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Cientific Paper

Hydrological modeling in a rural catchment in Germany

Cristiano André Pott[1]
Nicola Fohrer[2]

Abstract

The use of ecohydrological modeling in studies of water balance, sediment and nutrient load is increasing worldwide. Important in modeling is a good calibration and validation of the model in order to use it as a tool to study land use change. The aim of this study is to calibrate and validate the model Soil and Water Assessment Tool (SWAT) and to estimate the main components of river discharge in a rural lowland catchment. 462 km² of the upper part of the Stör catchment, located in Northern Germany was investigated. The results of modeling showed a good performance for calibration and validation of daily discharge at three gauging stations of the upper Stör catchment. SWAT calibration shows that discharge components are represented by 34.3% of drainage, 52.8% of groundwater flow, 7.7% of lateral flow and 5.2% of surface runoff in this rural lowland catchment.
Key words: SWAT model, calibration, validation, lowland watershed.

Resumo

Modelagem hidrológica em uma bacia hidrográfica rural na Alemanha

O uso de modelagem eco hidrológica em estudos de balanço hídrico, descarga de sedimentos e de nutrientes tem aumentado em todo o mundo. Importante na modelagem é a calibração e validação do modelo para que possa ser usado como ferramenta de estudo de mudança de cenários de uso e manejo. O objetivo deste estudo é calibrar e validar o modelo SWAT (Soil and Water Assessment Tool) e estimar os principais componentes da vazão do rio em uma bacia de planície rural. Foi investigada uma área de 462 km² da parte superior da bacia hidrográfica do rio Stör, localizada no norte da Alemanha. Os resultados da modelagem revelaram boa performance da calibração e validação da vazão diária do rio em três estações de medição da bacia Stör superior. De acordo com o modelo SWAT, os componentes da vazão são representados por 34,3% de fluxo de drenagem, 52,8% de fluxo de águas subterrâneas, de 7,7% de fluxo lateral e 5,2% de fluxo de escoamento superficial de água nesta bacia hidrográfica de planície.
Palavra Chave: Modelo SWAT, calibração, validação, bacia hidrográfica de planície.

Resumen

Modelaje hidrológico en una cuenca hidrográfica rural en Alemania

El uso de modelado eco-hidrológico en estudios de balance hídrico, descarga de sedimentos y de nutrientes ha aumentado en todo el mundo. Importante en el modelado es la calibración y validación del modelo para que pueda ser utilizado como herramienta de estudio de cambio de escenarios de uso y manejo. El objetivo de este estudio es calibrar y validar el modelo SWAT (Soil and WaterAssessment Tool) y estimar los principales componentes del caudal del río en una cuenca de llanura rural. Se investigó un área de 462 km² de la parte superior de la cuenca hidrográfica del río Stör, ubicada en el norte de Alemania. Los resultados de la modelaje revelaron un buen desempeño de la calibración y validación del flujo diario del río en tres

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[1] Eng. Agrônomo. Dr. Prof Depto Agronomia. Universidade Estadual do Centro Oeste-UNICENTRO - Rua Simeão Camargo Varela de Sá, 03, Bairro Cascavel, Guarapuava - PR, 85040-080. Email: cpott@unicentro.br

[2] Dra. Prof. Institute for Natural Resource Conservation, Christian-Albrechts-University, Kiel, Germany. Email: nfohrer@hydrology.uni-kiel.de

estaciones de medición de la cuenca Stör superior. De acuerdo con el modelo SWAT, los componentes del caudal son representados por el 34,3% de flujo de drenaje, el 52,8% de flujo de agua subterránea, el 7,7% de flujo lateral y el 5,2% de flujo superficial de agua en esta cuenca hidrográfica de llanura.
Palabras clave: Modelo SWAT, calibración, validación, cuenca hidrográfica de tierras bajas.

Introduction

Lowland river systems and their catchments are typical ecosystems with small amplitude in altitude, low flow velocity, high groundwater table and a substantial share of typical organic soils (HESSE et al., 2008). Artificial drainage systems like tile drainage and open ditches change the natural water balance and influence the instream water quality due to a faster nutrient transport (SCHMALZ et al., 2007). The hydrological cycle of lowland areas is governed by the close interaction of surface water dynamics and the corresponding directly connected shallow groundwater aquifer. Runoff generation processes, as well as the extent and spatial distribution of the interaction between surface water and groundwater, are controlled by floodplain topography and by surface water dynamics (KRAUSE e BRONSTERT, 2007).

The SWAT model (ARNOLD et al., 1998) is an ecohydrological model development by the US Department of Agriculture (USDA) Agricultural Research Service. The SWAT model is applied in various watersheds of the world (GASSMAN et al., 2007; BIEGER et al., 2012; BAKER e MILLER, 2013). The SWAT components include weather, hydrology, erosion/sedimentation, plant growth, nutrients, pesticides, agricultural management, stream routing and pond/reservoir routing (ARNOLD e FOHRER, 2005).

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The objective of this study was to calibrate and validate the SWAT model and to simulate the rivers components with the SWAT model that influence the river discharge in a rural lowland catchment.

Material and methods

The study area

The river Stör, a tributary of the river Elbe is located in the lowland area of Schleswig-Holstein in Northern Germany (Figure 1). In this study, 462 km² of the upper part of the Stör catchment up to the gauge Willenscharen were under investigation, because the lower part is already influenced by the tide of the North Sea. The topography is very flat and varies between 90 and 1 m above sea level. The main tributaries of the upper Stör are Aalbek, Buckener Au, Bünzener Au, Dosenbek, Höllenau and Schwale.

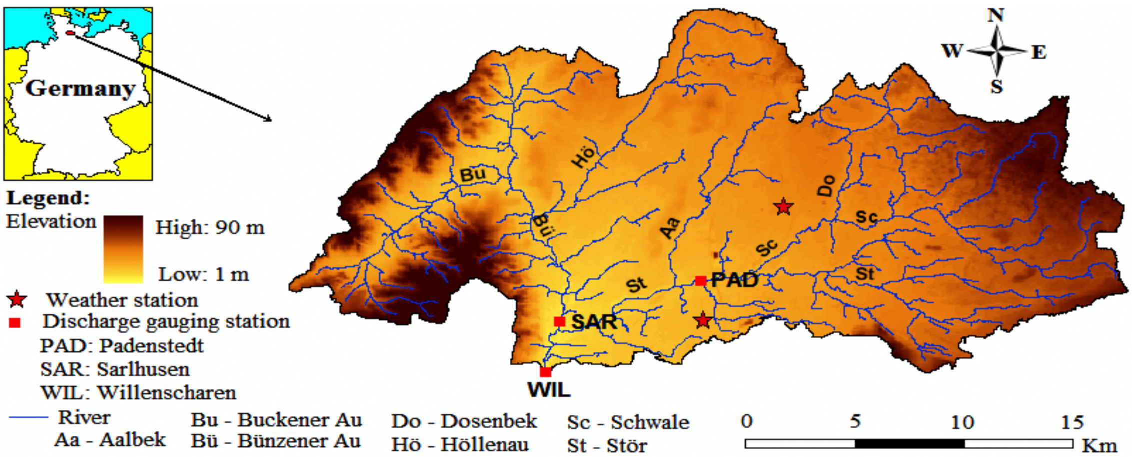

Figure 1. Location of the upper Stör catchment, its main tributaries and the localization of the discharge gauging Stations.

The main soils in the upper Stör catchment are Histosol (13%), Gley (12%), Gley-Podsol (20%), Cambisol (4%), Podsol (32%), Planosol (12%) and Luvisol (7%) (FINNERN, 1997). The mean annual precipitation is 851 mm and the mean annual temperature 8.2ºC at the Padenstedt and Neumünster weather station (DWD, 2012). Land use is dominated by arable land and pasture. According to OPPELT et al. (2011), in 2010 the pasture area was represented by 33%. The major crops used in agricultural areas are winter wheat (14%), rapeseed (2%) and corn for silage (27%) (OPPELT et al., 2011). The urban area represents about 10% of the total area. The most important city is Neumünster with nearly 88 thousand citizens.

River water flow

In this study, daily discharge data set from 1991 until 2011 was used from three gauging stations located in the upper Stör catchment (LKN, 2012). One is the Padenstedt gauging station where the discharge of the river Stör is measured at the Padenstedt village (PAD at Figure 1). Another gauge used in this study is the Sarlhusen gauging station located at the mouth of the Bünzener Au tributary at the Sarlhusen village (SAR at Figure 1). The third gauging station is located at the Willenscharen village (WIL at Figure 1) and represents the outlet of the study area.

SWAT modeling

In this study, the software ArcSWAT2009 (version 2009.93.7b Revision Nr. 488) was used to simulate water discharge. It is a SWAT interface for ESRI ArcGIS 9.3.1 SP2 (http://swat.tamu.edu). In this study, water discharge was simulated in daily time steps. The model represents the large-scale spatial heterogeneity of the study area by dividing the watershed into subbasins. The subbasins are then further subdivided into hydrologic response units (HRUs) based on homogeneous soils, land use and slopes (NEITSCH et al., 2011). The hydrologic cycle in the SWAT (ARNOLD et al., 1998) is based on the water balance equation (Equation 1):

1)

$$= SW_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_{\alpha} - W_{seep} - Q \right.$$

where: SWt is the final soil water content (mm); SW0 is the initial soil water content on day i (mm); t is the time (days); Rday is the amount of precipitation on day i (mm); Qsurf is the amount of surface runoff on day i (mm); Ea is the amount of evapotranspiration on day i (mm).

Wseep is the amount of water entering the vadose zone from the soil profile on day i (mm); Qgw is the amount of return flow on day i (mm). Soil water processes include evaporation, surface runoff, infiltration, plant uptake, lateral flow and percolation to lower layers (ARNOLD et al., 1998; NEITSCH et al., 2011).

Performance of the model

The reliability of results from a model is based on performance of the calibration and validation. Calibration is the process of estimating model parameters by comparing model predictions (output) for a given set of assumed conditions with observed data for the same conditions. Validation involves running a model in a study period different of the calibration and using input parameters measured or determined during the calibration process (MORIASI et al., 2007). To evaluate the performance of a model, measured and simulated values need to be compared. Two methods were applied in parallel to calibrate the SWAT model. Firstly, the measured and simulated values were subjected to a graphical comparison, in addition, the adjustment by statistical analyses was assessed.

The most important statistical index parameters used in this study to evaluate the performance of the SWAT model were: Coefficient of determination (R^2) describes the degree of collinearity between simulated and measured data. R^2 ranges from 0 to 1, with higher values indicating less error variance. Equation 2 describes R^2. Nash-Sutcliffe efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance (NASH e SUTCLIFFE, 1970). NSE is calculated as shown in Equation 3. Percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (GUPTA et al., 1999). Zero is the optimal value for PBIAS. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias. PBIAS is calculated with Equation 4.

Root mean square error (RMSE) is an index statistic. However SINGH et al. (2004) developed the RMSE standard deviation observations (STDEV) ratio named RSR. RSR standardizes RMSE using the standard deviation observations and it combines both an error index. RSR is calculated as the ratio of the RMSE and STDEV of measured data, as shown in

5)

$$\frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}}{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - \overline{Y}^{obs}\right)^2}}$$

Equation 5.

2)

$$R^2 = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - \overline{Y}^{obs}\right)\left(Y_i^{sim} - \overline{Y}^{sim}\right)}{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - \overline{Y}^{obs}\right)^2}\sqrt{\sum_{i=1}^{n}\left(Y_i^{sim} - \overline{Y}^{sim}\right)^2}}\right]$$

3)

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - \overline{Y}^{obs}\right)^2}\right]$$

4)

$$PBIAS = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)\times 100}{\sum_{i=1}^{n}\left(Y_i^{obs}\right)}\right]$$

where: Yobs is the measured value; Ysim is the simulated value; is the arithmetical mean; n is the number of values.

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Table 1 shows the statistical index parameters ranked according to MORIASI et al. (2007) to determine the quality performance of the simulations.

Input data

The basic data sets required to set up the model inputs are: topographical map (LVERMA, 2008), soil map (FINNERN, 1997), land use map (OPPELT et al., 2011) and climatic data set (DWD, 2012). In this study, the SWAT model was subdivided in 21 subbasins and 1402 HRUs. The inclusion of drainage parameters in SWAT was based on information from VENOHR et al. (2005). Thus, drainage systems were included in the area of soils Histosol, Gley, Gley-podsol, Planosol and Luvisol in the areas of agriculture, pasture and forest on slopes of 0 to 2 %. The classification of the hydrologic soil group (HYDGRP) was ranked as suggested by NEITSCH et al. (2011).

Table 1. General performance rating for recommended statistics for discharge (Adapted from MORIASI et al., 2007).

Performance rating	RSR	NSE	PBIAS (%)
Very good	0≤RSR≤0.5	0.75<NSE≤1.0	PBIAS<±10
Good	0.5<RSR≤0.6	0.65<NSE≤0.75	±10≤PBIAS<±15
Satisfactory	0.6<RSR≤0.7	0.50<NSE≤0.65	±15≤PBIAS<±25
Unsatisfactory	RSR>0.7	NSE≤0.50	PBIAS≥±25

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Model calibration and validation

The standard procedure for the simulation is to use a period of time for the calibration and a subsequent time for validation. For this study, the calibration was carried out between Jan. 1st 2006 - Dec. 31st 2011 and the validation period between Jan. 1st 2001 - Dec. 31st 2005. This division was due to fit the actual land use with the map dated from July 2010 (OPPELT et al., 2011) for the calibration period. Furthermore, it is important that the water balance (calibrated by the discharge) has a long time simulation. For all simulations, a period of five years warm up of the model was used, aiming to stabilize the main water and nutrient processes that occur in the SWAT model.

Results and discussion

The calibration and validation of daily discharge were successfully achieved as can be seen graphically in Figure 2 and Figure 3, respectively, as well as from the performance measures shown in Table 2. The measured and simulated daily discharge from the calibration period (Jan. 1st 2006 - Dec. 31st 2011) at the discharge gauge stations Padenstedt, Sarlhusen and Willenscharen are shown in Figure 2.

Daily discharge calibration showed an underestimation of simulated data at gauges Sarlhusen and Willenscharen, with lower peaks compared with the measured data set, specially in winter months. The underestimation of discharge in winter was also observed by SCHMALZ et al. (2007) and LAM et al. (2012) in rural lowland areas in northern Germany with SWAT modeling. Nevertheless, at the three gauge stations, the calibration period showed NSE and R^2 greater than 0.80, indicating a very good agreement between measured and simulated daily discharge (Table 2). Daily discharge validation (Jan. 1st 2000 - Dec. 31st 2005) was done for the same three discharge gauge stations, as can be seen in Figure 3. An underestimation of simulated data can be observed at the three discharge gauge stations (Figure 3) indicated by positive values of PBIAS (Table 2). Daily discharge validation was also carried out successfully, with NSE and R^2 greater than 0.79 and 0.80, respectively.

Daily discharge simulations using the SWAT model have reached success (SCHMALZ et al., 2008, LAM et al., 2010, KIESEL et al., 2010). Usually, in lowland catchments, the NSE is less than 0.80. LAM et al. (2010) using the SWAT model obtained a good agreement between simulated and measured daily discharge in the lowland Kielstau catchment in Schleswig-Holstein, Germany, with a NSE and R^2 of 0.75 and 0.78 for the calibration period and 0.78 and 0.84 for the validation period, respectively. In the same catchment, KIESEL et al. (2010) achieved a NSE of 0.78 for the daily calibration (1999-2003) and validation (2004-2009). The quality of input data is very important for obtaining success in modeling. A SWAT modeling of discharge in the upper Stör achieved NSE= 0.76 for the daily discharge calibration, using a DEM resolution map of 50 m (SCHMALZ and FOHRER, 2009). In this study, a DEM map with 5 m resolution was used. In a catchment with a total difference of 90 m of elevation (Figure 1), a high resolution data set can influence the final results. Thus, adequate performance of the model is due to the quality of data used to run the model as well the good performance of the calibration.

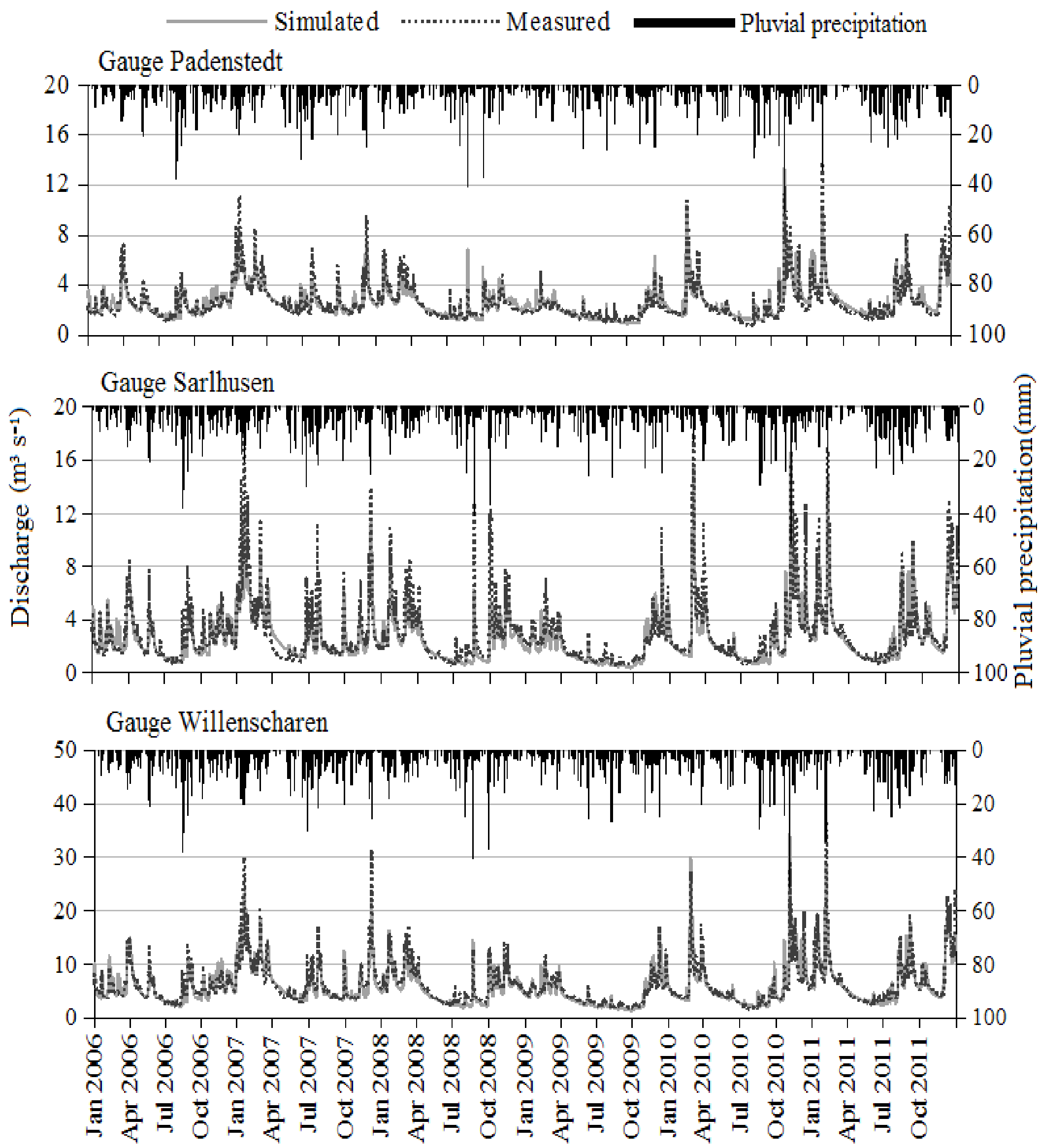

Figure 2. Measured and simulated daily discharge at the gauge stations Padenstedt, Sarlhusen and Willenscharen over the calibration period (2006-2011).

Table 2. Performance rating parameters of the daily discharge (Q) over the calibration and validation periods of the SWAT modeling.

Gauge	Q measured (m^3/s)	Q simulated (m^3/s)	R^2	NSE	PBIAS	RSR
			Calibration period (2006-2011)			
Padenstedt	2.52	2.58	0.85	0.84	-2.2	0.39
Sarlhusen	2.82	2.64	0.84	0.83	6.7	0.42
Willenscharen	5.99	5.92	0.86	0.86	1.1	0.38
			Validation period (2000-2005)			
Padenstedt	2.57	2.48	0.82	0.79	3.4	0.46
Sarlhusen	2.52	2.47	0.86	0.85	2.3	0.38
Willenscharen	5.97	5.61	0.84	0.83	6.1	0.41

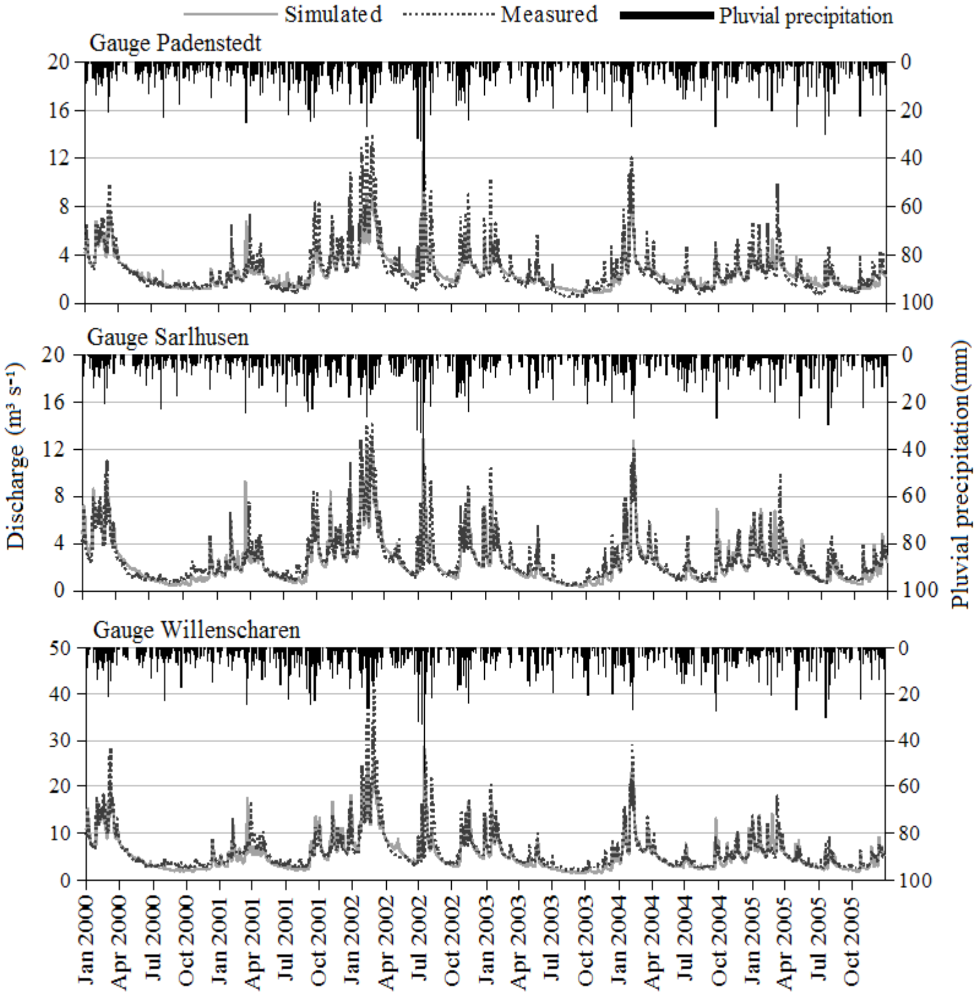

Figure 3. Measured and simulated daily discharge at the gauge stations Padenstedt, Sarlhusen and Willenscharen over the validation period (2000-2005).

After successful validation of the Integrated Modelling of Water Balance and Nutrient Dynamics (IWAN) for the lower Havel River basin (mean NSE = 0.82), KRAUSE and BRONSTERT (2007) applied the model for quantitative water balance analyses at the Havel River basin in Germany.

LI et al. (2016) using the Hydrological Interference Model (HIM) obtained R^2 and NSE of 0.93 and 0.93 for the calibration and 0.73 and 0.66 for the validation, respectively. BAKER and MILLER (2013) achieved NSE result for the annual calibration plot of 0.93 and the regression coefficient of determination (R2) of 0.95. They don't measured a validation period in a East African watershed.

BIEGER et al. (2013) obtained NSE = 0.69 and 0.68 for the calibration and validation, respectively for Xiangxi Catchment in China. These authors became R2 of 0.71 and 0.69, for the calibration and validation, respectively, and PBIAS = 9.1 for the validation and PBIAS = 3.6.

SHAO et al. (2013) using the SWAT model during to predict stream flows.

The R2 values were between 0.69 and 0.83, for the calibration and 0.72 to 0.81 for the validation period. NSE were between 0.41 and 0.82 for the validation and 0.24 to 0,78 for the validation in four sub-watersheds in the USA.

After the good performance of the SWAT model, the main processes were calculated by the SWAT model and are graphically represented in Figure 4, which are predominantly influenced by groundwater (52.8 %) and drainage flow (34.3%). Surface runoff and lateral flow contributed only with 5.2 and 7.7 % to the flow discharge at the outlet of the upper Stör catchment (Willenscharen).

LAM et al (2011), also studying in a lowland catchment, verified that the groundwater flow (57.4%) and drainage flow (22.2%) were dominant components from river discharge. Schmalz et al. (2009) add that these pathways are very important because of the high interaction between surface water and the shallow groundwater, while the surface runoff was very low due to the topography.

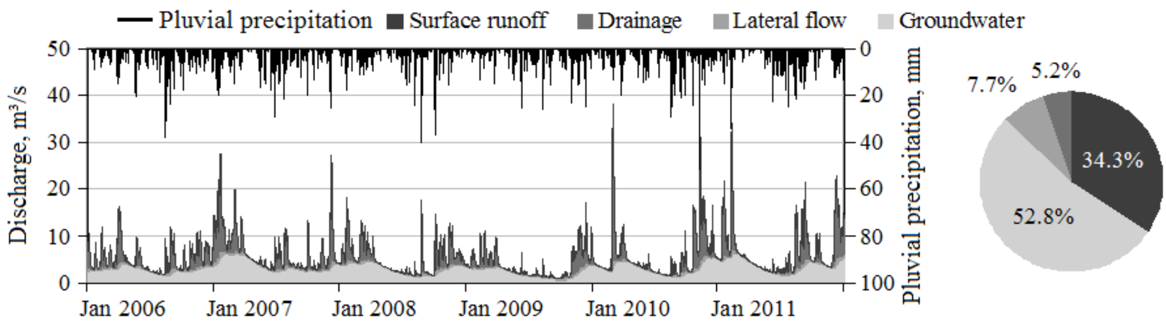

Figure 4. Graphic representation of discharge components calculated by SWAT model during the calibration period at the gauge station Willenscharen.

Conclusions

Daily discharge was successfully calibrated and validated in the three gauging stations in the upper Stör catchment with the SWAT model.

The SWAT model stressed the importance of drainage (34.3%) and groundwater flow (52.8%) compared to other flow components. Lateral flow (7.7%) and surface runoff (5.2%) are the hydrological components that less affect the river discharge in this lowland catchment.

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