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Temporal parameter sensitivity guided verification of process dynamics

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Abstract

To ensure reliable results of a hydrological model, it is essential that the model reproduces the hydrological processes adequately. Information about process dynamics is provided by looking at the temporal sensitivities of the corresponding model parameters. For this, the temporal dynamics of parameter sensitivity are used to describe the dominance of parameters for each time step. The parameter dominance is then related to the corresponding hydrological process, since the temporal parameter sensitivity represents the modelled hydrological process. For a reliable model application it has to be verified that the modelled hydrological processes match the expectations of real-world hydrological processes.

We present a framework, which distinguishes between a verification of single model components and of the overall model behaviour. We analyse the temporal dynamics of parameter sensitivity of a modified groundwater component of a hydrological model. The results of the single analysis for the modified component show that the behaviour of the parameters of the modified groundwater component is consistent with the idea of the structural modifications. Additionally, the appropriate simulation of all relevant hydrological processes is verified as the temporal dynamics of parameter sensitivity represent these processes according to the expectations. Thus, we conclude that temporal dynamics of parameter sensitivity are helpful for verifying modifications of hydrological models.

1 Introduction

Hydrological models are driven by different interacting processes that are implemented into the model. To investigate the reliability of model results, it is essential to understand how these processes are represented. It needs to be analysed whether the model results are consistent with the hydrological processes in the catchment. These analyses

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are performed for the model structure, which is described by the model equations and different model parameters.

Knowledge about the model structures is crucial, especially when hydrological processes that control a response variable are not simulated appropriately (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).

A first step to evaluate modifications to the model structures is the comparison between simulated and observed discharge. However, this comparison is not sufficient. It is essential to investigate if the newly introduced parameters match the expected sequence of processes. More specifically, there is the need to analyse how well they represent the corresponding real-world processes.

As stated by Yilmaz et al. (2008), a systematic approach is needed to analyse the adequacy of model structure and model improvements. There is a need to diagnose, if the modified model structures and their newly introduced parameters are consistent with the expected sequence of hydrological processes according to the model concept. This is a step towards a general framework for model accuracy verification as emphasized by Wagener et al. (2001) and Yilmaz et al. (2008).

The relevance of model structure analysis for model improvement is highlighted by Clark et al. (2011) since the processes are not always reproduced appropriately. According to Massmann et al. (2014), the detection of periods in which a parameter or a set of parameters controls the model output provides diagnostic information. Guse et al. (2014) showed that this information is obtained by TEmporal Dynamics of PArameter Sensitivity (TEDPAS, Sieber and Uhlenbrook, 2005; Reusser et al., 2011). TEDPAS detects dominant parameters by analysing their sensitivity in a high temporal resolution. Since typical patterns of temporal parameter sensitivity change over time, the parameters can be related to corresponding hydrological processes. These hydro-

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logical processes and discharge phases vary temporally and hence 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). The high temporal resolution supports the confirmation of the expected sequence of processes that is related to changing hydrological conditions.

In this context, Guse et al. (2014) used TEDPAS (Reusser et al., 2011) and temporal model performance analysis (TIGER, Reusser et al., 2009) to detect the component of a hydrological model, which was responsible for poorly simulated baseflow in dry years. Although the simulated sequence of temporal parameter sensitivity was reasonable, the model performed poor 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. Despite the well fitted discharge, there is the need to analyse if the hydrological processes are adequately represented by the model structure.

To fill this gap in knowledge, we present a framework that makes use of TEDPAS to verify improvements when model components were modified. TEDPAS provides temporal sensitivities of the newly introduced parameters. Furthermore, the sequence of high temporal parameter sensitivity can be interpreted to a sequence of processes. These results are then used for the verification. Hypotheses of the expected sequence of parameter sensitivity are derived from the model structure and the expected sequence of hydrological processes are derived from observations and known processes within the modelled catchment. The verification is performed by comparing the simulation results with the hypotheses of expected sequence of parameter sensitivity and expected sequence of hydrological processes within the catchment. For this, we assume that hypotheses for the sequence of parameter sensitivity sequence and hypothesised hydrological processes represent expectations derived by the analysis of the

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model structure and the known processes wihthin the catchment. The framework distinguishes between verification of single model components ($TEDPAS_{single}$) and verification of the overall model behaviour ($TEDPAS_{all}$). $TEDPAS_{single}$ is used to assess the consistency between expected and simulated sequence of temporal parameter sensitivity for a single, newly introduced model component. $TEDPAS_{all}$ is used to verify if the implementation of the modified component into the model structure is appropriate by analysing the sequence of processes of the modified component in relation to the other model components. For both approaches, the expectations for the verification are hypothesised on the basis of model structure and hydrological processes within the studied catchment.

Since the parameter sensitivities are related to the hydrological processes, the consistency in representing the whole hydrological system is investigated. For this, we propose a general framework for the verification of hydrologically consistent model modifications which are in principal applicable to any model in any catchment. We demonstrate:

- how a single component of a model, which was modified or newly introduced, can be verified by relating the sequence of high temporal parameter sensitivity to the expected sequence according to its underlying process equations ($TEDPAS_{single}$);
- how temporal parameter sensitivities can be used to assess the consistency between expected and simulated sequence of processes by analysing the model component based overall hydrological process representation ($TEDPAS_{sall}$).

2 Methods

The general idea to achieve hydrologically consistent model structures with model diagnostics and model improvements includes three steps (Fig. 1). Firstly, the reason for poor model performance for distinct discharge periods is detected (cf. Guse et al., 2014). The temporal parameter sensitivities are used to identify the corrsponding model

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component, which is responsible for the poor model performance due to model structure deficiencies (cf. Guse et al., 2014). Secondly, the structure of a single model component that is responsible for the poor hydrological process representation is modified to improve the model performance (cf. Pfannerstill et al., 2014a). Thirdly, the modified model component is verified by comparing simulated and hypothesised temporal parameter sensitivities using a framework, which is demonstrated in this study. This framework integrates two elements of consecutive TEDPAS analyses that is described in the following. In this context, we define TEDPAS as a diagnostic method, which provides results in terms of temporal dynamics of parameter sensitivity.

2.1 TEDPAS methods

As shown in recent studies (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), a high temporal resolution is essential for proper diagnostic model evaluation. Therefore, TEDPAS aims to improve the understanding of model dynamics and to identify temporal dynamics of parameter sensitivity. For each time step, the sensitivity of the model output (e.g. discharge) is calculated on different parameters (cf. Reusser et al., 2009; Guse et al., 2014).

The temporal parameter sensitivities are 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. The temporal dynamics of parameter sensitivity can be attributed to the temporal dynamics of hydrological processes. Accordingly, the dominant model processes for different periods of time can be determined (Sieber and Uhlenbrook, 2005; Cloke et al., 2008; Reusser et al., 2011).

There are three distinguishable goals in sensitivity analysis, namely factor prioritisation, factor fixing and factor mapping (Saltelli et al., 2006). The presented study focuses on the factor prioritisation setting to identify dominant model processes. These processes can be related to parameters that are dominant for the analysed time series

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(Reusser and Zehe, 2011). Thereby, periods of time that are especially useful for model calibration can be determined (Guse et al., 2014). 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. Thus, TEDPAS investigates how a variation in model parameter values influences the variance of the model output (Eq. 1, from Reusser and Zehe, 2011). According to Reusser and Zehe (2011), the first-order partial variance is estimated by dividing the changes due to a specific parameter with the total variance V that is described by all model runs.

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

V = total variance

V_i = variance of parameter θ_i (first order variance)

V_{ij} = covariance of θ_i (second order variance) and

θ_j and higher order terms

For all parameters, the first-order partial variance is summed up. The sum of all partial variances cannot be higher than one by definition. However, it can be smaller than one due to parameter interactions. This is the case for the sensitivity of one parameter that is affected by other parameters.

As shown by Saltelli et al. (2006), Nossent et al. (2011), Reusser and Zehe (2011), Sudheer et al. (2011), Herman et al. (2013) and 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

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(Reusser, 2012), all analyses were made within the R environment. Readers are referred to Reusser and Zehe (2011) for further details.

2.2 TEDPAS as a framework for the verification of model improvements

The presented framework for the verification of model improvements 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. The presented framework for a TEDPAS-based verfication aims to provide insights into the modelled hydrological system in a high temporal resolution by using generally available data (e.g. daily discharge). In general, TEDPAS is applicable with or without measured data.

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 two different TEDPAS-based analyses, $\text{TEDPAS}_{\text{single}}$ and $\text{TEDPAS}_{\text{all}}$.

2.2.1 $\text{TEDPAS}_{\text{single}}$

$\text{TEDPAS}_{\text{single}}$ aims to analyse the temporal parameter sensitivity within a modified or newly introduced model component. The main outcome of this analysis is a sequence of temporal parameter sensitivity, which is compared with the concept of the analysed model component. Focusing on the parameters of an individual model component, the relevance of each parameter can be identified precisely since possible interactions with parameters of other model components are excluded.

2.2.2 $\text{TEDPAS}_{\text{all}}$

$\text{TEDPAS}_{\text{all}}$ is used to verify the simulated sequence of hydrological processes using knowledge about the real processes. The main assumption of the $\text{TEDPAS}_{\text{all}}$ is that the sequence of hydrological processes is represented by temporal parameter sensitivities

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of different model components. A high temporal parameter sensitivity of a model component is assumed to reflect the hydrological process that is simulated by the model component. By applying $\text{TEDPAS}_{\text{all}}$, an accurate process implementation can be verified, especially for the modified or newly introduced model component.

2.2.3 Expected temporal parameter sensitivity and expected sequence of processes

To verify the single model component using $\text{TEDPAS}_{\text{single}}$, it is necessary to firstly define hypotheses about the expected temporal parameter sensitivity of the model. These hypotheses are derived from the concept of the model structure. By comparing the calculated parameter sensitivities with the hypothesised parameter sensitivities, the consistency between model parameter behaviour and the idea of the improved model structure is estimated.

To determine the hydrological consistency for the whole hydrological model with respect to the modified, single model component, the results of $\text{TEDPAS}_{\text{all}}$ are analysed. Therefore, the expected sequence of processes is hypothesised based on the knowledge of general hydrological and catchment specific processes. The hypotheses are compared with the results of $\text{TEDPAS}_{\text{all}}$, which provide information about the simulated sequence of hydrological processes.

3 Framework demonstration example

3.1 Catchment description and data

The Kielstau catchment comprises an area of about 50 km^2 and is located in the federal state of Schleswig-Holstein in the North Germany. It is a subbasin of the Treene catchment to which TEDPAS has been applied by Guse et al. (2014). The catchment is characterised by a maritime climate with a mean annual precipitation of 918.9 mm

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and mean annual temperature of 8.2 °C (Station: Gluecksburg-Meierwik, period: 1961–1990; DWD, 2012).

As reported by Kiesel et al. (2010), the catchment has a high water retention potential. However, due to the flat topography (27 to 78 m a.m.s.l. – 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 conribute to fast runoff and consequently increase peak flows, especially in winter (Kiesel et al., 2010). During drier periods decreasing tile drainage flow has been observed from April and May before tile drainage flow stops in 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).

Catchment specific input data for the model includes a soil map (resolution 1 : 200 000, BGR, 1999) and a digital elevation model (resolution 5 m; LVermA, 1995). To define land use and crop rotations, data from mapping campaigns of 2011/2012 and 2012/2013 were available from Pfannerstill et al. (2014a, b). The soil and crop databases, and the spatial distribution of tile drainages were obtained from Fohrer et al. (2013, 2007).

Precipitation data was provided by the Gluecksburg-Meierwik weather station located north of the Kielstau catchment (DWD, 2012). Additional weather input from the STAtistical Regional model (STAR, Orlowsky et al., 2008) was used to fill gaps of needed data. The STAR data were already used as recent climate data for the SWIM model (e.g. Huang et al., 2010; Martinkova et al., 2011). In this study, wind speed, temperature, solar radiation, and humidity of STAR were used to fill data gaps.

3.2 Model description and setup

In the following, the hydrological model is described, which was used to exemplarily show the application of TEDPAS for verification of a modified model component. The semi-distributed, eco-hydrological SWAT model (Arnold et al., 1998) 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 high number of parameters which increase 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).

To set up the model, 36 subbasins and 2214 HRUs, which were determined using three slope classes (< 2.6, 2.6–4.6 and > 4.6 %), were defined with 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 $SWAT_{3S}$. To obtain 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.

3.3 Demonstration of verification framework

The verification framework for a modified model component is demonstrated by applying $TEDPAS_{single}$ and $TEDPAS_{all}$ to the modified groundwater component of $SWAT_{3S}$. $TEDPAS_{single}$ was used to verify the sequence of temporal parameter sensitivity for

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the groundwater module. With $TEDPAS_{all}$ the expected sequence of processes of surface runoff, tile drainage flow, evaporation and soil water storage is analysed. For $TEDPAS_{single}$ and $TEDPAS_{all}$, the model parameters (Table 1) and their ranges were selected according to previous SWAT model studies (Guse et al., 2014; Pfannerstill et al., 2014a).

3.3.1 $TEDPAS_{single}$ for model parameter verification

In the following, the $SWAT_{3S}$ groundwater component with its parameters (Fig. 2) is briefly described. Also, we formulate hypotheses about the expected sequence of temporal parameter sensitivity. These hypotheses are the basis for the verification with $TEDPAS_{single}$. For the detailed process equations we refer to the Appendix. A brief description of the main groundwater processes of the original SWAT version can be found in the Supplement.

According to the concept for the $SWAT_{3S}$ groundwater module, the delay in the recharge of groundwater (GW_DELAY_{fsh}) is expected to be the first sensitive parameter. The delayed recharge is then partitioned ($RCHRG_{ssh}$) into a recharge to a fast shallow aquifer and to conceptually underlying aquifers (slow shallow and deep). Next, a recession constant ($ALPHA\_BF_{fsh}$) controls the contribution of the fast shallow aquifer to the stream. Based on the groundwater model concept, we expect the sequence of temporal parameter sensitivity to follow the order: GW_DELAY_{fsh}, $RCHRG_{ssh}$ and $ALPHA\_BF_{fsh}$ for the fast shallow aquifer (Hypothesis H1: sequence fast).

$SWAT_{3S}$ simulates also a delayed recharge (GW_DELAY_{ssh}) for aquifers conceptually located beneath the fast shallow aquifer (slow shallow and deep aquifer). The delayed recharge is partitioned ($RCHRG_{dp}$) into a recharge to a slow shallow and a deep aquifer. Finally, the contribution for the slow shallow aquifer is controlled by a recession constant ($ALPHA\_BF_{ssh}$). Consequently, we expect the temporal dynamics of parameter sensitivity to be similar to the expected sequence of the shallow aquifer parameters (H2: GW_DELAY_{ssh}, $RCHRG_{dp}$ and $ALPHA\_BF_{ssh}$ for sequence slow).

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In general, the fast shallow aquifer was implemented to represent fast reacting groundwater processes in times of high discharge. In contrast, the slow shallow aquifer is intended to control the low flow phases by contributing delayed groundwater recharge. This concept should lead to an explicit sequence of temporal parameter sensitivity for the different aquifers. We hypothesise, that the parameters controlling the fast shallow aquifer (GW_DELAY_{fsh}, $RCHRG_{ssh}$, and $ALPHA\_BF_{fsh}$) are most relevant directly after a precipitation event, before the parameters controlling the slow shallow aquifer (GW_DELAY_{ssh}, $RCHRG_{dp}$, and $ALPHA\_BF_{ssh}$) become dominant later (H3: relation fast to slow).

3.3.2 $\mathbf{TEDPAS_{all}}$ for model component verification

The consistency between the expected and the simulated sequence of processes is verified with $TEDPAS_{all}$. The sensitivity of parameters controlling the processes of surface runoff, tile drainage flow, evaporation and soil water storage is related to the groundwater processes. Thereby, the groundwater component is verified in the context of the overall process representation of the hydrological cycle.

The results of $TEDPAS_{all}$ are compared with hypotheses of temporal process patterns, which were developed for the case study catchment. These hypotheses are based on the concept of vertical water redistribution (Yilmaz et al., 2008) and on qualitative knowledge of the catchment processes. The vertical redistribution of water after excess rainfall between faster and slower runoff components 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 Fig. 3 and findings of Kiesel et al. (2010) for the study catchment, it is hypothesised that the surface runoff (CN2) and the surface runoff lag (SURLAG) are relevant during the whole year whenever the amount of precipitation exceeds the soil infiltration capacity (H4: surface runoff upon rainfall).

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The amount of water that does not run off on the surface infiltrates into the soil and is stored (SOL_AWC) for a limited time and depending on soil water storage capacity. The storage capacity is directly connected with tile drainage and groundwater dynamics as shown by Kiesel et al. (2009, 2010) and Schmalz et al. (2008) for the study catchment. 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), it is expected that tile drainage flow leads to peak flows in winter due to groundwater ponding and a high soil water content. Consequently, we hypothesise that the effective lateral hydraulic conductivity factor (LATKSATF), the spacing for tile drainages (SDRAIN), and their storage and lag time (GDRAIN) to be of high relevance mainly in winter (H5: tile drainage flow in winter).

In addition, high groundwater tables are the most important characteristic 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 river (Schmalz et al., 2008). In contrast, the dynamics of groundwater interaction decreases in summer but groundwater storage remains the main contributor of flow to the river. Based on these assumptions, we hypothesise a high relevance of fast groundwater flow represented by GW_DELAY_{fsh}, $RCHRG_{ssh}$, and $ALPHA\_BF_{fsh}$ in winter and high relevance of the slow groundwater flow represented by GW_DELAY_{ssh}, $RCHRG_{dp}$, and $ALPHA\_BF_{ssh}$ in the beginning of summer (H6: variable recession slope).

More specifically, GW_DELAY_{fsh} is expected to be the first dominant parameter controlling fast groundwater recharge during high discharge periods in winter. This fast groundwater recharge is followed by increasing dominance of $RCHRG_{ssh}$ and $ALPHA\_BF_{fsh}$ which control the outflow from the aquifer at decreasing high discharge (H7: fast groundwater flow at high discharge). At the beginning of the recession, the delayed recharge (GW_DELAY_{ssh}) is expected the be the main process controlling the discharge generation, followed by an increasing relevance of $RCHRG_{dp}$, and $ALPHA\_BF_{ssh}$ (H8: flat recession at low discharge).

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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 of the drainage model component. Also, due to the climatic conditions in the Kielstau catchment, the summer periods are characterized 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 module is decreasing. Based on this observation, we hypothesise high relevance of the soil water storage capacity (SOL_AWC) and the soil evaporation compensation (ESCO) in dry summer months until the beginning of resaturation phases (H9: evaporation at resaturation).

4 Description and discussion of the results

4.1 Temporal sensitivity of groundwater parameters ($\text{TEDPAS}_{\text{single}}$)

The sensitivity of all six groundwater parameters varied considerably between different discharge phases (Fig. 4). Based on the temporal parameter sensitivities, a pattern of parameter relevance could be observed. The delay time of the fast shallow aquifer ($\text{GW\_DELAY}_{\text{fsh}}$) had the strongest effect on high discharge events caused by large amounts of precipitation (Fig. 4a). Next, the relevance for controlling the percolation to the fast and slow shallow aquifers ($\text{RCHRG}_{\text{ssh}}$) increased. Finally, the recession constant $\text{ALPHA\_BF}_{\text{fsh}}$ was sensitive at the end of high discharge phases (Fig. 4c). Thus, hypothesis H1 is verified, as the expected sequence of temporal parameter sensitivity of $\text{GW\_DELAY}_{\text{fsh}}$, $\text{RCHRG}_{\text{ssh}}$, and $\text{ALPHA\_BF}_{\text{fsh}}$ was confirmed.

Regarding hypothesis H2, the expected sequence of temporal parameter sensitivity of $\text{GW\_DELAY}_{\text{ssh}}$, RCHRG_{dp}, and $\text{ALPHA\_BF}_{\text{ssh}}$ were confirmed as well. In comparison to the fast shallow aquifer, this sequence is much clearer as the sensitivity of the parameters of the slow shallow aquifer showed a much higher temporal variability (Fig. 4).

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The most important finding about the overall parameter sensitivity is an earlier reaction of the parameters for the fast shallow aquifer compared to the slow shallow aquifer, which was the expectation of the modified groundwater concept and hypothesised with H3. Overall, the fast aquifer parameters were most sensitive during recession phases following discharge peaks. In contrast, the slow aquifer parameters dominated the low flow periods. Thus, hypothesis H3 was confirmed as well, which expected an earlier reaction of the parameters controlling the response of the fast shallow aquifer to precipitation events compared to the parameters controlling the response of the slow shallow aquifer.

4.2 Overall process verification (TEDPAS$_{all}$)

TEDPAS$_{all}$ is used to determine the sequence of processes by analysing the temporal sensitivities of the different model components. The results show that the impact of the different components on discharge changed remarkably over time.

The impact of the model component controlling surface runoff (SURLAG and CN2) was observed during discharge peaks throughout the year (Fig. 5). The model component for surface runoff is the first component to become sensitive during a rainfall event, which confirms hypothesis H4. The expected sequence of processes, which was based on the observations of Kiesel et al. (2010) for the study catchment are confirmed by the sensitivity of the two parameters, which is clearly linked to short peak flow events during the whole simulation period (Fig. 5).

All other parameters showed a characteristic sequence of parameter sensitivity, which depends on to 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. This finding verifies hypotheses H5 and H9: tile drainages are inactive due to low water tables, which do not rise during the short and low precipitation events in summer periods. The highest dynamic of sensitivity and influence on the discharge was observed during wet periods in winter and spring (Fig. 5), where rising water tables are expected due to sufficient precipitation.

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The low impact of the tile drainages can be further explained by the groundwater dominance at low flow periods, which is the next step in the sequence of processes as described by the concept of vertical water redistribution (see Fig. 3). 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 is in accordance with hypothesis H8.

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_{fsh}) becomes less relevant as soon as the influence of the time delay parameter of the slow shallow aquifer (GW_DELAY_{ssh}) increases. This result was expected, as the model structure expects a recharge to the fast shallow aquifer at high discharge with fast groundwater contribution ($ALPHA\_BF_{fsh}$), followed by a delayed recharge to the slow shallow aquifer at recession phases with slow groundwater contribution ($ALPHA\_BF_{fsh}$, hypotheses H6, H7, H8). Consequently, the low flow during dry periods is controlled by flow from the slow shallow aquifer to the channel (Fig. 5). This finding supports hypothesis H6, 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. In comparison to the results of $TEDPAS_{single}$, the impact of the fast shallow aquifer is lower, because the tile drainage flow controls the water amount for the groundwater recharge. Consequently, the process of fast discharge generation is controlled by both, the tile drainage flow and the fast shallow aquifer. This result was partly expected, since the parameters of the fast shallow aquifer were expected to be mainly relevant in winter (H5). Due to the low parameter sensitivity of the fast shallow aquifer, hypothesis H5 is partly verified. The overlap of high sensitivity of the parameters controlling tile drainage flow and the fast shallow aquifer emphasizes the relevance of a single model component analysis as performed with $TEDPAS_{single}$.

The partitioning of recharge of the slow shallow and the deep aquifer ($RCHRG_{dp}$) was especially important at the beginning of recession phases (Fig. 5), because it con-

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trols 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 flows into the fast shallow aquifer, the less is available for the slow shallow and the inactive deep aquifer. This behaviour is consistent with the model concept since the recharge to the fast shallow aquifer is intended to be more important during wet phases with fast groundwater recharge (H6, H7). In contrast, the slow shallow aquifer is designed to control the slow recharge before recession phases (H6, H8).

The processes expected to become relevant last according to the concept of vertical water redistribution (Fig. 3) is the storage function of the soils and evaporation. The evaporation and soil water availability (ESCO and SOL_AWC) are most relevant during low flow periods in late summer and during phases of resaturation in the beginning of autumn. During these periods, the influence of all other processes is very limited. This highlights the relevance of additional storages besides the groundwater storages for the generation of baseflow in dry periods. Since the parameter sensitivities of the groundwater component is very low in these periods, hypothesis H9 is verified.

5 Relevance of TEDPAS for the verification of model modifications

TEDPAS is a central method for model diagnostics and the verification of model improvements (Fig. 1). We build a framework with two different TEDPAS applications. In the following, it is discussed, whether the results of the presented TEDPAS framework provides diagnostic information for model verification upon modified or newly introduced model components. In this context, it is discussed if the application of TEDPAS can be interpreted as the last step for model verifications.

In this study, we exemplify the analysis of a modified model in regard to two different aspects: (i) the hydrological consistency within the model and (ii) the hydrological processes within a catchment. The general application of this framework is shown by abstracting our findings into a more general context. We hypothesise that this frame-

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work is applicable for any hydrological model in any catchment, which needs further demonstration.

Based on our analysis results of the modified model component, it was shown that there is the necessity to analyse the role of the newly introduced parameters. We interpret the results of the demonstration example to focus on the hydrological processes which are identified with high temporal resolution.

Due to the daily resolution, the hydrological processes of a single model component were clearly identified (fast and slow reacting aquifer). According to the model structure and our derived hypotheses, $\text{TEDPAS}_{\text{single}}$ confirmed the expected sequence of parameter sensitivity. Furthermore, the case study results revealed a simulated sequence of processes that is consistent with the concept of vertical water redistribution (Fig. 3) and according to our knowledge based process understanding for the study catchment. The simulated sequence of processes consistently exhibited the order with surface runoff as first process, followed by tile drainage. Finally, this sequence of processes continues with fast groundwater flow and slow groundwater flow (Figs. 4 and 5). However, the low sensitivity of the parameters for the fast shallow aquifer limits the verification to a small extent. Nonetheless, the sequence of processes is identifiable. Consequently, the confirmation of the consistency is the core result of the diagnostic analysis. It indicates that the simplified representation of the groundwater processes is in accordance with the concept of vertical process dynamics.

In this study, $\text{TEDPAS}_{\text{single}}$ and $\text{TEDPAS}_{\text{all}}$ were 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 occurring 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 the TEDPAS framework to evaluate the consistency of parameters and process structure using qualitative data. We used observed processes occurring the catchment, as well as the concept of vertical water redistribution (Fig. 3) and the theoretical foundations of the modified model structure (Fig. 2) to derive hy-

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potheses for the model verification. This procedure can be transferred to any model and can be performed for studies in any catchment.

The results of this study show, that $\text{TEDPAS}_{\text{single}}$ and $\text{TEDPAS}_{\text{all}}$ are needed for the extraction of comprehensive model diagnostic information. The $\text{TEDPAS}_{\text{single}}$ method is used to check the consistency between expected and simulated sequence of temporal parameter sensitivity for the modified or newly introduced model component. With this approach, the role of each parameter can be clearly identified, especially due to the high temporal resolution. The application of $\text{TEDPAS}_{\text{all}}$ in our demonstration example revealed, that the highest sensitivity of single parameters of a modified model component and parameters of other model components may occur simultaneously. This finding emphasizes the importance of $\text{TEDPAS}_{\text{all}}$, since this method is able 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 temporal dynamics of parameter sensitivities (TEDPAS) as a verification method in model diagnostics. We propose three steps for model diagnostics and the verification of model improvements. Firstly, inappropriate model structures are detected (cf. Guse et al., 2014) and secondly, the related process description within the model is modified to improve the representation of hydrological processes (cf. Pfannerstill et al., 2014a). The third step is the model verification with a TEDPAS-based framework, which is presented in this study.

Based on our results, we propose TEDPAS as a method to provide relevant diagnostic information after a modification of a model component. The presented framework includes the application of $\text{TEDPAS}_{\text{single}}$ and $\text{TEDPAS}_{\text{all}}$. In a high temporal resolution, $\text{TEDPAS}_{\text{single}}$ aims to provide information about the reasonable sequence of temporal parameter sensitivities within a single model component. Thereby, the intended

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role of parameters within a modified or newly introduced model component is verified. $TEDPAS_{all}$ is applied to analyse the sequence of processes including not only the modified, but all model components.

The main outcomes of this study are:

- TEDPAS provides diagnostic information for the verification of the consistency between the expected and simulated sequence of processes. The expected sequence of processes is derived from the model concept, qualitative knowledge of the catchment, and the concept of vertical water redistribution.
- $TEDPAS_{single}$ provides the sequence of temporal parameter sensitivity within a single modified or newly introduced model component.
- $TEDPAS_{all}$ provides the simulated sequence of processes of the whole model for the verification with the expected sequence of processes.

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

Appendix: The groundwater component for $SWAT_{3S}$

The idea of the modified groundwater component of $SWAT_{3S}$ (Pfannerstill et al., 2014a) is the integration of two aquifers that may contribute to the river and one aquifer that accounts for percolation into deep geologic formations. For this, the shallow aquifer was split into a fast and a slow reacting storage. A detailed description of the groundwater processes of $SWAT_{3S}$ can be found in Pfannerstill et al. (2014a). For comparisons with the original SWAT version, the governing process equations are described in the Supplement.

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In the following, the modified groundwater processes of $SWAT_{3S}$ are briefly described. In a first step, a delay for soil water that percolates out of the soil $w_{\mathrm{perc},i}$ (mm H_2O) is considered in Eq. (A1). The parameter $\mathrm{GW\_DELAY}_{\mathrm{fsh}}$ (days) describes the time delay for percolating water, entering the geologic formation of the fast shallow aquifer. The amount of water, percolating to the aquifer on the day before $(i-1)$ is represented by $w_{\mathrm{delay,fsh},i-1}$ (mm H_2O).

$$w_{\mathrm{delay,fsh},i} = \left(1 - \exp\left[\frac{-1}{\mathrm{GW\_DELAY}_{\mathrm{fsh}}}\right]\right) \cdot w_{\mathrm{perc},i} + \exp\left[\frac{-1}{\mathrm{GW\_DELAY}_{\mathrm{fsh}}}\right] \cdot w_{\mathrm{delay,fsh},i-1} \tag{A1}$$

$SWAT_{3S}$ considers the delayed percolation water $w_{\mathrm{delay,fsh},i}$ (mm H_2O) which is split into recharge of the fast shallow aquifer and into recharge that is entering the geologic formation of the slow shallow aquifer. Water percolating to the slow shallow aquifer is represented by $w_{\mathrm{seep,ssh},i}$ (mm H_2O, Eq. A2). The parameter $\mathrm{RCHRG}_{\mathrm{ssh}}$ is a partitioning coefficient, which is used to calculate the percolation into the slow shallow aquifer. The recharge of the fast shallow aquifer $w_{\mathrm{rchrg,fsh},i}$ (mm H_2O) is calculated by subtracting the water that is percolating into the geologic formation of the slow shallow aquifer with Eq. (A3):

$$w_{\mathrm{seep,ssh},i} = \mathrm{RCHRG}_{\mathrm{ssh}} \cdot w_{\mathrm{rchrg},i} \tag{A2}$$

$$w_{\mathrm{rchrg,fsh},i} = w_{\mathrm{rchrg},i} - w_{\mathrm{seep,ssh},i} \tag{A3}$$

The concept of $SWAT_{3S}$ assumes a delay of the calculated seepage to the slow shallow aquifer $w_{\mathrm{seep,ssh},i}$ (Eqs. A2 and A4). Thereby, the time delay of recharge due to different geologic formations is described with $\mathrm{GW\_DELAY}_{\mathrm{ssh}}$ (days).

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$$w_{\text{delay,ssh},i} = \left(1 - \exp\left[\frac{-1}{\text{GW\_DELAY}_{\text{ssh}}}\right]\right) \cdot w_{\text{seep,ssh},i} + \exp\left[\frac{-1}{\text{GW\_DELAY}_{\text{ssh}}}\right] \cdot w_{\text{delay,ssh},i-1} \tag{A4}$$

To consider percolation to the slow shallow aquifer on the day before, the parameter $w_{\text{delay,ssh},i-1}$ (mm H_2O) is used. SWAT_{3S} incorporates the simulation of groundwater recharge to deep geologic formations. The percolation to the deep aquifer $w_{\text{seep,dp},i}$ (mm H_2O) is calculated with Eq. (A5):

$$w_{\text{seep,dp},i} = \text{RCHRG}_{\text{dp}} \cdot w_{\text{delay,ssh},i} \tag{A5}$$

The delayed recharge to the slow shallow aquifer $w_{\text{rchrg,ssh},i}$ (mm H_2O) is then simulated with Eq. (A6):

$$w_{\text{rchrg,ssh},i} = w_{\text{delay,ssh},i} - w_{\text{seep,dp},i} \tag{A6}$$

Finally, the groundwater flow into the stream is calculated. As SWAT_{3S} considers two contributing groundwater storages, there are two equations for the simulation of groundwater flow. The groundwater flow out of the fast shallow aquifer is calculated with Eq. (A7). The parameter $\text{ALPHA\_BF}_{\text{fsh}}$ (1 days^{-1}), which is the baseflow recession constant, is used to describe the outflow of the qaifer ($Q_{\text{gw,fsh},i}$, mm H_2O):

$$Q_{\text{gw,fsh},i} = Q_{\text{gw,fsh},i-1} \cdot \exp\left[-\text{ALPHA\_BF}_{\text{fsh}} \cdot \Delta t\right] + w_{\text{rchrg,fsh},i} \cdot \left(1 - \exp\left[-\text{ALPHA\_BF}_{\text{fsh}} \cdot \Delta t\right]\right) \tag{A7}$$

The contribution of the slow shallow aquifer to the discharge is calculated with Eq. (A8):

$$Q_{\text{gw,ssh},i} = Q_{\text{gw,ssh},i-1} \cdot \exp\left[-\text{ALPHA\_BF}_{\text{ssh}} \cdot \Delta t\right] + w_{\text{rchrg,ssh},i} \cdot \left(1 - \exp\left[-\text{ALPHA\_BF}_{\text{ssh}} \cdot \Delta t\right]\right) \tag{A8}$$

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The modified $SWAT_{3S}$ calculates the groundwater contribution of the slow shallow aquifer to the river $Q_{gw,ssh,i}$ (mm H_2O) using $ALPHA\_BF_{ssh}$ (1 $days^{-1}$), which is the baseflow recession constant for the slow shallow aquifer. The recharge of the slow shallow aquifer is described with the parameter $w_{rchrg,ssh,i}$ (mm H_2O).

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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. 1739

BGR: Bodenübersichtskarte im Maßstab 1 : 200.000 – Verbreitung der Bodengesellschaften, Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, 1999. 1738

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. 1732

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. 1732

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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. 1739

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. 1731

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. 1734

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. 1735

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. 1735

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. 1735

DWD: Weather and climate data from the German Weather Service (DWD) of the station Flensburg (1961–1990), Online climate data, Offenbach, 2012. 1738

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. 1731

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. 1738

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. 1738

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. 1738

HESSD
12, 1729–1764, 2015

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. 1732, 1734

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. 1731, 1734

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. 1731, 1732, 1733, 1734, 1735, 1737, 1740, 1748

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. 1734

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, 400–414, doi:10.1002/wrcr.20124, 2013. 1734, 1735

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. 1731

Huang, S., Krysanova, V., Österle, H., and Hattermann, F. F.: Simulation of spatiotemporal dynamics of water fluxes in Germany under climate change, Hydrol. Process., 24, 3289–3306, doi:10.1002/hyp.7753, 2010. 1738

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. 1738, 1742, 1743

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. 1738, 1741, 1742, 1743, 1744

LVermA: Digital elevation model of Schleswig-Holstein, TK25, Grid size 25 m × 25 m, TK50 Grid size 50 m × 50 m, ATKIS-DGM2 1 m × 1 m Grid size, DEM 5 m × 5 m Grid size, derived from LiDAR Data, Land survey office Schleswog-Holstein, Kiel, 1995. 1738

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12, 1729–1764, 2015

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Martinkova, M., Hesse, C., Krysanova, V., Vetter, T., and Hanel, M.: Potential impact of climate change on nitrate load from the Jizera catchment (Czech Republic), Phys. Chem. Earth, 36, 673–683, doi:10.1016/j.pce.2011.08.013, 2011. 1738

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. Modell. Softw., 51, 190–194, doi:10.1016/j.envsoft.2013.09.033, 2014. 1731, 1735

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, Texas, 2011. 1739

Nossent, J., Elsen, P., and Bauwens, W.: Sobol' sensitivity analyses of a complex environmental model, Environ. Modell. Softw., 26, 1515–1525, doi:10.1016/j.envsoft.2011.08.010, 2011. 1735

Orlowsky, B., Gerstengarbe, F. W., and Werner, P. C.: A resampling scheme for regional climate simulations and its performance compared to a dynamical RCM, Theor. Appl. Climatol., 92, 209–223, doi:10.1007/s00704-007-0352-y, 2008. 1738

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. 1732, 1734, 1738, 1739, 1740, 1748, 1749, 1761

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. 1732, 1734, 1738

R Core Team: R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria, 2013. 1739

Reusser, D. E.: Implementation of the Fourier Amplitude Sensitivity Test (FAST), R-package, 0.61, 2012. 1736

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. 1731, 1735, 1736

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. 1732, 1734

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12, 1729–1764, 2015

Process verification with temporal parameter sensitivity

M. Pfannerstill et al.

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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. 1731, 1732, 1734

Saltelli, A. and Bolado, R.: An alternative way to compute Fourier amplitude sensitivity test (FAST), Comput. Stat. Data An., 26, 445–460, doi:10.1016/S0167-9473(97)00043-1, 1998. 1735

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. 1734, 1735

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", 11–13 July 2007, Perugia, Italy, IAHS Press, 21–29, 2008. 1738, 1742

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. 1731, 1734

Sudheer, K. P., Lakshmi, G., and Chaubey, I.: Application of a pseudo simulator to evaluate the sensitivity of parameters in complex watershed models, Environ. Modell. Softw., 26, 135–143, doi:10.1016/j.envsoft.2010.07.007, 2011. 1735

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. 1734

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. 1731

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. 1732

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. 1732

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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. 1731, 1734, 1741

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Table 1. Selection of parameters and its ranges for the temporal sensitivity analyses. The variation type distinguishes between replacing (r), multiplication (m) and addition/subtraction (as). The parameters are assigned according to the hydrological process 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 fast shallow aquifer	GW_DELAY_{fsh}	GW	1–15	r
Recession fast shallow aquifer	$ALPHA\_BF_{fsh}$	GW	0.3–1	r
Percolation slow shallow aquifer	$RCHRG_{ssh}$	GW	0.65–0.80	r
Delay slow shallow aquifer	GW_DELAY_{ssh}	GW	15–60	r
Recession slow shallow aquifer	$ALPHA\_BF_{ssh}$	GW	0.0001–0.3000	r
Percolation deep aquifer	$RCHRG_{dp}$	GW	0.1–0.4	r

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Table 2. Hypotheses for model verification, derived from model concept, theory of vertical water redistribution and known hydrological processes within the catchment with related model parameters.

Abbreviation	Description	Source	Parameter
H1	sequence fast	model concept	GW_DELAY_{fsh}, $ALPHA\_BF_{fsh}$, $RCHRG_{ssh}$
H2	sequence slow	model concept	GW_DELAY_{ssh}, $ALPHA\_BF_{ssh}$, $RCHRG_{dp}$
H3	relation fast to slow	model concept	$GW\_DELAY_{fsh+ssh}$, $ALPHA\_BF_{fsh+ssh}$, $RCHRG_{ssh+dp}$
H4	surface runoff upon rainfall	vertical water redistribution	CN2, SURLAG
H5	tile drainage flow in winter	observation in catchment	GDRAIN, SDRAIN, LATKSATF
H6	variable recession slope	observation in catchment	GW_DELAY_{fsh}, GW_DELAY_{ssh}
H7	fast groundwater flow at high discharge	vertical water redistribution	GW_DELAY_{fsh}, $ALPHA\_BF_{fsh}$, $RCHRG_{ssh}$
H8	flat recession at low discharge	vertical water redistribution	GW_DELAY_{ssh}, $ALPHA\_BF_{ssh}$, $RCHRG_{dp}$
H9	evaporation at resaturation	observation in catchment, vertical water redistribution	ESCO, SOL_AWC

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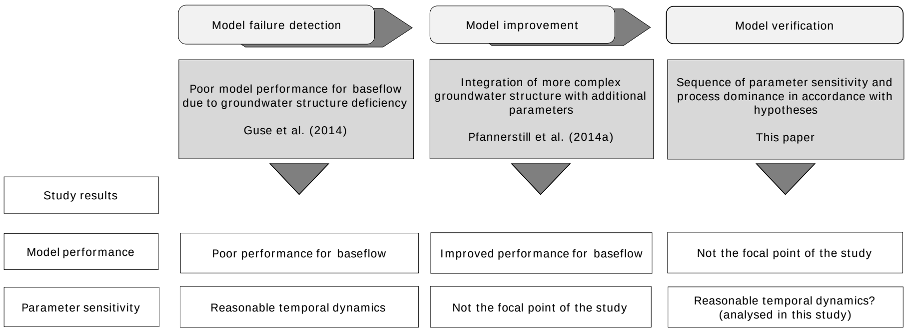

Figure 1. Steps for a hydrologically consistent model improvement.

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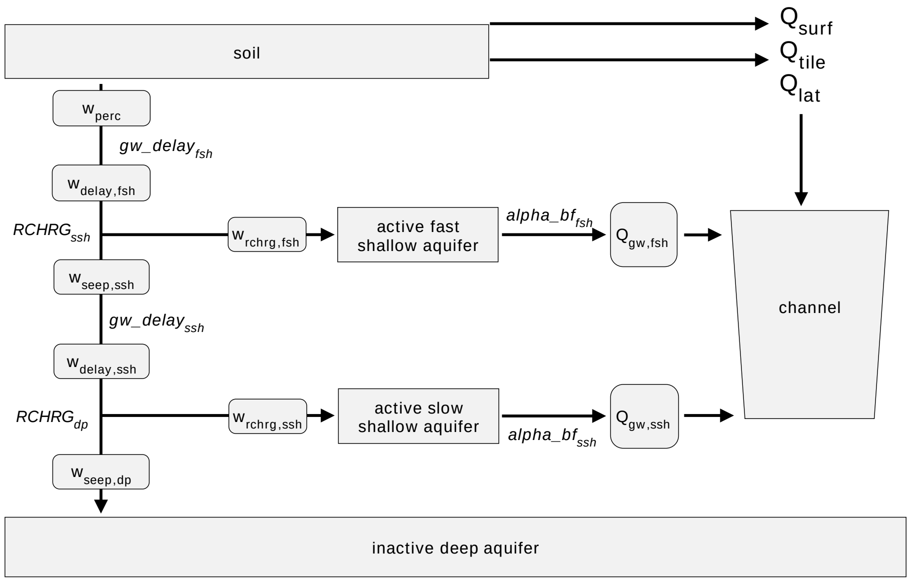

Figure 2. Description of the main groundwater processes and its parameters (highlighted in italic) of $SWAT_{3S}$ (cf. Pfannerstill et al., 2014a).

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Interactive Discussion

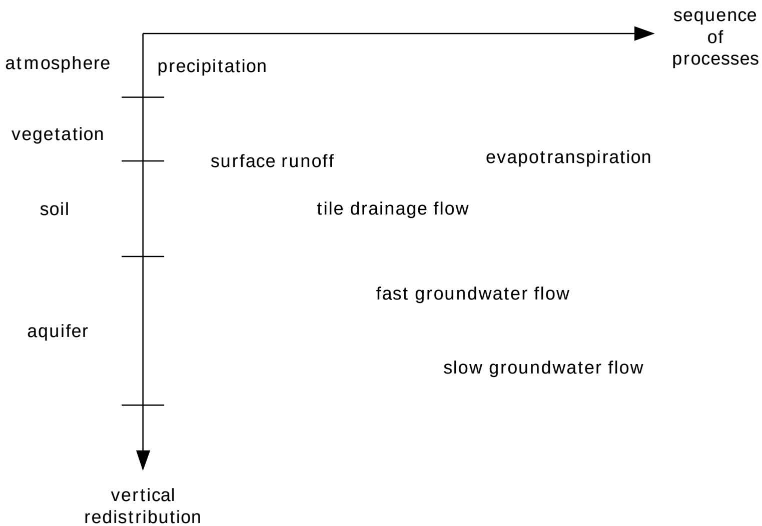

Figure 3. Schema of the expected sequence of processes after a precipitation event based on the concept of vertical water redistribution.

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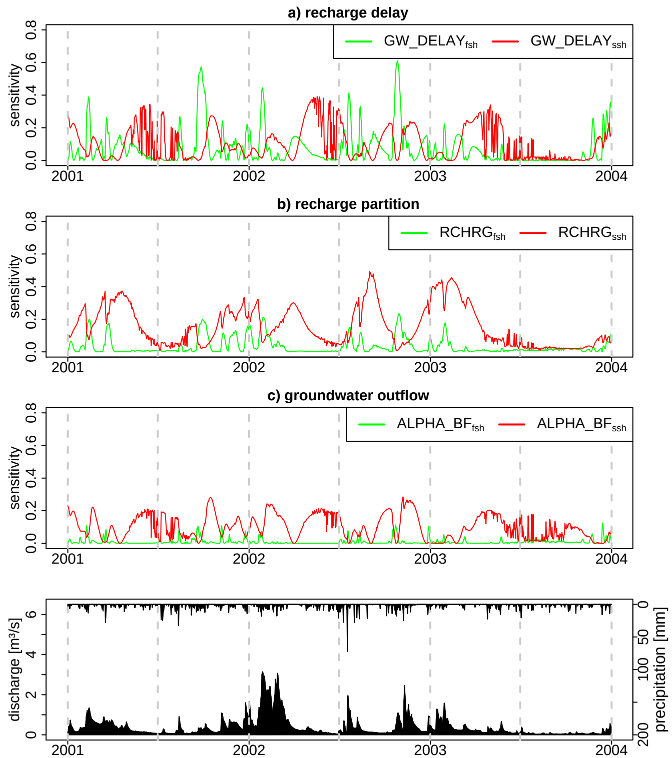

Figure 4. Temporal sensitivity for groundwater parameters of the fast (fsh) and the slow shallow aquifer (ssh). The different groundwater processes are seperated into recharge delay **(a)**, the partition of groundwater recharge **(b)**, and the groundwater outflow **(c)** according to the fast (fsh) and the slow shallow aquifer (ssh). The observed discharge and precipitation are shown additionally from 2001 to 2004 in the last subplot.

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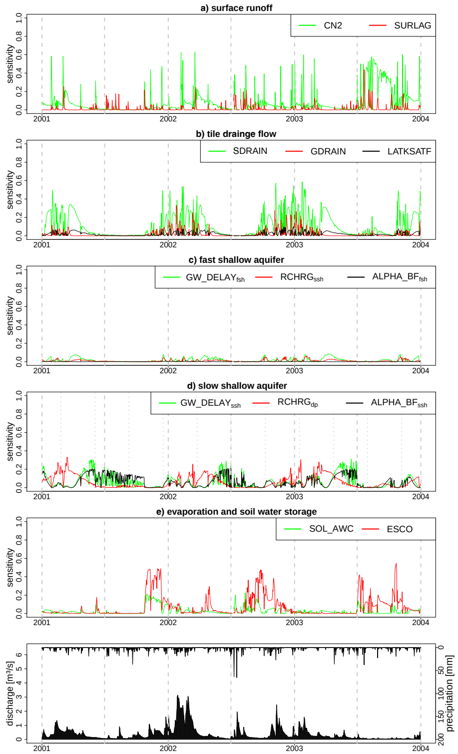

Figure 5. Temporal sensitivities for the groundwater parameters together with additional parameters for surface runoff (SURLAG, CN2), tile drainage flow (GDRAIN, SDRAIN and LATKSATF) and evaporation (ESCO, SOL_AWC). The parameters are ordered according to the processes of surface runoff **(a)**, tile drainage flow **(b)**, the process dynamics of the fast shallow aquifer **(c)** and the slow shallow aquifer **(d)**, and the evaporation together with soil water storage **(e)**. The observed discharge and precipitation are shown additionally from 2001 to 2004 in the last subplot.

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