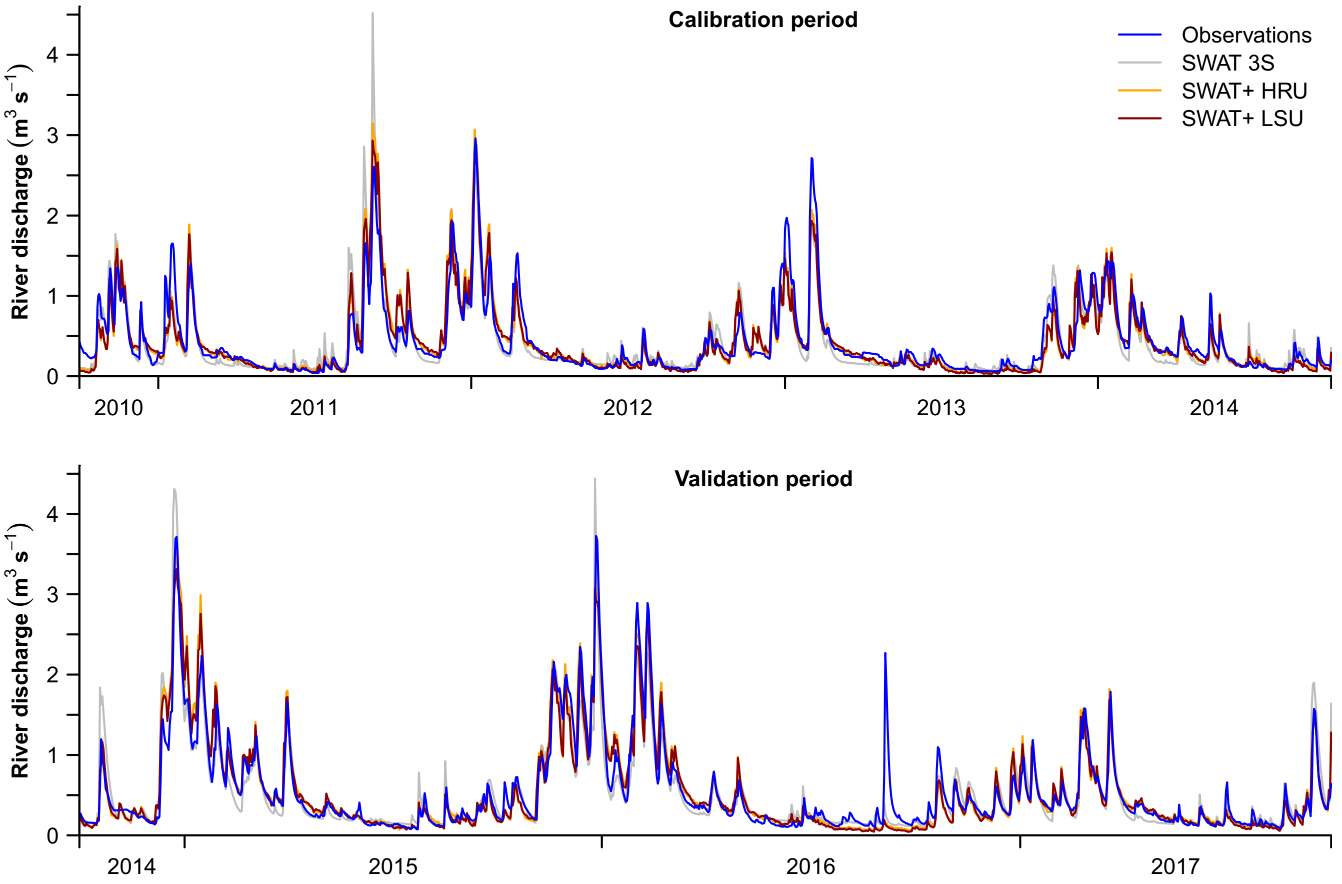

FIGURE 2 Comparison of modelled and measured hydrographs at the catchment outlet for the calibration (1 October 2010 to 30 September 2014) and validation (1 October 2014 to 30 September 2017) periods.

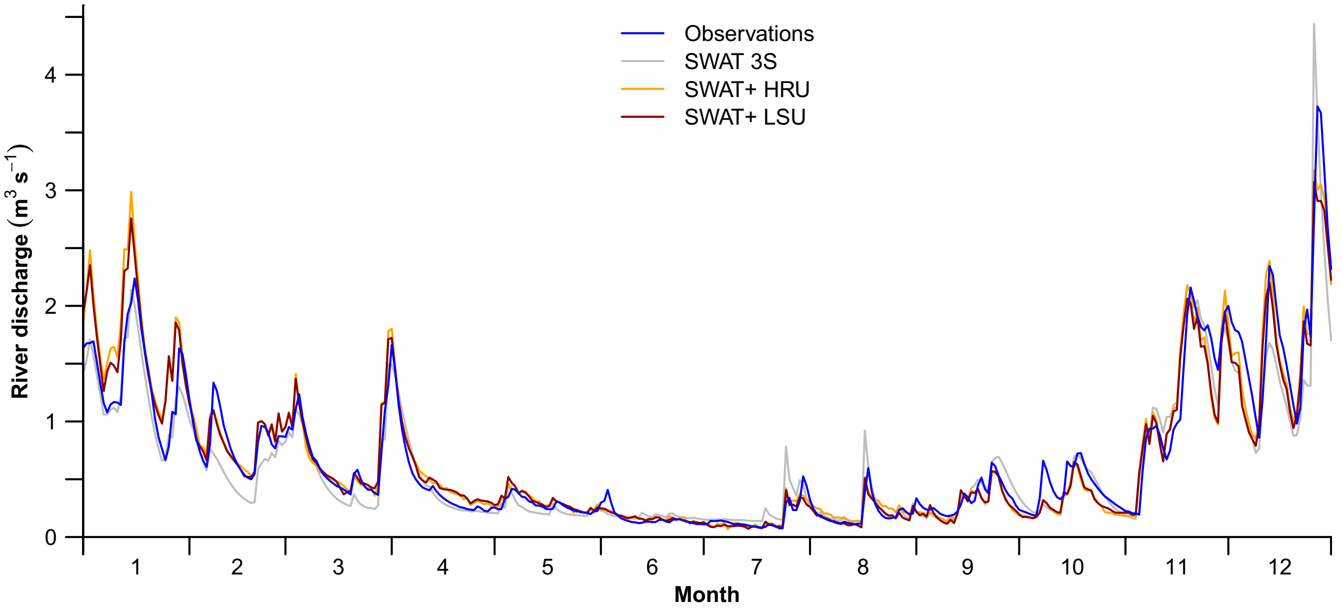

FIGURE 3 Comparison of modelled and measured hydrographs at the catchment outlet for the year 2015.

Among the SWAT+ model applications, SWAT+$_{LSU}$ performs better than SWAT+$_{HRU}$ with regard to NSE, PBIAS, KGE, and RSR with the exception of PBIAS (difference of 1.8 percentage points) during the calibration period (Table 3). Hence, the performance values indicate that SWAT+$_{LSU}$ generally performs best when compared with the other two model configurations.

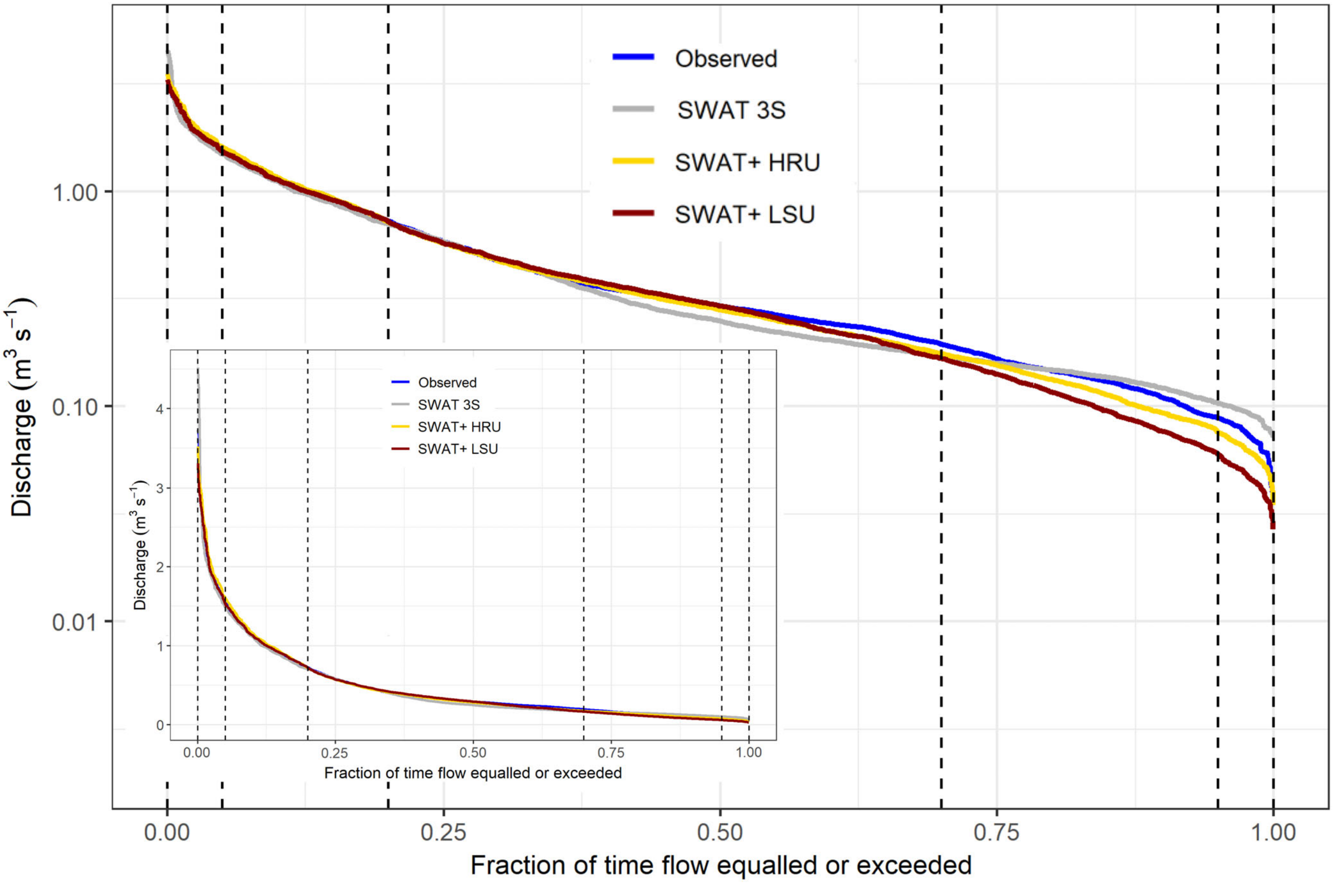

FIGURE 4 Comparison of measured and modelled flow duration curves using a logarithmic scale (main) and a linear scale (inset).

3.2 | Aggregated water balance components

The average annual amount of evapotranspiration is very similar in all three model applications. The ratio of evapotranspiration to precipitation (0.57–0.58) agrees very well with the values estimated by Fohrer et al. (2014) for the periods 2003–2005 (0.62) and 2006–2009 (0.55). Lateral flow is also similar in all three model applications, but surface runoff, tile drainage flow, and percolation differ considerably (Table 4). Surface runoff and tile drainage flow are low in $SWAT_{3S}$, whereas percolation is high, i.e., water is mainly routed through the groundwater to the streams. In the SWAT+ model applications, surface runoff and tile drainage flow are much higher and percolation is much lower, i.e., water is mainly routed through the (near-surface) landscape. $SWAT+_{HRU}$ predicts the highest surface runoff, whereas tile drainage flow is highest in $SWAT+_{LSU}$, indicating different flow paths in the two model applications.

The mean monthly distribution of the water balance components (Figure 5) provides deeper insights into the differences between the three model applications. The lower average annual evapotranspiration in the SWAT+ model applications (Table 4) derives from lower ET values between September and May. These differences may be attributed to differences in plant growth as well as a different partition of the flow components. The lateral flow predicted in all three model applications is similar throughout the year, but since it only accounts for less than 4 mm per month, its impact on the overall water balance and streamflow in the Kielstau is negligible. The remaining runoff components differ considerably between SWAT+ and $SWAT_{3S}$. Figure 5 confirms that surface runoff and tile drainage flow are the dominant flow components in SWAT+, whereas groundwater flow dominates in $SWAT_{3S}$, particularly in the winter half of the year. While the seasonal variability of stream flow is mainly reflected in surface runoff and tile drainage in the SWAT+ model applications, $SWAT_{3S}$ represents this variability through groundwater as the comparison of percolation past the bottom of the soil layer indicates (Figure 5). $SWAT+_{LSU}$ predicts a slightly lower evapotranspiration

TABLE 4 Mean annual water balance components aggregated for the entire model run

	$SWAT_{3S}$	$SWAT+_{HRU}$	$SWAT+_{LSU}$
Precipitation (mm)	899	899	899
Evapotranspiration (mm)	525	514	508
Surface runoff (mm)	39	108	85
Lateral flow (mm)	19	18	21
Tile drainage flow (mm)	13	109	118
Percolation (mm)	294	135	156
Delta storage (mm)	9	15	11

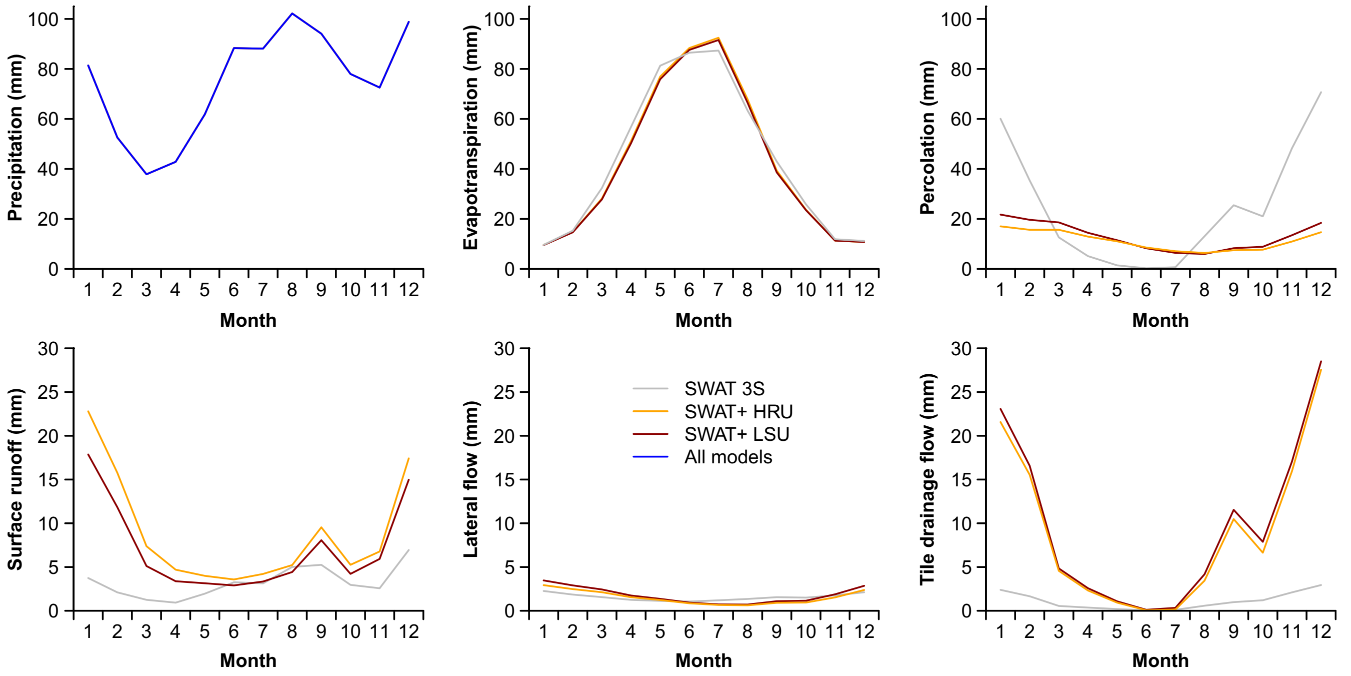

FIGURE 5 Mean monthly distribution of water balance components in the three different model configurations for the entire model run.

than SWAT+$_{\mathrm{HRU}}$ during the summer. Tile drainage flow is higher in SWAT+$_{\mathrm{LSU}}$ than in SWAT+$_{\mathrm{HRU}}$ and vice versa surface runoff is higher in SWAT+$_{\mathrm{HRU}}$ throughout the year. Except for slightly lower values in summer (June–August) percolation is higher in SWAT+$_{\mathrm{LSU}}$ than in SWAT+$_{\mathrm{HRU}}$.

3.3 | Spatially distributed water fluxes

The spatial distribution of the water balance components at HRU level is depicted in Figure 6. Although the catchment average of ET is similar in all model applications (Table 4), SWAT+ predicts a stronger spatial heterogeneity with a larger standard deviation (sd; SWAT+$_{\mathrm{HRU}}$: 74 mm, SWAT+$_{\mathrm{LSU}}$: 73 mm, SWAT$_{3S}$: 25 mm) and higher maximum values of 590 mm (SWAT+$_{\mathrm{HRU}}$) and 594 mm (SWAT+$_{\mathrm{LSU}}$) as compared to SWAT$_{3S}$ (548 mm maximum). Maximum ET values in the SWAT+ model applications can be observed in the lowlands near the river that often correspond to pasture areas. This is in agreement with our assumption that the new model structure leads to more available water for ET in the lowlands (where the SWAT+ model applications predict the maximum ET). Lupon et al. (2018) underline the importance of riparian evapotranspiration in hydrologic modelling. All model applications show that sealed surfaces like roads yield maximum values for surface runoff, which agrees very well with our expectations and the literature (e.g. Shi et al., 2007). The maximum surface runoff is highest in SWAT+$_{\mathrm{LSU}}$ (707 mm) and much lower in SWAT+$_{\mathrm{HRU}}$ (604 mm) and especially in SWAT$_{3S}$ (462 mm). Similarly, the variability of surface runoff is largest in SWAT+$_{\mathrm{LSU}}$ (sd: 123 mm), followed by SWAT+$_{\mathrm{HRU}}$ (sd: 118 mm) and SWAT$_{3S}$ (sd: 92 mm). Higher surface runoff values in the floodplain in SWAT+$_{\mathrm{LSU}}$ result from the fact that surface runoff from the upland is routed to the floodplain and serves as an additional input. As mentioned above, lateral flow is generally low, but values are comparatively high in the northwestern part of the catchment, where the slopes are steeper. The variability of lateral flow is larger in the SWAT+ model applications (sd: 50 mm (SWAT+$_{\mathrm{HRU}}$) and 56 mm (SWAT+$_{\mathrm{LSU}}$)) than in the SWAT$_{3S}$ model application (sd: 21 mm).

The spatial variability of percolation is high in all three model applications (sd: 88 mm (SWAT$_{3S}$), 115 mm (SWAT+$_{\mathrm{HRU}}$), 135 mm (SWAT+$_{\mathrm{LSU}}$)), but only for the SWAT+ model applications the influence of the soil types, for example, lower percolation for Haplic Luvisol (loam) in the northwestern part of the catchment and higher percolation for Stagnic Cambisol (sandy loam) in the middle and Haplic Podzol (sand) at the western edge of the catchment, is clearly visible. Moreover, percolation is lower in tile drained areas, which becomes obvious when comparing the patterns of tile drainage flow to the patterns of percolation in Figure 6. Land use is rather fragmented and explains the small-scale variabilities in the observed patterns (Figures 1 and 6). In general, the spatial variability of the flow components is greater in the SWAT+ model applications and particularly in SWAT+$_{\mathrm{LSU}}$ than in the SWAT$_{3S}$ model application. This can be attributed to the spatially differentiated parameterization of each HRU for high, moderate, or low leaching and runoff potentials (parameters PERCO, CN3_SWF, and LATQ_CO) in the SWAT+ model applications and in the case of SWAT+$_{\mathrm{LSU}}$ to the routing of runoff from the upland areas to the floodplains.

4 | DISCUSSION

Among the main reasons for the differences between the SWAT$_{3S}$ and the SWAT+ model applications are the replacement of DEP_IMP

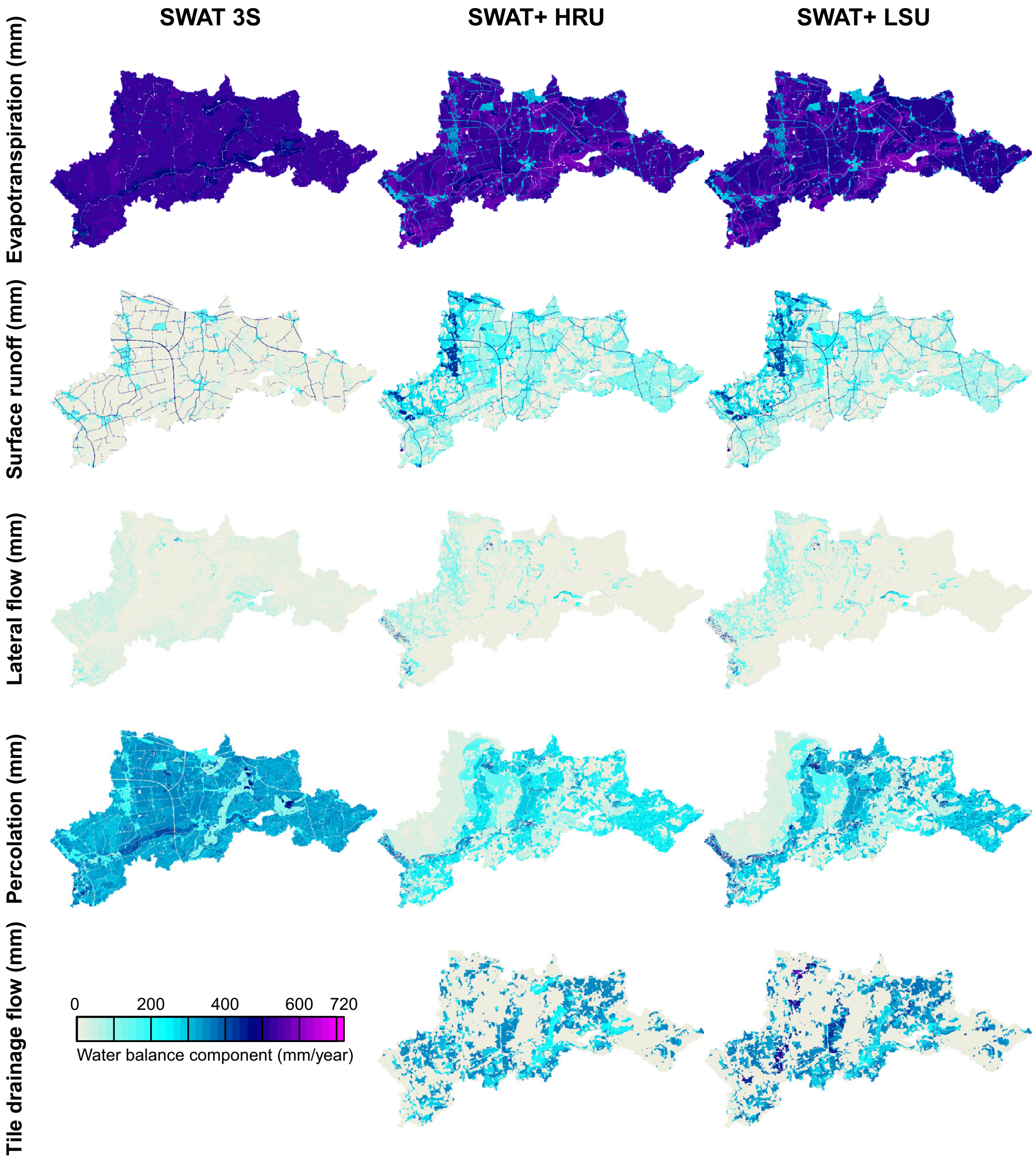

FIGURE 6 Comparison of the spatial distribution of water balance components for all land hydrologic response units (HRUs) based on mean annual values for the entire model run. Tile drainage flow is not provided as an output on HRU level in SWAT_{3S} and therefore only shown for the SWAT+ model applications. Water areas are masked and depicted in white.

with PERCO, the introduction of the new parameters CN3_SWF and LATQ_CO, and the parameterization of these three parameters based on Hydrologic Soil Group and slope at HRU level. Since a percent change was applied to all three of them, the original variability of runoff and leaching potentials was preserved during calibration. This resulted not only in a larger variability of surface runoff and percolation within the catchment, but also in the dominance of surface runoff and tile drainage flow in the SWAT+ model applications as opposed to groundwater flow in the SWAT_{3S} model application.

Tile drainage flow is most likely too low in the SWAT_{3S} model application. Pfannerstill et al. (2014) applied the same model in the same catchment and suggested an amount of about 100 mm tile drainage flow per year, which agrees well with those modelled by SWAT+. Kiesel et al. (2010) estimated 56 mm tile drainage flow per year. The underestimation of tile drainage flow by the SWAT_{3S} model application may be attributed to the fact that the tile drainage parameter values reported by Kiesel et al. (2010) were used for all three model applications in this study, whereas they were calibrated in the study by Pfannerstill et al. (2014). In contrast to the underestimation of tile drainage flow in SWAT_{3S}, percolation and the associated groundwater contribution might be underestimated in the SWAT+ model applications. Like groundwater flow, tile flow mostly contributes to the baseflow portion of stream hydrographs (Schilling & Helmers, 2008), but the two pathways differ significantly with regard to nutrient loadings, especially nitrate, but also phosphorus (Smith et al., 2015). Therefore, a realistic simulation of the proportions of groundwater and tile flow is extremely important for the simulation of water quality and the identification of critical source areas and pathways of pollution. Modelling water quality with the three model setups would therefore provide an opportunity to evaluate which representation of groundwater and tile drainage flow is more suitable in the study area.

Similarly, the different representation of surface runoff in the three model applications (Table 4; Figures 5 and 6) requires further investigation. The values in SWAT_{3S} are in better agreement with the model results of previous studies in the catchment (Kiesel et al., 2010; Pfannerstill et al., 2014) than the values estimated by SWAT+. However, Bailey et al. (2022) applied SWAT+ with a new spatially distributed groundwater and tile drainage routine to the South Fork Watershed in Iowa and found that surface runoff amounted to 46% of the catchment water yield and can thus play a significant role in tile-drained catchments. A study by Koch et al. (2013) suggested that the contribution of surface runoff to stream flow varies significantly in lowland catchments of Northern Germany. Figure 6 shows that the spatial distribution of surface runoff in the SWAT+ model applications is reasonable as high values are associated with settlement areas, steeper slopes, and areas without tile drainage. Field measurements of surface runoff as well as sediment and nutrient modelling can help to identify the most suitable model representation of surface runoff and thus improve process representation.

Further calibration of the groundwater module in the SWAT+ model configurations and of tile drainage parameters in SWAT_{3S} may improve the model results, as different combinations of parameter values can lead to a similar performance in simulating discharge (equifinality, Beven & Freer, 2001). Our results indicate that the selection of the best model runs based on the KGE value that was applied in this study does not guarantee a reasonable representation of all water balance components. To avoid this, model parameters can be constrained during model selection (Pfannerstill et al., 2017), for example, by a minimum tile drainage flow and percolation criterion that all model applications would need to meet. Shafii et al. (2019) also propose constraining model predictions using flow pathway data. As there is no observed hard data available for the ratios of different flow components in the Kielstau catchment, these constraints would have to rely on expert knowledge or might be derived from water quality measurements.

The better representation of low flows in SWAT_{3S} may be attributed to the possibly better calibrated SWAT_{3S} groundwater module for which parameters and parameter ranges were available from a previous study by Pfannerstill et al. (2014). While similar parameters were calibrated in both models, the parameter GW_DELAY is not available in SWAT+. Moreover, the RCHRG_DP parameter that controls aquifer percolation from the fast to the slow aquifer differs between the three setups. Its value is much smaller in the SWAT+ model applications ($\text{SWAT+}_{\text{HRU}}$: 0.045, $\text{SWAT+}_{\text{LSU}}$: 0.040) as compared to 0.439 in SWAT_{3S} (Tables 1 and 2). And while a considerable amount of water recharges the deep aquifer in SWAT_{3S} (adapted parameter (0.38) from Pfannerstill et al. (2014)), recharge to the deep aquifer was inhibited in the SWAT+ model configurations. A better performance of the SWAT+ model applications for low and very low flows might be achieved if the groundwater parameters are further calibrated. Alternatively, the MODFLOW-based groundwater module for SWAT+ provides further options to better represent groundwater (Bailey, Bieger, et al., 2020; Bailey, Park, et al., 2020) and tile drainage (Bailey et al., 2022) flow in SWAT+. Several authors compared SWAT and SWAT-MODFLOW simulations and found that the latter performed better, especially in simulating low flow periods and the recession of peak flows (Aliyari et al., 2019; Bailey et al., 2016; Liu et al., 2020; Molina-Navarro et al., 2019). Since the groundwater flow module by Bailey, Bieger, et al. (2020) and Bailey, Park, et al. (2020) is using the same algorithms as MODFLOW, it can be assumed that its use would also improve SWAT+ simulations. The Kielstau catchment would be a very suitable study area for verifying this assumption.

Another difference between the SWAT_{3S} model application and the two SWAT+ model applications is the representation of Lake Winderatt and the large number of small ponds in the catchment. This improvement of the representation of the lake may also have contributed to the better performance of SWAT+. However, little is known about to what extent they contribute to retention of water in the landscape and a slow release during low flow periods. Vyse et al. (2020) conclude from their study of ponds in the northeast of Germany that the interactions of ponds with the shallow groundwater table should be analysed with the help of hydrologic models. Ongoing measurements of these ponds in the Kielstau catchment offer an opportunity to do so in the future (Ulrich et al., 2019). A detailed analysis of discharge directly downstream of Lake Winderatt could provide further insights into the lake's impact on discharge at the catchment outlet during recession phases and low flow periods, indicate whether the representation of the lake in the SWAT+ model configurations is reasonable or not, and contribute to improving the simulation of lake outflow.

The $\text{SWAT+}_{\text{LSU}}$ model application generally performed slightly better than the $\text{SWAT+}_{\text{HRU}}$ model application, which can be attributed to the effects of routing surface runoff and groundwater flow from upland areas to floodplains. The buffering effect of the floodplains could also explain that peak flow values are usually lower in $\text{SWAT+}_{\text{LSU}}$ than in $\text{SWAT+}_{\text{HRU}}$. These findings suggest that distinguishing between upland and floodplain areas within the Kielstau catchment can contribute to a better representation of lowland hydrology. However, in this case, the differences between the two SWAT+ model applications are very small. This is partly due to the spatial setup being the same for both SWAT+ model configurations, i.e., the subbasins were divided into uplands and floodplains during both setups, resulting in an identical HRU definition. In addition, upland areas and floodplains were not parameterized and calibrated separately. Therefore, the only difference between the two configurations is the routing of groundwater flow and a fraction of surface runoff through the floodplain in the $\text{SWAT+}_{\text{LSU}}$ model configuration. By adjusting selected parameters differently for upland areas and floodplains, the representation of differences in the hydrological characteristics and processes of these two landscape units in the model application can potentially be further improved. In addition, during model calibration different parameter sets were identified as the best ones for the two SWAT+ model applications which may also contribute to differences in water fluxes.

5 | CONCLUSIONS

Three different model configurations with different parameterizations were set up and calibrated, all of which performed very good with regard to stream flow. The goodness-of-fit indices indicate that the performance of the three model setups is similar or better when compared with previous modelling studies carried out in the catchment. Overall performance values of the SWAT+ model applications - and particularly of $\text{SWAT+}_{\text{LSU}}$ - are slightly better. Low flows are better represented in SWAT_{3S}, whereas very high flows are better represented by the SWAT+ model configurations. One reason for this different performance is a different separation of water fluxes in the models. SWAT_{3S} has a strong groundwater component, whereas the SWAT+ model has a stronger contribution from tile drainage and surface runoff, i.e., the contribution to the slow component in the hydrograph is different in SWAT_{3S} and SWAT+.

Groundwater and tile drainage are integral parts of lowland hydrology. In this study, SWAT_{3S} favoured groundwater flow, whereas SWAT+ favoured tile drainage flow. A better model representation might balance groundwater and tile drainage flow. This could be achieved by constraining the selection of suitable model parameter sets by defining acceptable groundwater (SWAT+) or tile drainage (SWAT_{3S}) flow volumes as additional criteria. In general, after this first comparison of SWAT+ to a previous model version in a lowland catchment, the model can be recommended for modelling lowland catchments.

Despite possible further improvements, the new capability of SWAT+ of including landscape units that has been tested in the $\text{SWAT+}_{\text{LSU}}$ model setup is very promising with regard to a better representation of hydrological processes, as indicated by the very good performance at the catchment outlet and the depiction of spatial heterogeneity in the model. The stronger spatial heterogeneity in SWAT+ is assumed to be more reasonable than the more uniform spatial distributions in SWAT_{3S}. However, this requires further spatial validation of model results, for example, with the help of satellite-based products of evapotranspiration.

ACKNOWLEDGEMENTS

We thank the governmental agencies (BGR, LVermA, LKN, DWD) for providing environmental data for our models. We are grateful to our laboratory and field team, in particular to Bettina Hollmann and Monika Westphal, as well as to all student assistants and everybody else who supports and contributes to the long-term monitoring of water resources in the catchment of the Kielstau. Moreover, we appreciate the constructive comments on our manuscript from two anonymous reviewers.

DATA AVAILABILITY STATEMENT

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

ORCID

Paul D. Wagner https://orcid.org/0000-0002-1594-398X

REFERENCES

Aliyari, F., Bailey, R. T., Tasdighi, A., Dozier, A., Arabi, M., & Zeiler, K. (2019). Coupled SWAT-MODFLOW model for large-scale mixed agro-urban river basins. *Environmental Modelling & Software*, *115*, 200–210. https://doi.org/10.1016/j.envsoft.2019.02.014

Arnold, J. G., Bieger, K., White, M. J., Srinivasan, R., Dunbar, J. A., & Allen, P. M. (2018). Use of decision tables to simulate management in SWAT+. *Water*, *10*(6), 713.

Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modeling and assessment - part 1: Model development. *Journal of the American Water Resources Association*, *34*, 73–89.

Arnold, J. G., White, M. J., Allen, P. M., Gassman, P. W., & Bieger, K. (2021). Conceptual framework of connectivity for a National Agroecosystem Model based on transport processes and management practices. *JAWRA Journal of the American Water Resources Association*, *57*(1), 154–169.

Bailey, R. T., Bieger, K., Arnold, J. G., & Bosch, D. D. (2020). A new physically-based spatially-distributed groundwater flow module for SWAT+. *Hydrology*, *7*(4), 75.

Bailey, R. T., Bieger, K., Flores, L., & Tomer, M. (2022). Evaluating the contribution of subsurface drainage to watershed water yield using SWAT+ with groundwater modeling. *Science of the Total Environment*, *802*, 149962.

Bailey, R. T., Park, S., Bieger, K., Arnold, J. G., & Allen, P. M. (2020). Enhancing SWAT+ simulation of groundwater flow and groundwater-surface water interactions using MODFLOW routines. *Environmental Modelling & Software*, *126*, 104660.

Bailey, R. T., Wible, T. C., Arabi, M., Records, R. M., & Ditty, J. (2016). Assessing regionalscale spatio-temporal patterns of groundwater–surface water interactions using a coupled SWAT-MODFLOW model. *Hydrological Processes*, *30*, 4420–4433. https://doi.org/10.1002/hyp.10933

Beven, K., & Freer, J. (2001). Equifinality, data assimilation, and data uncertainty estimation in mechanistic modelling of complex environmental systems using the GLUE methodology. *Journal of Hydrology*, *249*, 11–29.

BGR. (1999). *BUK 200, Bodenübersichtskarte 1:200 000*. Bundesanstalt für Geowissenschaften und Rohstoffe: CC.1518 Flensburg.

Bieger, K., Arnold, J. G., Rathjens, H., White, M. J., Bosch, D. D., & Allen, P. M. (2019). Representing the connectivity of upland areas to floodplains and streams in SWAT+. *JAWRA Journal of the American Water Resources Association*, *55*(3), 578–590.

Bieger, K., Arnold, J. G., Rathjens, H., White, M. J., Bosch, D. D., Allen, P. M., Volk, M., & Srinivasan, R. (2017). Introduction to SWAT+, a completely restructured version of the soil and water assessment tool. *Journal of the American Water Resources Association*, *53*(1), 115–130.

Chawanda, C. J., Arnold, J., Thiery, W., & van Griensven, A. (2020). Mass balance calibration and reservoir representations for large-scale hydrological impact studies using SWAT+. *Climatic Change*, *163*, 1307–1327. https://doi.org/10.1007/s10584-020-02924-x

Chawanda, C. J., George, C., Thiery, W., van Griensven, A., Tech, J., Arnold, J., & Srinivasan, R. (2020). User-friendly workflows for catchment modelling: Towards reproducible SWAT+ model studies. *Environmental Modelling & Software*, *134*, 104812.

DWD. (2017). Weather stations of the German weather service (DWD) in Flensburg (Schäferhaus), Glücksburg-Meierwik, and Schleswig.

DWD. (2021). *Vieljährige Mittelwerte 1961–1990: Niederschlag und Temperatur, Station Flensburg. Deutscher Wetterdienst, Offenbach a.M.*. https://www.dwd.de/DE/leistungen/klimadatendeutschland/vielj_mittelwerte.html.

Femeena, P. V., Chaubey, I., Aubeneau, A., McMillan, S. K., Wagner, P. D., & Fohrer, N. (2020). An improved process-based representation of stream solute transport in the soil and water assessment tools. *Hydrological Processes*, *34*(11), 2599–2611.

Fohrer, N., Dietrich, A., Kolychalow, O., & Ulrich, U. (2014). Assessment of the environmental fate of the herbicides flufenacet and metazachlor with the SWAT model. *Journal of Environment Quality*, *43*(1), 75–85.

Fohrer, N., & Schmalz, B. (2012). Das UNESCO Ökohydrologie-Referenzprojekt Kielstau-Einzugsgebiet - nachhaltiges Wasserressourcenmanagement und Ausbildung im ländlichen Raum. *Hydrologie und Wasserbewirtschaftung*, *56*(4), 160–168. https://doi.org/10.5675/HyWa_2012,4_1

Fohrer, N., Schmalz, B., Tavares, F., & Golon, J. (2007). Modelling the landscape water balance of mesoscale lowland catchments considering agricultural drainage systems (in German). *Hydrologie und Wasserbewirtschaftung*, *51*(4), 164–169.

Gupta, H. V., Kling, H., Yilmaz, K. K., & Martinez, G. F. (2009). Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. *Journal of Hydrology*, *377*, 80–91.

Her, Y., & Jeong, J. (2018). SWAT+ versus SWAT2012: Comparison of sub-daily urban runoff simulations. *Transactions of the ASABE*, *61*(4), 1287–1295.

Hesse, C., Krysanova, V., Päzolt, J., & Hattermann, F. F. (2008). Eco-hydrological modelling in a highly regulated lowland catchment to find measures for improving water quality. *Ecological Modelling*, *218*(1–2), 135–148.

Kiesel, J., Fohrer, N., Schmalz, B., & White, M. J. (2010). Incorporating landscape depressions and tile drainages of a northern German lowland catchment into a semi-distributed model. *Hydrological Processes*, *24*(11), 1472–1486.

Kiprotich, P., Wei, X., Zhang, Z., Ngigi, T., Qiu, F., & Wang, L. (2021). Assessing the impact of land use and climate change on surface runoff response using gridded observations and SWAT+. *Hydrology*, *8*(1), 48. https://doi.org/10.3390/hydrology8010048

Koch, S., Bauwe, A., & Lennartz, B. (2013). Application of the SWAT model for a tile-drained lowland catchment in north-eastern Germany on subbasin scale. *Water Resources Management*, *27*, 791–805. https://doi.org/10.1007/s11269-012-0215-x

Krause, S., Bronstert, A., & Zehe, E. (2007). Groundwater-surface water interactions in a north German lowland floodplain—Implications for the river discharge dynamics and riparian water balance. *Journal of Hydrology*, *347*, 404–417.

Lei, C., Wagner, P. D., & Fohrer, N. (2019). Identifying the most important spatially distributed variables for explaining land use patterns in a rural lowland catchment in Germany. *Journal of Geographical Sciences*, *29*(11), 1788–1806.

Liu, W., Park, S., Bailey, R. T., Molina-Navarro, E., Andersen, H. E., Thodsen, H., Nielsen, A., Jeppesen, E., Jensen, J. S., Jensen, J. B., & Trolle, D. (2020). Quantifying the streamflow response to groundwater abstractions for irrigation or drinking water at catchment scale using SWAT and SWAT–MODFLOW. *Environmental Sciences Europe*, *32*, 1–25.

LKN. (2021). Landesbetrieb für Küstenschutz, Nationalpark und Meeresschutz Schleswig-Holstein. Discharge data for the gauge Soltfeld.

Lupon, A., Ledesma, J. L. J., & Bernal, S. (2018). Riparian evapotranspiration is essential to simulate streamflow dynamics and water budgets in a Mediterranean catchment. *Hydrology and Earth System Sciences*, *22*, 4033–4045. https://doi.org/10.5194/hess-22-4033-2018

LVermA. (2006). *Digitales Geländemodell für Schleswig-Holstein, Gitterweite 5 m x 5 m (DGM5) basierend auf LiDAR-Daten*. Landesvermessungsamt Schleswig-Holstein.

MELUND (Ministerium für Energiewende, Landwirtschaft, Umwelt, Natur und Digitalisierung). (2021). *Winderatter See - Charakteristische Daten*. http://www.umweltdaten.landsh.de/db/dbnuis?thema=see&seenummer=0448

Molina-Navarro, E., Bailey, R. T., Andersen, H. E., Thodsen, H., Nielsen, A., Park, S., Jensen, J. S., Jensen, J. B., & Trolle, D. (2019). Comparison of abstraction scenarios simulated by SWAT and SWAT-MODFLOW. *Hydrological Sciences Journal*, *64*, 1–21. https://doi.org/10.1080/02626667.2019.1590583

Moriasi, D. N., Arnold, J. G., Liew, M. W. V., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, *50*, 885–900.

Nkwasa, A., Chawanda, C. J., Msigwa, A., Komakech, H. C., Verbeiren, B., & van Griensven, A. (2020). How can we represent seasonal land use dynamics in SWAT and SWAT+ models for African cultivated catchments? *Water*, *12*(6), 1541. https://doi.org/10.3390/w12061541

Pfannerstill, M., Bieger, K., Guse, B., Bosch, D., Fohrer, N., & Arnold, J. G. (2017). How to constrain multi-objective calibrations of the SWAT model using water balance components. *Journal of the American Water Resources Association*, *53*(3), 532–546.

Pfannerstill, M., Guse, B., & Fohrer, N. (2014). A multi-storage groundwater concept for the SWAT model to emphasize nonlinear groundwater dynamics in lowland catchments. *Hydrological Processes*, *28*(22), 5599–5612.

Ryan, J. A., Ulrich, J. M.. (2020). *xts: eXtensible Time Series*. R package version 0.12.1. https://CRAN.R-project.org/package=xts

Schilling, K. E., & Helmers, M. (2008). Effects of subsurface drainage tiles on streamflow in Iowa agricultural watersheds: Exploratory hydrograph analysis. *Hydrological Processes*, *22*(23), 4497–4506. https://doi.org/10.1002/hyp.7052

Schmalz, B., Bieger, K., & Fohrer, N. (2008). A method to assess instream water quality – The role of nitrogen entries in a north German rural lowland catchment. *Advances in Geosciences*, *18*, 37–41. https://doi.org/10.5194/adgeo-18-37-2008

Schmalz, B., Tavares, F., & Fohrer, N. (2008). Modelling hydrological processes in mesoscale lowland river basins with SWAT–capabilities and challenges. *Hydrological Sciences Journal*, *53*, 989–1000.

Senent-Aparicio, J., George, C., & Srinivasan, R. (2021). Introducing a new post-processing tool for the SWAT+ model to evaluate environmental flows. *Environmental Modelling & Software*, *136*, 104944.

Shafii, M., Craig, J. R., Macrae, M. L., English, M. C., Schiff, S. L., Van Cappellen, P., & Basu, N. B. (2019). Can improved flow partitioning in hydrologic models increase biogeochemical predictability? *Water Resources Research*, *55*, 2939–2960. https://doi.org/10.1029/2018WR024487

Shi, P.-J., Yuan, Y., Zheng, J., Wang, J.-A., Ge, Y., & Qiu, G.-Y. (2007). The effect of land use/cover change on surface runoff in Shenzhen region, China. *Catena*, *69*(1), 31–35.

Smith, D. R., King, K. W., Johnson, L., Francesconi, W., Richards, P., Baker, D., & Sharpley, A. N. (2015). Surface runoff and tile drainage transport of phosphorus in the Midwestern United States. *Journal of Environmental Quality*, *44*, 495–502. https://doi.org/10.2134/jeq2014.04.0176

Soetaert, K., & Petzoldt, T. (2010). Inverse modelling, sensitivity and Monte Carlo analysis in R using package FME. *Journal of Statistical Software*, *33*, 1–28.

Sun, X., Bernard-Jannin, L., Grusson, Y., Arnold, J. G., Srinivasan, R., Sauvage, S., & Sanchez Pérez, J. M. (2016). Assessment of the surface water - groundwater exchange and shallow aquifer denitrification in the floodplain area using the SWAT-LUD model. *Hydrological Processes*, *30*(2), 187–202.

Thompson, A. L., Baffaut, C., Lohani, S., Duriancik, L. F., Norfleet, M. L., & Ingram, K. (2020). Purpose, development, and synthesis of the Soil Vulnerability Index for inherent vulnerability classification of cropland soils. *Journal of Soil and Water Conservation*, *75*(1), 1–11. https://doi.org/10.2489/jswc.75.1.1

Ulrich, U., Lange, J., Pfannerstill, M., Loose, L., & Fohrer, N. (2019). Hydrological tracers, the herbicide metazachlor and its transformation products in a retention pond during transient flow conditions. *Environmental Science and Pollution Research*, *26*(26), 26706–26720.

Ulrich, U., Pfannerstill, M., Ostendorp, G., & Fohrer, N. (2021). Omnipresent distribution of herbicides and their transformation products in all water body types of an agricultural landscape in the North German Lowland. *Environmental Science and Pollution Research*, *28*, 44183–44199.

UNESCO. (2011). *Ecohydrology for sustainability*, 24 https://unesdoc.unesco.org/ark:/48223/pf0000210826

van Tol, J., Bieger, K., & Arnold, J. G. (2021). A hydropedological approach to simulate streamflow and soil water contents with SWAT+. *Hydrological Processes*, *35*(6), e14242.

Vyse, S., Taie Semiromi, M., Lischeid, G., & Merz, C. (2020). Characterizing hydrological processes within kettle holes using stable water isotopes in the Uckermark of northern Brandenburg, Germany. *Hydrological Processes*, *34*, 1868–1887.

Wagner, P. D., Hoermann, G., Schmalz, B., & Fohrer, N. (2018). Characterisation of the water and nutrient balance in the rural lowland catchment of the Kielstau (in German). *Hydrologie und Wasserbewirtschaftung*, *62*(3), 145–158.

Wu, J., Yen, H., Arnold, J. G., Yang, Y. E., Cai, X., White, M. J., Santhi, C., Miao, C., & Srinivasan, R. (2020). Development of reservoir operation functions in SWAT+ for national environmental assessments. *Journal of Hydrology*, *583*, 124556.

Yen, H., Park, S., Arnold, J. G., Srinivasan, R., Chawanda, C. J., Wang, R., Feng, Q., Wu, J., Miao, C., Bieger, K., Daggupati, P., van Griensven, A., Kalin, L., Lee, S., Sheshukov, A. Y., White, M. J., Yuan, Y., Yeo, I.-Y., Zhang, M., & Zhang, X. (2019). IPEAT+: A built-in optimization and automatic calibration tool of SWAT+. *Water*, *11*(8), 1681. https://doi.org/10.3390/w11081681

Zajíček, A., Kvítek, T., Kaplická, M., Doležal, F., Kulhavý, Z., Bystřický, V., & Žlábek, P. (2011). Drainage water temperature as a basis for verifying drainage runoff composition on slopes. *Hydrological Processes*, *25*, 3204–3215.

Zambrano-Bigiarini, M., 2020. *hydroGOF: Goodness-of-fit functions for comparison of simulated and observed hydrological time series*, R package version 0.4-0, https://github.com/hzambran/hydroGOF, https://doi.org/10.5281/zenodo.839854.

Zeileis, A., & Grothendieck, G. (2005). Zoo: S3 infrastructure for regular and irregular time series. *Journal of Statistical Software*, *14*(6), 1–27. https://doi.org/10.18637/jss.v014.i06

How to cite this article: Wagner, P. D., Bieger, K., Arnold, J. G., & Fohrer, N. (2022). Representation of hydrological processes in a rural lowland catchment in Northern Germany using SWAT and SWAT+. *Hydrological Processes*, *36*(5), e14589. https://doi.org/10.1002/hyp.14589