Hydrol. Earth Syst. Sci., 19, 4365–4376, 2015
www.hydrol-earth-syst-sci.net/19/4365/2015/
doi:10.5194/hess-19-4365-2015

Hydrology and Earth System Sciences
Open Access

Process verification of a hydrological model using a temporal parameter sensitivity analysis

M. Pfannerstill[1], **B. Guse**[1], **D. Reusser**[2], **and N. Fohrer**[1]

[1]Christian-Albrechts-University of Kiel, Institute of Natural Resource Conservation, Department of Hydrology and Water Resources Management, Kiel, Germany
[2]Potsdam Institute for Climate Impact Research, Potsdam, Germany

Correspondence to: M. Pfannerstill (mpfannerstill@hydrology.uni-kiel.de)

Received: 11 December 2014 – Published in Hydrol. Earth Syst. Sci. Discuss.: 5 February 2015
Revised: 4 October 2015 – Accepted: 7 October 2015 – Published: 29 October 2015

Abstract. To ensure reliable results of hydrological models, it is essential that the models reproduce the hydrological process dynamics adequately. Information about simulated process dynamics is provided by looking at the temporal sensitivities of the corresponding model parameters. For this, the temporal dynamics of parameter sensitivity are analysed to identify the simulated hydrological processes. Based on these analyses it can be verified if the simulated hydrological processes match the observed processes of the real world.

We present a framework that makes use of processes observed in a study catchment to verify simulated hydrological processes. Temporal dynamics of parameter sensitivity of a hydrological model are interpreted to simulated hydrological processes and compared with observed hydrological processes of the study catchment. The results of the analysis show the appropriate simulation of all relevant hydrological processes in relation to processes observed in the catchment. Thus, we conclude that temporal dynamics of parameter sensitivity are helpful for verifying simulated processes of hydrological models.

1 Introduction

Discharge, one of the major outputs of hydrological models, is controlled by a number of interacting processes. However, a simple comparison of observed and simulated discharge, which is often the only criterion used for model calibration and evaluation, does not take into account the underlying processes that shape the hydrograph. For a more profound assessment of the reliability of model results, a deeper understanding of how these processes are described in the model and a more detailed analysis of how well the corresponding real-world processes are represented are essential. To determine if the model behaviour is consistent with the hydrological processes observed in a catchment, the model structure, i.e. the model equations and parameters, needs to be considered when evaluating the model output (e.g. Gupta et al., 2008; Hrachowitz et al., 2014).

Model diagnostic analyses as proposed by Gupta et al. (2008) and Yilmaz et al. (2008) determine the appropriateness of process descriptions in the model structure. Thus, diagnostic methods help to detect failures in models and the corresponding components that need to be improved (Fenicia et al., 2008; Reusser and Zehe, 2011; Guse et al., 2014).

As stated by Yilmaz et al. (2008), a systematic approach to analysing the adequacy of model structures is needed, since the processes occurring in a catchment are not always represented appropriately within hydrological models (Clark et al., 2011). There is a need to assess if the model structures and the simulated processes are consistent with observed hydrological processes within the catchment (Gupta et al., 2012). This is a step towards establishing a general framework for model accuracy verification (Wagener et al., 2001; Yilmaz et al., 2008).

The analysis of parameter sensitivity is an established method for identifying and comparing the effects of changes in model parameter values on the model output (e.g. van Griensven et al., 2006; Nossent et al., 2011; Guse et al., 2014; Haas et al., 2015). As summarised by Razavi et al. (2015), parameter sensitivity analyses aim at examining various aspects such as the impact of certain parameters on the model output or similarity between the functioning of the model and the hydrologic system it describes.

Temporal parameter sensitivity analyses detect periods in which a certain parameter or a set of parameters controls the model output (e.g. Massmann et al., 2014). This information can be obtained by TEmporal Dynamics of PArameter Sensitivity (TEDPAS, Sieber and Uhlenbrook, 2005; Reusser et al., 2011; Guse et al., 2014; Haas et al., 2015).

In contrast to other temporally resolved sensitivity analyses, which were applied on performance metrics (van Werkhoven et al., 2009; Herman et al., 2013), TEDPAS detects dominant model parameters by analysing their sensitivity on the modelled discharge in a high temporal resolution. Thereby, it helps to explain the model's behaviour by detecting the temporal dominance of individual model components. Reusser et al. (2009) used TEDPAS in combination with TIGER, a temporal model performance analysis (Reusser et al., 2009), to characterise the types of errors in the output of hydrological models (e.g. the simulation of discharge). Wagener et al. (2003) analysed parameter variations over time to reproduce observed hydrological data. Both approaches have in common that they focus on the link between model performance and deficiencies of the model structure. However, the capabilities of TEDPAS for examining model structures have not been fully exploited yet.

Typical patterns of temporal parameter sensitivity can provide information about simulated hydrological processes. This approach is based on the fact that hydrological processes and discharge phases vary temporally and hence also the dominance of model components (Boyle et al., 2000, 2001; Wagener et al., 2003, 2009; Reusser et al., 2011; Garambois et al., 2013; Guse et al., 2014).

In this context, Guse et al. (2014) used TEDPAS and TIGER to detect which component of a hydrological model was responsible for poorly simulated baseflow in dry years. Although the temporal variability of the parameter sensitivity was reasonable, the model performed poorly for several performance metrics in phases of groundwater dominance (Guse et al., 2014). Based on this temporal diagnostic analysis, Pfannerstill et al. (2014a) modified the aquifer structure of the model to emphasise non-linear dynamics of the groundwater processes. The analysis of Pfannerstill et al. (2014b) showed that the modification improved the simulation of the discharge with respect to different performance metrics. However, an analysis of the hydrological processes and their representation by the model structure is required to prove that the simulation of discharge was improved for the right reasons (Kirchner, 2006).

Therefore, this study aims at developing a method that verifies appropriate process simulation of hydrological models using TEDPAS and observed hydrological processes of the study catchment. Based on an application example, we propose a general framework for the verification of hydrological consistency of models that is in principal applicable to any model in any catchment.

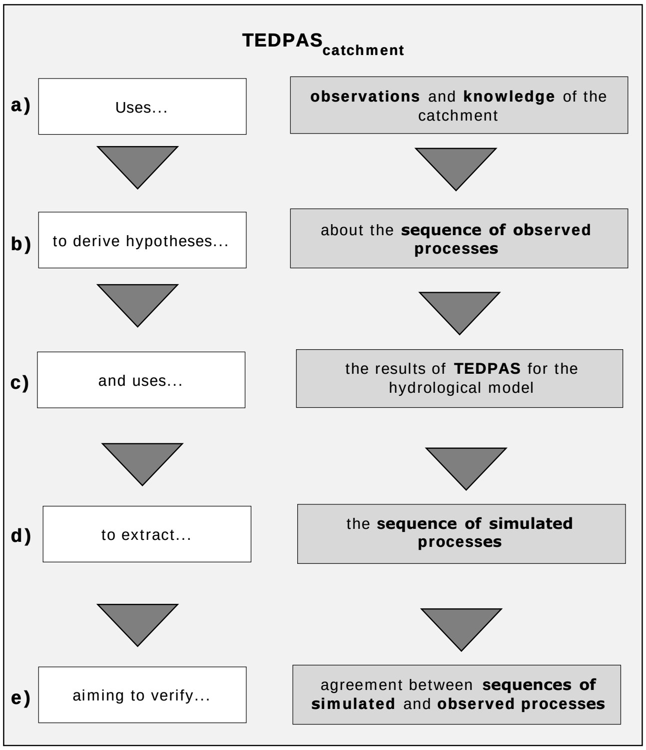

Figure 1. General idea of TEDPAS$_{\text{catchment}}$ as a verification framework. The framework integrates processes observed in the catchment **(a)** to derive hypotheses about the temporal sequence of observed processes **(b)** and the calculation of temporal parameter sensitivities with TEDPAS, **(c)** to extract the temporal sequence of simulated processes **(d)** for the investigated hydrological model. The verification of the model is performed by comparing the temporal sequences of observed and simulated processes **(e)**.

We demonstrate how to (i) use observed hydrological processes of a catchment for (ii) comparison with TEDPAS results to (iii) verify that processes are adequately simulated by a hydrological model.

2 Methods

The general idea of the proposed framework is to make use of processes observed within the catchment and results of TEDPAS to verify hydrological models (Fig. 1). For this, all available information about processes occurring in the study catchment is collected (Fig. 1a). These processes are then ordered according to the timing of their occurrence, which is controlled by seasonal hydrological conditions. Hypotheses about assumed process dynamics are formulated based on this temporal sequence of observed processes (Fig. 1b).

Temporal parameter sensitivity analyses aim at detecting the similarity between the hydrological model and its underlying system (Razavi et al., 2015), which is in this case described by hydrological processes observed in the catchment. Since TEDPAS is used to provide information about the model behaviour, there is no need for previous model calibration. In principle, the central aim of TEDPAS is not to provide direct information of how to define model parameters in a calibration of a hydrological model, but rather to derive information about the behaviour of model parameters over time (Fig. 1c). The temporal dynamics of parameter sensitivity are used to draw inferences to hydrological processes. In a similar manner, the temporal sequence of simulated processes is derived from the timing of simulated hydrological processes (Fig. 1d).

Since the sequences of observed and simulated processes both describe the timing of hydrological processes, they are directly comparable to each other. An appropriate simulation of the hydrological processes is then verified by comparing the temporal sequences of observed and simulated processes (Fig. 1e). Consequently, the hydrological consistency in representing the whole hydrological system is investigated (e.g. Martinez and Gupta, 2011; Euser et al., 2013). In the following, the individual methods that are part of the proposed framework are described in detail.

2.1 Processes observed in the catchment

To achieve hydrologically consistent model results, the model should be able to simulate all relevant hydrological processes of the study catchment. Therefore, knowledge about observed hydrological processes is crucial to evaluate the hydrological consistency of the model results. For this, all available information available from previous field studies and general knowledge about hydrological characteristics of the study catchment needs to be collected (Fig. 1a). This information is then used to identify all relevant hydrological processes of the study catchment and the timing of their occurrence.

2.2 Derived hypotheses

The knowledge about processes observed in the catchment is translated into information that is comparable with processes simulated by the model. For this, qualitative hypotheses about seasonal process occurrences, process dynamics and specific hydrological situations observed in the catchment are formulated (Fig. 1b). Each hypothesis incorporates knowledge such as the activity of tile drainages, the seasonal groundwater contribution to the total discharge or the impact of soil water dynamics on surface runoff. However, it has to be emphasised that the incorporated hydrological information needs to be derived from observed data of the catchment (Fig. 1a). In this way, real-world processes are considered for the verification framework.

2.3 TEDPAS methods

TEDPAS was selected to provide the temporal sequence of simulated processes for comparison to the temporal sequence of observed processes (Fig. 1c). As shown in recent studies for several models with different complexity (Gupta et al., 2008; Yilmaz et al., 2008; Herbst et al., 2009; Reusser et al., 2009; van Werkhoven et al., 2009; Garambois et al., 2013; Herman et al., 2013; Pfannerstill et al., 2014b; Guse et al., 2014; Haas et al., 2015), a high temporal resolution is essential for proper diagnostic model evaluation. TEDPAS aims at improving the understanding of model dynamics and identifying temporal dynamics of parameter sensitivity. For each time step, the sensitivity of changes in the values of different parameters to the model output (e.g. discharge) is calculated (cf. Reusser et al., 2009; Guse et al., 2014). The presented framework for a TEDPAS-based verification aims at providing insights into the modelled hydrological system in a high temporal resolution by using the widely available daily discharge. However, TEDPAS is generally applicable with or without measured data.

The temporal parameter sensitivities on the discharge are provided by TEDPAS and related to hydrological processes. It is assumed that the parameter sensitivity represents the hydrological process that is described by process equations of the model and the corresponding parameters (Fig. 1c). Accordingly, the temporal dynamics of parameter sensitivity can be attributed to the temporal dynamics of hydrological processes and the dominant model processes for different periods of time can be determined (Sieber and Uhlenbrook, 2005; Cloke et al., 2008; Reusser et al., 2011).

The presented study focuses on the factor prioritisation setting to identify dominant model processes (Saltelli et al., 2006). These processes can be related to parameters that are dominant for the analysed time series (Reusser and Zehe, 2011). The first-order partial variance is estimated to determine a measure of sensitivity (Saltelli et al., 2006). Parameters are simultaneously modified during partial variance estimations. Thereby, TEDPAS investigates how a variation in model parameter values influences the variance of the model output (Eq. 1, from Reusser and Zehe, 2011). In contrast to other sensitivity analysis methods, TEDPAS uses the direct model output instead of performance metrics, i.e. the deviation between simulated and measured discharge. The first-order partial variance is calculated by dividing the changes due to a specific parameter with the total variance V that is described by all model runs (Reusser and Zehe, 2011). For all parameters, the first-order partial variance is summed up. Because of parameter interactions the sum of all partial variances fluctuates between 0 and 1, but cannot be higher than 1.

$$V = \sum_i V_i + \sum_{i<j} V_{ij} + \cdots + V_{1,2,3,\cdots,n} \tag{1}$$

V is the total variance, V_i is the variance due to changes in parameter θ_i (first-order variance), V_{ij} is the covariance caused by changes in θ_i and θ_1 (second-order variance), and $V_{1,2,3,\ldots,n}$ represents higher-order terms.

As shown by Saltelli et al. (2006), Nossent et al. (2011), Reusser and Zehe (2011), Sudheer et al. (2011), Herman et al. (2013), Massmann et al. (2014), the (extended) Fourier Amplitude Sensitivity Test (FAST) and Sobol's method are applicable to determine the effect of parameter interactions. In this study, the FAST method was used. The FAST method considers non-linearities as an important factor in hydrology (Cukier et al., 1973, 1975, 1978) and has a high computational efficiency. In contrast with other methods such as Sobol's, the number of required model runs is lower, which is of particular relevance for complex models (Saltelli and Bolado, 1998; Reusser and Zehe, 2011). Since this algorithm has been implemented in the R-package FAST (Reusser, 2012), all analyses were made within the R environment. Readers are referred to Reusser and Zehe (2011) for further details.

2.4 Identification of simulated processes with TEDPAS

The presented framework $\text{TEDPAS}_{\text{catchment}}$, which is used for the verification of models, is based on the main assumption that the provided information about high parameter sensitivity in a certain time period indicates the dominance of the corresponding model component (Fig. 1d). Parameters with a strong impact on the selected model output are assumed to be relevant for the process description in the model and can be related to model components. The provided diagnostic information is then used for $\text{TEDPAS}_{\text{catchment}}$.

2.5 Model verification by combining hypotheses and TEDPAS

TEDPAS provides the temporal sequence of simulated processes for comparison with the hypotheses about the temporal sequence of observed processes. Consequently, the results of TEDPAS are used to verify an accurate process implementation. The hypotheses are accepted in the case of agreement between temporal sequence of simulated and observed processes (Fig. 1e). Consequently, hydrological consistency is assumed since real-world processes are reproduced appropriately.

3 Framework application example

3.1 Catchment description

The Kielstau catchment comprises an area of about 50 km^2 and is located in the federal state of Schleswig-Holstein in north Germany. It is a subbasin of the Treene catchment to which TEDPAS has previously been applied by Guse et al. (2014) and Haas et al. (2015). The catchment is characterised by a maritime climate with a mean annual precipitation of 918.9 mm and mean annual temperature of 8.2 °C (station: Gluecksburg–Meierwik, period: 1961–1990; DWD, 2012).

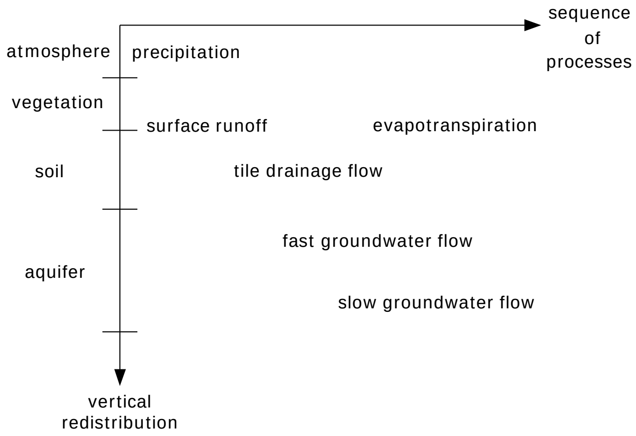

Figure 2. Schema of the timing of processes after a precipitation event based on the concept of vertical water redistribution.

As reported by Kiesel et al. (2010), the catchment has a high water retention potential. Due to the flat topography (27 to 78 m above mean sea level), the water tables are very high in this region (Kiesel et al., 2010) and a high fraction of the agricultural area is drained (Fohrer et al., 2007). The installed tile drainages contribute to fast runoff and consequently increase peak flows, especially in winter (Kiesel et al., 2010). Decreasing tile drainage flow is observed from April and May before tile drainage flow stops during the relatively dry summer months (Kiesel et al., 2009).

Another main characteristic of the Kielstau catchment is the close interaction between river and groundwater, which is due to high groundwater water tables that are directly connected to the river (Schmalz et al., 2008). The near-surface groundwater is controlled by precipitation, especially in winter (Schmalz et al., 2008). A more detailed description of the catchment can be found in Fohrer and Schmalz (2012).

3.2 Hypotheses derived from observed processes

The processes observed in the catchment are used in combination with the concept of vertical water redistribution (Yilmaz et al., 2008) to derive hypotheses about the temporal sequence of observed processes (Table 1). The vertical redistribution of water between faster and slower runoff components after excess rainfall is one of the primary functions of the watershed system (Yilmaz et al., 2008). Accordingly, we distinguish between the different processes of surface runoff, tile drainage flow, fast (primary) and slow (secondary) groundwater flow and evapotranspiration (Fig. 3).

Based on the findings of Kiesel et al. (2010) for the study catchment and Fig. 2, it is hypothesised that the magnitude and timing of surface runoff is relevant during the whole year whenever the amount of precipitation exceeds the soil infiltration capacity (H1: surface runoff upon rainfall).

The amount of water that does not run off on the surface infiltrates into the soil and is stored for a limited time

Table 1. Hypotheses for model verification, derived from theory of vertical water redistribution and hydrological processes observed within the catchment.

Abbreviation	Description	Source
H1	surface runoff upon rainfall	vertical water redistribution
H2	tile drainage flow in winter	observation in catchment
H3	seasonality of groundwater flow	observation in catchment
H4	fast groundwater flow at high discharge	vertical water redistribution
H5	delayed groundwater flow at baseflow	vertical water redistribution
H6	evaporation at resaturation	observation in catchment, vertical water redistribution

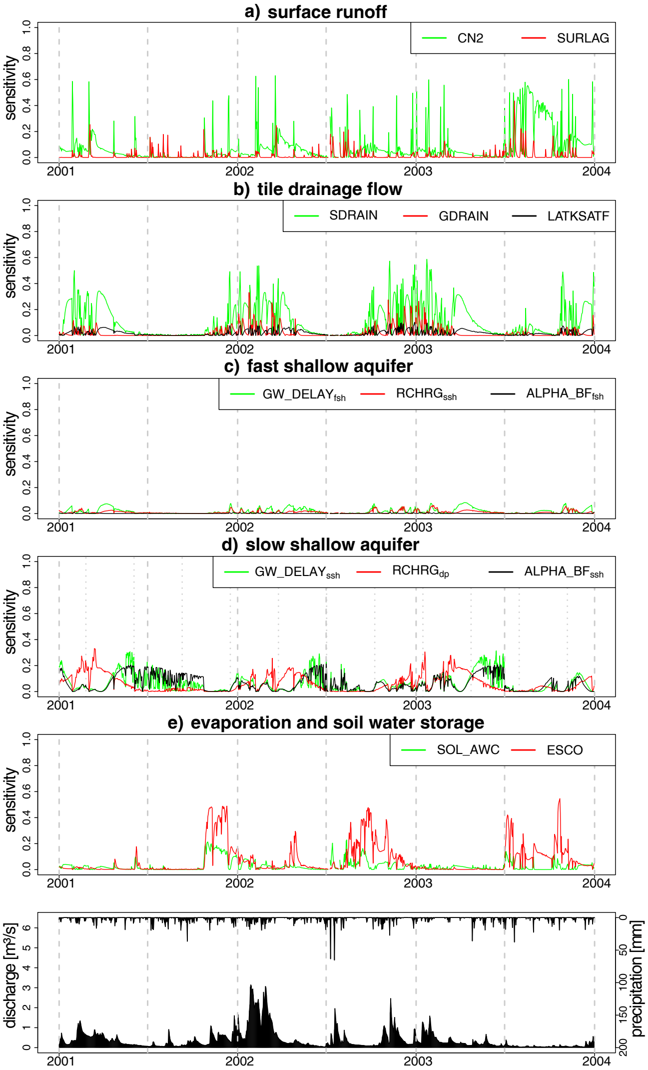

Figure 3. Temporal parameter sensitivities for all analysed model parameters from 2001 to 2004. Based on the processes they control, the parameters are grouped into surface runoff **(a)**, tile drainage flow **(b)**, process dynamics of the fast shallow aquifer **(c)** and the slow shallow aquifer **(d)**, evaporation, and soil water storage **(e)**. The bottom plot shows the observed discharge and precipitation.

depending on the soil water storage capacity. As shown by Kiesel et al. (2009, 2010) and Schmalz et al. (2008), the storage capacity in the catchment is directly connected with tile drainage and groundwater dynamics. In winter, groundwater tables are high, which results in a high potential for groundwater extraction through the tile drainages (Kiesel et al., 2010). Based on the observations of Kiesel et al. (2009), tile drainage flow is expected to cause peak flows in winter due to groundwater ponding and a high soil water content. Consequently, we hypothesise that the tile drainage flow is highly relevant in winter and of minor importance in summer (H2: tile drainage flow in winter).

High groundwater tables are one of the most important hydrological characteristics in the study catchment. During winter periods, the groundwater dynamics are mainly controlled by precipitation inputs due to a direct hydraulic connection between groundwater and the river (Schmalz et al., 2008). In summer, the extent of groundwater–surface water interactions decreases, but groundwater storage remains the main contributor of flow to the river (Schmalz et al., 2008). Based on these assumptions, we hypothesise a high relevance of fast groundwater flow in winter and high relevance of the slow groundwater flow in the beginning of summer (H3: seasonality of groundwater flow).

More specifically, recharge from the quickly reacting aquifer is high during high discharge periods in winter. This fast groundwater recharge leads to increasing dominance of the outflow from this aquifer at decreasing high discharge (H4: fast groundwater flow at high discharge). At the beginning of the recession, the delayed recharge is expected to be the main process controlling the discharge generation (H5: slow groundwater contribution at baseflow).

Since Kiesel et al. (2009) observed that tile drainage flow decreases during April and May before tile drainages run completely dry in the summer period, we expect decreasing relevance for these particular periods. Also, due to the climatic conditions in the Kielstau catchment, the summer periods are characterised by dry soil layers and extraction of soil water by vegetation (Kiesel et al., 2010). As a consequence, groundwater recharge is very limited and the dominance of the groundwater decreases in this season. Based on this observation, we hypothesise high relevance of the soil water storage capacity and the soil evaporation compensation in dry summer months until the beginning of resaturation phases in autumn (H6: evaporation at resaturation).

3.3 TEDPAS application

TEDPAS was applied to a hydrological model to obtain temporal parameter sensitivities, which are used to derive information about the timing of specific hydrological processes. Based on this, a temporal sequence of simulated processes is derived. In the following, the hydrological model and the application of TEDPAS is described in detail.

3.3.1 Model description and setup

In our study, TEDPAS was applied to the semi-distributed, ecohydrological SWAT model (Arnold et al., 1998). The SWAT model uses distinct spatial positions for the subbasins within the catchment. Within the subbasins, Hydrological Response Units (HRU) are used to describe areas of the same land use, slope and soil. The different components of the SWAT model have an empirical and process-oriented character. Due to the incorporation of several model components, there is a high number of parameters, which strongly increases the complexity of the SWAT model (Cibin et al., 2010).

The water balance is driven mainly by the processes of precipitation, evapotranspiration, runoff, soil water percolation, drainage and groundwater flow. Runoff is routed through the main reaches of the subbasins to the catchment outlet. A detailed description of process implementation and the theory about the SWAT model can be found in Neitsch et al. (2011).

Catchment-specific input data are required to set up the model, including a soil map (resolution 1 : 200 000, BGR, 1999) and a digital elevation model (resolution 5 m; LVermA, 1995). The data on land use and crop rotations used in this study were derived from two mapping campaigns during the cropping seasons 2011/2012 and 2012/2013 (Pfannerstill et al., 2014a, b). The spatial distribution of tile drainages and databases for soil and crops were obtained from Fohrer et al. (2013, 2007).

Precipitation data were provided by the Gluecksburg–Meierwik weather station located north of the Kielstau catchment (DWD, 2012). Additional weather input that is based on regional interpolation (Oesterle, 2001) was used to fill gaps of data that are needed. In this study, interpolated data of wind speed, temperature, solar radiation, and humidity were used to fill data gaps.

During model setup, 36 subbasins and 2214 HRUs, which were determined using three slope classes (< 2.6, 2.6–4.6 and > 4.6 %), were defined with the ArcSWAT interface (version 2012.10.1.6). For the application of the TEDPAS-based model verification, the SWAT$_{3S}$ version (Pfannerstill et al., 2014a) with its modified groundwater structure was used. Therefore, the groundwater input files were reprocessed using a script in the R environment (R Core Team, 2013) to add the additional groundwater input parameters required by SWAT$_{3S}$.

3.3.2 Model simulations

Model simulations were carried out to obtain a basis for the analysis with TEDPAS. To achieve equilibrium for the different storages of the model, a warm-up period from 1997 to 2000 was chosen. The temporal sensitivity analysis was performed for the hydrological years of 2001 to 2004. TEDPAS provided the dynamics of temporal parameter sensitivity for the analysed model. The model parameters (Table 2) and their ranges were selected according to previous SWAT model studies (Pfannerstill et al., 2014a; Guse et al., 2014, 2015). Based on the parameter variation set that was generated with FAST (Reusser, 2012), TEDPAS required 687 model runs.

After performing all model runs, TEDPAS provides a temporal sequence of simulated processes that is based on the parameter sensitivity. The sensitivity of parameters was assigned to the processes of surface runoff, tile drainage flow, groundwater flow, evaporation, and soil water storage. These simulated processes and its interpretation to a temporal sequence of simulated processes are the core results of TEDPAS for the model verification.

3.4 Process verification of SWAT$_{3S}$ with TEDPAS$_{\text{catchment}}$

The agreement between the temporal sequences of observed and simulated processes is determined by comparing both sequences with each other. The temporal sequence of processes observed in the study catchment is described with hypotheses that were formulated based on information about the hydrological processes occurring in the catchment. The temporal model parameter sensitivities that are provided by TEDPAS are used to analyse the timing of hydrological processes and to identify the temporal sequence of simulated processes. Finally, both temporal sequences are compared to verify the model results with respect to processes observed in the study catchment.

4 Description and discussion of the results

TEDPAS was used to determine the temporal sequence of simulated processes by analysing the temporal sensitivities of the different model parameters (Fig. 3). The results show that the impact of the different parameters on discharge changed remarkably over time (Fig. 3). To determine the agreement between the temporal sequences of observed and simulated processes, the results of TEDPAS shown in Fig. 3 were analysed in detail for each parameter. For this, we selected appropriate time periods for each model parameter and averaged model output of hydrological components to test

Table 2. Selection of parameters and their ranges for the temporal sensitivity analyses. The three methods to change parameter values used are replacement (r), multiplication (m), and addition/subtraction (as). The parameters are assigned to the hydrological process they control including surface runoff (SR), soil water storage (SW), drainage flow (DF), evapotranspiration (ETP), and groundwater flow (GW)

Parameter name	Abbreviation	Process	Range	Type
Curve number	CN2	SR/SW	−15–15	as
Surface runoff lag coefficient	SURLAG	SR	0.2–4.0	r
Available soil water capacity	SOL_AWC	SW	−0.07–0.10	as
Tile drain lag time	GDRAIN	DF	0.5–2.0	m
Distance between two tile drains	SDRAIN	DF	10 000–45 000	r
Multiplication factor for K_e	LATKSATF	DF	0.6–2.0	r
Soil evaporation compensation	ESCO	ETP	0.5–1.0	r
Delay of fast shallow aquifer	GW_DELAY$_{\mathrm{fsh}}$	GW	1–15	r
Recession of fast shallow aquifer	ALPHA_BF$_{\mathrm{fsh}}$	GW	0.3–1	r
Percolation into slow shallow aquifer	RCHRG$_{\mathrm{ssh}}$	GW	0.65–0.80	r
Delay of slow shallow aquifer	GW_DELAY$_{\mathrm{ssh}}$	GW	15–60	r
Recession of slow shallow aquifer	ALPHA_BF$_{\mathrm{ssh}}$	GW	0.0001–0.3000	r
Percolation into deep aquifer	RCHRG$_{\mathrm{dp}}$	GW	0.1–0.4	r

the derived hypotheses against the temporal parameter sensitivity (Fig. 4).

The impact of the model parameters controlling surface runoff (SURLAG and CN2) was observed during discharge peaks throughout the year (Fig. 4). The model component for simulated surface runoff is the first component to become sensitive during a rainfall event, which confirms hypothesis H1. The temporal sequence of observed processes in the study catchment, which was based on the observations of Kiesel et al. (2010), is confirmed by the sensitivity of the two parameters, which is clearly linked to short peak flow events and single surface runoff events (Figs. 3 and 4). Additionally, it is clearly shown that these events are connected to high amounts of daily precipitation.

All other parameters showed a characteristic temporal parameter sensitivity, which depends on the discharge magnitude and the moisture conditions. The impact of tile drainages (GDRAIN, SDRAIN, and LATKSATF) was very low in phases of low discharge during summer and especially high in winter (Fig. 4). This finding verifies hypotheses H1 and H2: tile drainages are inactive when groundwater tables, which do not rise during the short and low precipitation events in summer periods, are low. The most pronounced dynamic of sensitivity and influence on the discharge was observed during wet periods in winter and spring (Fig. 4), when rising water tables are expected due to sufficient precipitation.

The low impact of the tile drainages during low flow periods can be further explained by the groundwater dominance, which is the next step in the temporal sequence of observed processes that is described by the concept of vertical water redistribution (see Fig. 2). The high impact of groundwater on discharge for the studied lowland catchment is particularly visible at the beginning and the end of the long-lasting low flow periods, which confirms hypothesis H3.

Additionally, there is a clear separation for the relevance of the fast and the slow shallow aquifers. The time delay for recharge of the fast shallow aquifer (GW_DELAY$_{\mathrm{fsh}}$) becomes less relevant when the influence of the time delay parameter of the slow shallow aquifer (GW_DELAY$_{\mathrm{ssh}}$) increases. This result clearly depicts the fast shallow aquifer recharge at high discharge with fast groundwater contribution (ALPHA_BF$_{\mathrm{fsh}}$), followed by a delayed slow shallow aquifer recharge at recession phases with slow groundwater contribution (ALPHA_BF$_{\mathrm{fsh}}$, H3, H4, H5). Consequently, the low flow during dry periods is controlled by flow from the slow shallow aquifer to the channel (Fig. 4). This finding supports hypothesis H3, which expects a high relevance of the slow shallow aquifer parameters in the beginning of the low flow period in summer but low relevance in winter.

In general, the fast shallow aquifer had very limited impact on the discharge, because the tile drainage flow controls the water amount recharging the groundwater. Consequently, the process of fast discharge generation in winter is controlled by both the tile drainage flow and the fast shallow aquifer (Fig. 4). This was partly expected, since the parameters of the fast shallow aquifer were hypothesised to be mainly relevant in winter (H4). Due to the low parameter sensitivity of the fast shallow aquifer, hypothesis H4 is partly verified. However, the modelled discharge contribution of tile drainages and the fast shallow aquifer indicates simultaneous activity of both hydrological processes.

The partitioning of recharge of the slow shallow and the deep aquifer (RCHRG$_{\mathrm{dp}}$) was particularly important at the beginning of recession phases (Figs. 3 and 4), because it controls the water amount available for groundwater flow. According to the model structure, the total amount of recharge to the slow shallow and deep aquifers is affected by the partitioning of the recharge in the fast shallow aquifer. The more water recharges the fast shallow aquifer, the less is avail-

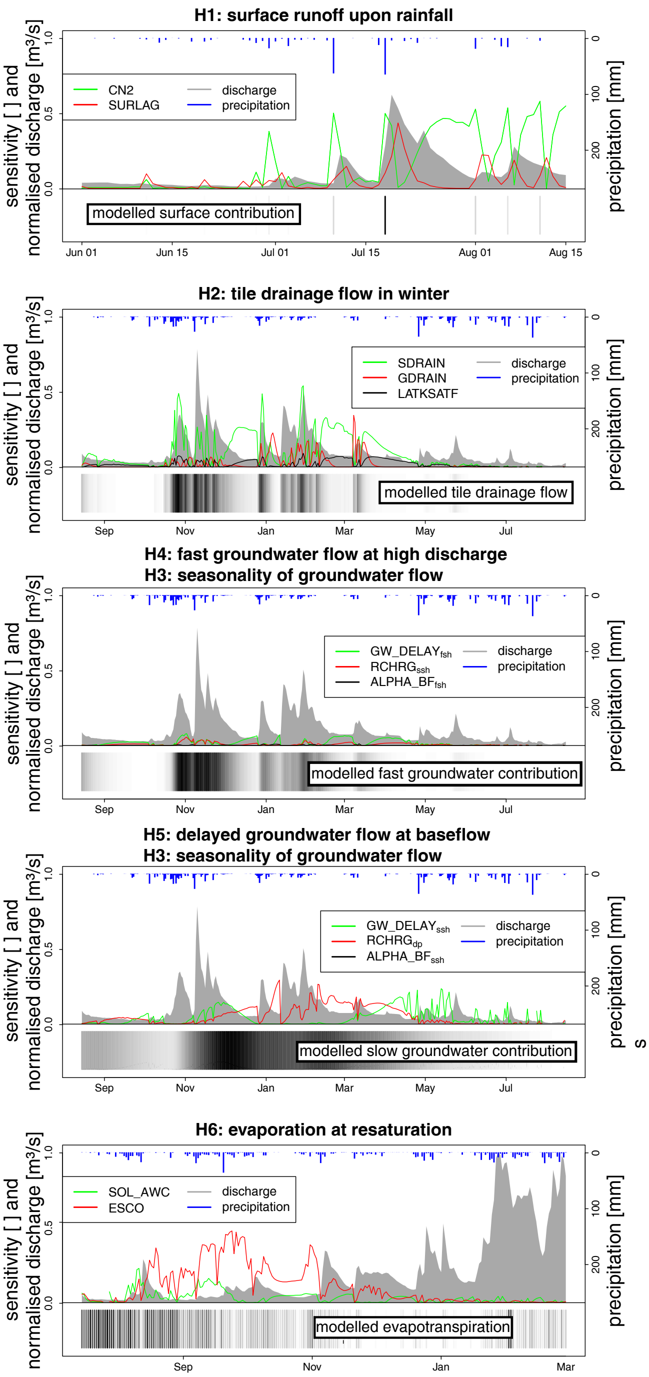

Figure 4. Periods of temporal parameter sensitivities for the verification of hypotheses about surface runoff (H1), tile drainage flow (H2), the process dynamics of the fast shallow aquifer (H3, H4) and the slow shallow aquifer (H3, H5), evaporation, and soil water storage (H6). The normalised observed discharge and the precipitation are shown for each subplot. Additionally, the modelled hydrological output is averaged and normalised to show the range between low (white) and high (black) intensity.

able for the slow shallow and the inactive deep aquifer. This behaviour is consistent with the observed processes of the study catchment as the recharge to the fast shallow aquifer is intended to be more important during wet phases with fast groundwater recharge (H3, H4). In contrast, the slow shallow aquifer controls the slow recharge before recession phases (H3, H5).

The processes expected to become relevant last according to the concept of vertical water redistribution (Fig. 2) are the storage function of the soils and evaporation. The evaporation and soil water availability parameters (ESCO and SOL_AWC) are most relevant during low flow periods in late summer and during phases of resaturation in the beginning of autumn (Figs. 3 and 4). During these periods, the influence of all other processes is very limited. This highlights the relevance of additional storages besides the aquifers for the generation of baseflow in dry periods. Since the parameter sensitivities of the groundwater component are very low in these periods, hypothesis H6 is verified (Fig. 4).

The verified temporal sequence of processes proves the hydrological consistency of the simulated processes. However, additional information about the model's behaviour may be used to support this finding. For this, we refer to previous studies of Pfannerstill et al. (2014b). In these studies, Pfannerstill et al. (2014b) clearly showed the ability of SWAT$_{3S}$ to reproduce the daily discharge for the study catchment. With respect to timing and dynamics, SWAT$_{3S}$ showed satisfactory model performance for the calibration and validation periods (Fig. 5). In addition, Pfannerstill et al. (2014b) validated the reproduction of discharge magnitudes for the validation and calibration periods by extracting information about the ability of SWAT$_{3S}$ to realistically simulate hydrologic characteristics for the study catchment (Fig. 6a and b).

In combination with the results of Pfannerstill et al. (2014b), the findings of this study confirm that SWAT$_{3S}$ is able to simulate the investigated hydrological processes adequately. This evidence is provided by satisfying model performance in simulating daily discharge dynamics and magnitudes and the appropriate simulation of process dynamics.

5 Relevance of TEDPAS for model verifications

TEDPAS is a central method for model diagnostics and the verification of models (Fig. 1). We developed TEDPAS$_{\text{catchment}}$, which is a verification framework that uses processes observed in a catchment in combination with TEDPAS. In the following, it is discussed if the presented verification framework provides useful diagnostic information for the verification of hydrological models.

In this study, we exemplify the analysis of a model in regard to the hydrological consistency and the hydrological processes within a catchment. The general application of this framework is discussed by abstracting our findings into a

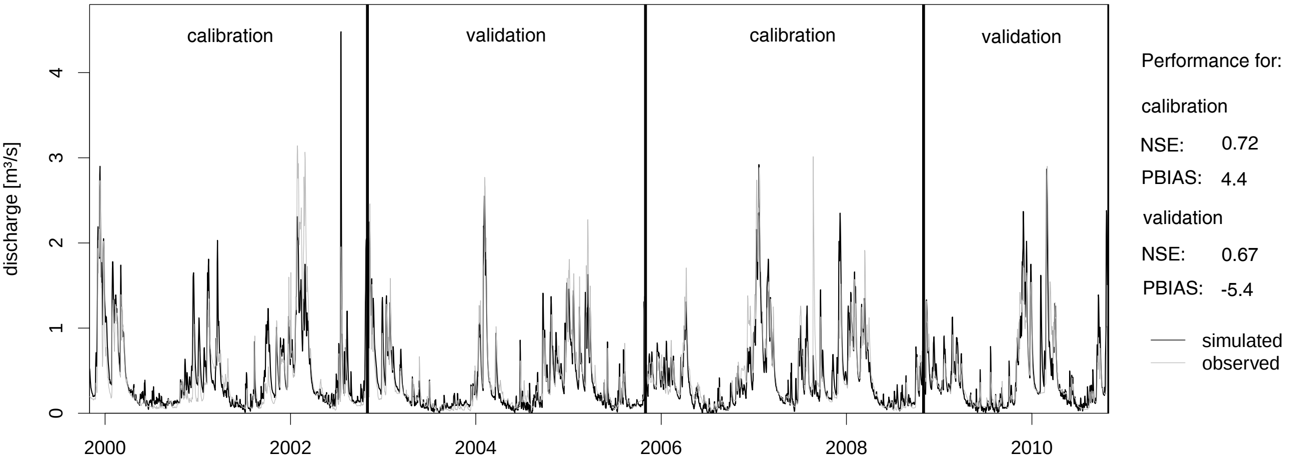

Figure 5. Daily observed (grey) and simulated (black) discharge for the study catchment with model performance (Nash–Sutcliffe efficiency (NSE) and percent bias (PBIAS)) for the calibration and validation period after Pfannerstill et al. (2014b).

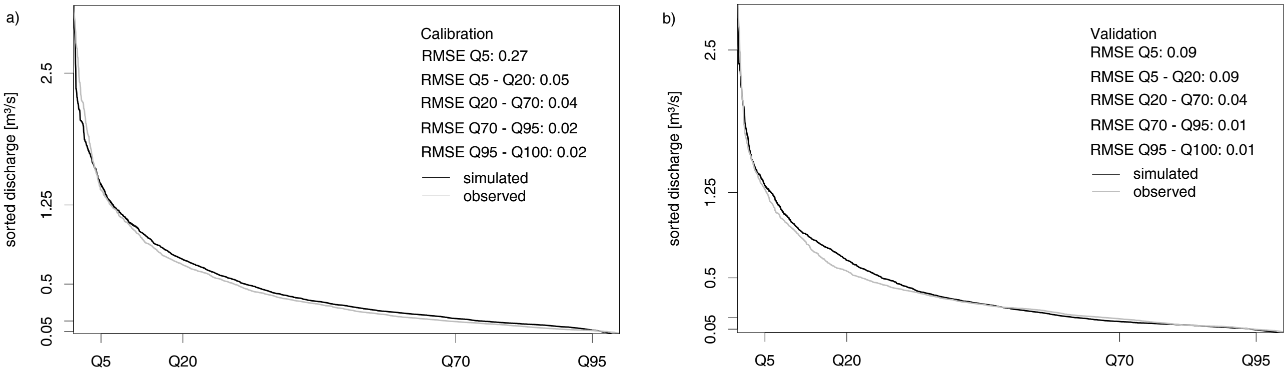

Figure 6. Flow duration curve of observed (grey) and simulated (black) discharge magnitudes for the calibration period **(a)** and the validation period **(b)**. The model performance is depicted with root-mean-square error (RMSE) of the different flow duration curve segments according to Pfannerstill et al. (2014b).

more general context. We hypothesise that $\text{TEDPAS}_{\text{catchment}}$ is applicable to any hydrological model in any catchment.

Our analysis of model results showed that there is the necessity to analyse the relevance of individual model parameters. In our study, we focused on hydrological processes that are identifiable at daily resolution, which facilitated the detection of the groundwater processes of the model (fast- and slow-reacting aquifer). Despite a clear separation of the two groundwater storages, the verification of dynamics for the fast aquifer was limited due to low parameter sensitivity of the fast groundwater model component. Nevertheless, all hypothesised processes were part of the temporal sequence of simulated processes. The case study results revealed a temporal sequence of simulated processes that is consistent with the processes observed in the study catchment and the concept of vertical water redistribution (Fig. 2). The temporal sequence of simulated processes exhibited the order with surface runoff as the first process, followed by tile drainage flow. Finally, this temporal sequence continues with fast groundwater flow and slow groundwater flow (Figs. 3 and 4). However, the low sensitivity of the parameters to the fast shallow aquifer limits the verification to a certain extent. Nonetheless, the temporal sequence of processes is identifiable. Consequently, the confirmation of the hydrological consistency is the core result of the diagnostic analysis. It indicates that the simplified process representation is in accordance with the concept of vertical process dynamics.

However, it has to be pointed out that the confirmation of a realistic temporal sequence of processes is just one side of the coin. In the context of hydrological consistency, the hydrological model should be also able to reproduce commonly available hydrological data (e.g. discharge). For this, we propose the combination of traditional model performance evaluation (as shown for the investigated model, Pfannerstill et al., 2014b) and the new verification framework presented in this study. Ideally, model performance evaluation and model verification should take all data available for a catchment into consideration.

In this study, TEDPAS$_{\text{catchment}}$ was applied using commonly available, daily observed discharge data. The high temporal resolution facilitated the diagnosis of the model structure and its ability to simulate the processes that were observed in the catchment. Thereby, TEDPAS provided additional diagnostic information to understand the representation of processes within the analysed model. Additionally, the presented example highlights the potential of TEDPAS$_{\text{catchment}}$ to evaluate the consistency of parameters and process structure using qualitative data. We used processes observed in the catchment, as well as the concept of vertical water redistribution (Fig. 2) to derive hypotheses for the model verification. Additional measured data would allow a more detailed quantitative evaluation but it has to be kept in mind that this kind of data is generally not available for large catchments.

Regardless of the kind and amount of available data, this study shows that TEDPAS is needed for the extraction of comprehensive model diagnostic information. The application of TEDPAS in our demonstration example revealed that the highest sensitivity of multiple parameters of different hydrological processes may occur simultaneously. This finding emphasises the importance of TEDPAS, which can be also used to identify the overlapping dominance of different model components and the corresponding hydrological processes.

6 Conclusions

The main capability of model diagnostics is the determination of the adequacy of process descriptions in model structures. In this study, we used TEDPAS as a verification method in model diagnostics. As shown in Fig. 1, we propose five aspects that need to be considered for model diagnostics and the verification of models.

The proposed framework for model verification requires (i) observations and knowledge about the catchment to (ii) derive hypotheses about the temporal sequence of observed processes. Contrary to processes observed in the catchment, TEDPAS is used to (iii) calculate temporal parameter sensitivities to (iv) extract the temporal sequence of simulated processes. Finally, the model verification is performed by (v) determining the agreement between the sequences of observed and simulated processes.

Based on our results, we propose TEDPAS as a method to provide relevant diagnostic information. TEDPAS is applied to analyse the temporal sequence of processes of all relevant hydrological processes.

The main outcomes of this study are as follows:

- TEDPAS$_{\text{catchment}}$ provides diagnostic information for the verification of the consistency between the temporal sequence of observed and simulated processes. The temporal sequence of observed processes is derived from qualitative knowledge of the catchment, and the concept of vertical water redistribution.
- TEDPAS provides the temporal sequence of simulated processes for comparison against the temporal sequence of observed processes.

We recommend the use of TEDPAS$_{\text{catchment}}$ as a verification framework for model diagnostics since it provides relevant information, which leads to an improved understanding of the relationship between model structure and the processes occurring in a catchment.

Acknowledgements. The Government-Owned Company for Coastal Protection, National Parks and Ocean Protection, provided the discharge data for this study. The digital elevation model and the river net were obtained from the land survey office of Schleswig-Holstein. We thank the German Weather Service (DWD) for providing the climate data and the Potsdam Institute for Climate Impact Research (PIK) for providing the STAR data.

Many thanks to Katrin Bieger (Blackland Research & Extension Center, Texas A&M AgriLife) for the proofreading of various manuscript versions. We are thankful to the Erwin Zehe, Shervan Gharari, and the anonymous reviewer for their insightful comments. The paper greatly benefitted from their comments.

Matthias Pfannerstill was supported by a scholarship of the German Environmental Foundation (DBU). The DFG-funded project GU 1466/1-1 (hydrological consistency in modelling) supported the work of Björn Guse. Dominik Reusser was supported by the BMBF via its initiative Potsdam Research Cluster for Georisk Analysis, Environmental Change and Sustainability (PROGRESS – grant: 03IS2191B). We want to thank the community of the open-source software R, which was used for the calibration of the SWAT model and following analysis.

Edited by: E. Zehe

References

Arnold, J. G., Srinivasan, R., Muttiah, R. S., and Williams, J. R.: Large area hydrologic modeling and assessment part I: Mmodel development, J. Am. Water Resour. As., 1, 73–89, doi:10.1111/j.1752-1688.1998.tb05961.x, 1998.

BGR: Bundesanstalt fuer Geowisschenschaften und Rohstoffe – Bodenuebersichtskarte im Maßstab 1 : 200.000, Verbreitung der Bodengesellschaften, 1999.

Boyle, D. P., Gupta, H. V., and Sorooshian, S.: Toward improved calibration of hydrologic models: Combining the strengths of manual and automatic methods, Water. Resour. Res., 36, 3663–3674, doi:10.1029/2000wr900207, 2000.

Boyle, D. P., Gupta, H. V., Sorooshian, S., Koren, V., Zhang, Z., and Smith, M.: Toward improved streamflow forecasts: Value of semidistributed modeling, Water. Resour. Res., 37, 2749–2759, doi:10.1029/2000WR000207, 2001.

Cibin, R., Sudheer, K. P., and Chaubey, I.: Sensitivity and identifiability of stream flow generation parameters of the SWAT model, Hydrol. Process., 24, 1133–1148, doi:10.1002/hyp.7568, 2010.

Clark, M. P., McMillan, H. K., Collins, D. B. G., Kavetski, D., and Woods, R. A.: Hydrological field data from a modeller's perspective: Part 2: process-based evaluation of model hypotheses, Hydrol. Process., 25, 523–543, doi:10.1002/hyp.7902, 2011.

Cloke, H., Pappenberger, F., and Renaud, J.-P.: Multi-method global sensitivity analysis (MMGSA) for modelling floodplain hydrological processes, Hydrol. Process., 22, 1660–1674, doi:10.1002/hyp.6734, 2008.

Cukier, R. I., Fortuin, C. M., Shuler, K. E., Petschek, A. G., and Schaibly, J. H.: Study of sensitivity of coupled reaction systems to uncertainties in rate coefficients. 1. Theory, J. Chem. Phys., 59, 3873–3878, doi:10.1063/1.1680571, 1973.

Cukier, R. I., Schaibly, J. H., and Shuler, K. E.: Study of sensitivity of coupled reaction systems to uncertainties in rate coefficients. 3. Analysis of approximations, J. Chem. Phys., 63, 1140–1149, doi:10.1063/1.431440, 1975.

Cukier, R. I., Levine, H. B., and Shuler, K. E.: Non-linear sensitivity analysis of multi-parameter model systems, J. Comput. Phys., 26, 1–42, doi:10.1016/0021-9991(78)90097-9, 1978.

DWD: Weather and climate data from the German Weather Service (DWD) of the station Flensburg (1961–1990), Online climate data, 2012.

Euser, T., Winsemius, H. C., Hrachowitz, M., Fenicia, F., Uhlenbrook, S., and Savenije, H. H. G.: A framework to assess the realism of model structures using hydrological signatures, Hydrol. Earth Syst. Sci., 17, 1893–1912, doi:10.5194/hess-17-1893-2013, 2013.

Fenicia, F., Savenije, H., and Winsemius, H.: Moving from model calibration towards process understanding, Phys. Chem. Earth, 33, 1057–1060, doi:10.1016/j.pce.2008.06.008, 2008.

Fohrer, N. and Schmalz, B.: Das UNESCO Oekohydrologie-Referenzprojekt Kielstau-Einzugsgebiet – Nachhaltiges Wasserressourcenmanagement und Ausbildung im laendlichen Raum, Hydrol. Wasserbewirts., 4, 160–168, doi:10.5675/HyWa_2012,4_1, 2012.

Fohrer, N., Schmalz, B., Tavares, F., and Golon, J.: Modelling the landscape water balance of mesoscale lowland catchments considering agricultural drainage systems, Hydrol. Wasserbewirts., 51, 164–169, 2007.

Fohrer, N., Dietrich, A., Kolychalow, O., and Ulrich, U.: Assessment of the Environmental Fate of the Herbicides Flufenacet and Metazachlor with the SWAT Model, J. Environ. Qual., 42, 1–11, doi:10.2134/jeq2011.0382, 2013.

Garambois, P. A., Roux, H., Larnier, K., Castaings, W., and Dartus, D.: Characterization of process-oriented hydrologic model behavior with temporal sensitivity analysis for flash floods in Mediterranean catchments, Hydrol. Earth Syst. Sci., 17, 2305–2322, doi:10.5194/hess-17-2305-2013, 2013.

Gupta, H. V., Wagener, T., and Liu, Y.: Reconciling theory with observations: Elements of a diagnostic approach to model evalution, Hydrol. Process., 22, 3802–3813, doi:10.1002/hyp.6989, 2008.

Gupta, H. V., Clark, M. P., Vrugt, J. A., Abramowitz, G., and Ye, M.: Towards a comprehensive assessment of model structural adequacy, Water Resour. Res., 48, W08301, doi:10.1029/2011WR011044, 2014.

Guse, B., Reusser, D. E., and Fohrer, N.: How to improve the representation of hydrological processes in SWAT for a lowland catchment – Temporal analysis of parameter sensitivity and model performance, Hydrol. Process., 28, 2651–2670, doi:10.1002/hyp.9777, 2014.

Guse, B., Pfannerstill, M., and Fohrer, N.: Dynamic modelling of land use change impacts on nitrate loads in rivers, Environ. Process., 1–18, doi:10.1007/s40710-015-0099-x, 2015.

Haas, M., Guse, B., Pfannerstill, M., and Fohrer, N.: Detection of dominant nitrate processes in ecohydrological modelling with temporal parameter sensitivity analysis, Ecol. Model., 314, 62–71, doi:10.1016/j.ecolmodel.2015.07.009, 2015.

Herbst, M., Gupta, H. V., and Casper, M. C.: Mapping model behaviour using Self-Organizing Maps, Hydrol. Earth Syst. Sci., 13, 395–409, doi:10.5194/hess-13-395-2009, 2009.

Herman, J. D., Reed, P. M., and Wagener, T.: Time-varying sensitivity analysis clarifies the effects of watershed model formulation on model behavior, Water Resour. Res., 49, 1400–1414, doi:10.1002/wrcr.20124, 2013.

Hrachowitz, M., Fovet, O., Ruiz, L., Euser, T., Gharari, S., Nijzink, R., Freer, J., Savenije, H., and Gascuel-Odoux, C.: Process consistency in models: The importance of system signatures, expert knowledge, and process complexity, Water Resour. Res., 50, 7445–7469, doi:10.1002/2014wr015484, 2014.

Kiesel, J., Schmalz, B., and Fohrer, N.: SEPAL – a simple GIS-based tool to estimate sediment pathways in lowland catchments, Adv. Geosci., 21, 25–32, doi:10.5194/adgeo-21-25-2009, 2009.

Kiesel, J., Fohrer, N., Schmalz, B., and White, M. J.: Incorporating landscape depressions and tile drainages of a northern German lowland catchment into a semi-distributed model, Hydrol. Process., 24, 1472–1486, doi:10.1002/hyp.7607, 2010.

Kirchner, J. W.: Getting the right answers for the right reasons: Linking measurements, analyses, and models to advance the science of hydrology, Water Resour. Res., 42, W03S04, doi:10.1029/2005WR004362, 2006.

LVermA: Landesvermessungsamt Schleswig-Holstein – Digitales Geländemodell fuer SchleswigHolstein. Quelle: TK25. Gitterweite 25 m × 25 m und TK50 Gitterweite 50 m × 50 m sowie ATKIS-DGM2-1 m × 1 m Gitterweite und DGM 5 m × 5 m Gitterweite, abgeleitet aus LiDAR-Daten, 1995.

Martinez, G. and Gupta, H.: Hydrologic consistency as a basis for assessing complexity of monthly water balance models for the continental United States: Hydrologic consistency and model complexity, Water Resour. Res., 47, W12540, doi:10.1029/2011WR011229, 2011.

Massmann, C., Wagener, T., and Holzmann, H.: A new approach to visualizing time-varying sensitivity indices for environmental model diagnostics across evaluation time-scales, Environ. Model. Softw., 51, 190–194, doi:10.1016/j.envsoft.2013.09.033, 2014.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., and Williams, J. R.: SWAT Theoretical Documentation Version 2009, Grassland, Soil and Water Research Laboratory, Agricultural Research Service, Blackland Research Center, Texas Agricultural Experiment Station, 2011.

Nossent, J., Elsen, P., and Bauwens, W.: Sobol' sensitivity analyses of a complex environmental model, Environ. Model. Softw., 26, 1515–1525, doi:10.1016/j.envsoft.2011.08.010, 2011.

Oesterle, H.: Reconstruction of daily global radiation for past years for use in agricultural models, Phys. Chem. Earth. Part B, 26, 253–256, doi:10.1016/S1464-1909(00)00248-3, 2001.

Pfannerstill, M., Guse, B., and Fohrer, N.: A multi-storage groundwater concept for the SWAT model to emphasize nonlinear groundwater dynamics in lowland catchments, Hydrol. Process., 28, 5599–5621, doi:10.1002/hyp.10062, 2014a.

Pfannerstill, M., Guse, B., and Fohrer, N.: Smart low flow signature metrics for an improved overall performance evaluation of hydrological models, J. Hydrol., 510, 447–458, doi:10.1016/j.jhydrol.2013.12.044, 2014b.

Razavi, S. and Gupta, H. V.: What do we mean by sensitivity analysis? The need for comprehensive characterization of "global" sensitivity in Earth and Environmental systems models, Water Resour. Res., 51, 3070–3092, doi:10.1002/2014WR016527, 2015.

R Core Team: R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing, 2013.

Reusser, D.: Implementation of the Fourier Amplitude Sensitivity Test (FAST), R-package, 0.61, 2012.

Reusser, D. E. and Zehe, E.: Inferring model structural deficits by analyzing temporal dynamics of model performance and parameter sensitivity, Water Resour. Res., 47, W07550, doi:10.1029/2010WR009946, 2011.

Reusser, D. E., Blume, T., Schaefli, B., and Zehe, E.: Analysing the temporal dynamics of model performance for hydrological models, Hydrol. Earth Syst. Sci., 13, 999–1018, doi:10.5194/hess-13-999-2009, 2009.

Reusser, D. E., Buytaert, W., and Zehe, E.: Temporal dynamics of model parameter sensitivity for computationally expensive models with FAST (Fourier Amplitude Sensitivity Test), Water Resour. Res., 47, W07551, doi:10.1029/2010WR009947, 2011.

Saltelli, A. and Bolado, R.: An alternative way to compute Fourier amplitude sensitivity test (FAST), Comput. Stat. Data Anal., 26, 445–460, doi:10.1016/S0167-9473(97)00043-1, 1998.

Saltelli, A., Ratto, M., Tarantola, S., and Campolongo, F.: Sensitivity analysis practices: Strategies for model-based inference, Reliab. Eng. Syst. Safe., 91, 1109–1125, doi:10.1016/j.ress.2005.11.014, 2006.

Schmalz, B., Springer, P., and Fohrer, N.: Interactions between near-surface groundwater and surface water in a drained riparian wetland, in: Proceedings of International Union of Geodesy and Geophysics XXIV General Assemble "A New Focus on Integrated Analysis of Groundwater/Surface Water Systems", Perugia, Italy, 11–13 July 2007, 21–29, IAHS Press, 2008.

Sieber, A. and Uhlenbrook, S.: Sensitivity analyses of a distributed catchment model to verify the model structure, J. Hydrol., 310, 216–235, doi:10.1016/j.jhydrol.2005.01.004, 2005.

Sudheer, K. P., Lakshmi, G., and Chaubey, I.: Application of a pseudo simulator to evaluate the sensitivity of parameters in complex watershed models, Environ. Model. Softw., 26, 135–143, doi:10.1016/j.envsoft.2010.07.007, 2011.

van Griensven, A., Meixner, T., Grundwald, S., Bishop, T., Diluzio, M., and Srinivasan, R.: A global sensitivity analysis tool for the parameters of multi-variable catchment models, J. Hydrol., 324, 10–23, doi:10.1016/j.jhydrol.2005.09.008, 2006.

van Werkhoven, K., Wagener, T., Reed, P., and Tang, Y.: Sensitivity-guided reduction of parametric dimensionality for multi-objective calibration of watershed models, Adv. Water Resour., 32, 1154–1169, doi:10.1016/j.advwatres.2009.03.002, 2009.

Wagener, T., Boyle, D. P., Lees, M. J., Wheater, H. S., Gupta, H. V., and Sorooshian, S.: A framework for development and application of hydrological models, Hydrol. Earth Syst. Sci., 5, 13–26, doi:10.5194/hess-5-13-2001, 2001.

Wagener, T., McIntyre, N., Lees, M., Wheater, H., and Gupta, H.: Towards reduced uncertainty in conceptual rainfall-runoff modelling: Dynamic identifiability analysis, Hydrol. Process., 17, 455–476, doi:10.1002/hyp.1135, 2003.

Wagener, T., Reed, P., van Werkhoven, K., Tang, Y., and Zhang, Z.: Advances in the identification and evaluation of complex environmental systems models, J. Hydroinform., 11, 266, doi:10.2166/hydro.2009.040, 2009.

Yilmaz, K. K., Gupta, H. V., and Wagener, T.: A process-based diagnostic approach to model evaluation: Application to the NWS distributed hydrologic model, Water Resour. Res., 44, W09417, doi:10.1029/2007WR006716, 2008.