Dear Prof. Zehe,

we would like to thank you for giving us the opportunity to revise our manuscript hess-2014-528 "Temporal parameter sensitivity guided verification of process dynamics". According to your recommendations and the remarks of the two reviewers, we carefully revised the current manuscript with regard to several aspects.

In the following, we would like to give a short summary about the most crucial aspects that were addressed in the revised manuscript version. In the case of similarity of your and the reviewer's remarks, we combined these remarks to a joint answer. We think that the modifications according to your suggestions and the comments of the two reviewers have significantly improved our manuscript. We hope that you are satisfied with our changes. In the following, the revision of the most crucial aspects is explained step-by-step:

1. The application of TEDPAS for the verification of hydrological models is the fundamental idea of our proposed verification framework. Our intention was to perform TEDPAS to investigate two different aspects. Firstly, the proper parameter implementation into the model structure was analysed with TEDPASsingle. Secondly, TEDPASall aimed to verify the model by comparing observations and known processes of the catchment with temporal dynamics of parameter sensitivity. The reviewing process revealed that this two-step approach leads to confusions, especially with regard to verification of hypotheses about process occurrences. All reviewers stated a problem of circular reasoning which is linked to TEDPASsingle.

According to your and the reviewer's remarks, we see the way of circular reasoning for the TEDPASsingle approach. The hypotheses for verification were based on the model structure. As this approach was found to be less substantial, we skipped this kind of verification to avoid confusion. To emphasise that the model verification is performed with hypotheses about observed processes of the real-world, we focused the revised manuscript on hypotheses based on process observations and removed all hypotheses which were related to the model structure. To emphasise this modification, we renamed TEDPASall to TEDPAScatchment, which describes a verification framework comparing the agreement between observed processes of the catchment and calculated temporal dynamics of parameter sensitivity. The framework is thus consistently named TEDPAScatchment.

Our revision aims to explain more clearly that TEDPAScatchment is based on hypotheses about observed processes of the catchment and the simulated processes of the hydrological model. We highlight as follows how we modified the chapter structure accordingly. Tchapters dealing with the method description and the framework application example were restructured (p.2 l.100 – 159, p.4 l.232-255). Since the catchment-based hypotheses are independent from the model, the method chapter begins with a description of the catchment and the following derivation of hypotheses (p.2 l.130 – 157). After that, the application of TEDPAS is described (p.3 l.159 - p.4 l.255). Finally the model verification is performed by comparing observed processes with simulated processes (p.4 l.248 – 257). The application example was restructured accordingly. The information about observed processes within the study catchment is collected (p.4 l.260 – 285). Based on this catchment information, hypotheses about the process occurrence are derived (p.4 l.286 – p.5 l.348). In a next step the application of TEDPAS with the hydrological model is described (p.5 l.348 – p.6 l.420). The verification is finally performed with these hypotheses and simulated processes (p.6 l.420 – 432). To explain this procedure of model verification visually, an additional figure was integrated to show the flowchart of our approach (Fig. 1).

2. The second aspect that was revised in the manuscript is the field of application of TEDPAS for model verification. The previous manuscript version focused exclusively on the verification of modified models. Since this verification is not limited to modified models, we modified the focus of the revised manuscript. The presented TEDPAS-verification framework is applicable to any hydrological model, no matter if the aim is to verify existing or modified model structures. Consequently, we adapted several paragraphs to show and discuss the TEDPAS-applicability with respect to model verification in a more general context (p.2 l.90 – 100, p.4 l.242– 257, p.6 l.420 – 432, p.10 l.630 - 639).

3. According to your suggestion, we revised the third aspect that deals about model performance. We agree that model performance is an essential step to decide about the model's ability to reproduce hydrological characteristics of the catchment (e.g. discharge). Satisfying model performance is needed together with appropriate process reproduction to achieve hydrological consistency. Referring to the application example of the manuscript, the performance evaluation has been done and was described in detail in Pfannerstill et al. (2014). However, to discuss the results of model verification as presented in the current manuscript, we see the requirement of considering the results of model performance evaluation. For this, the manuscript was revised to integrate a short summary of model performance that was determined in Pfannerstill et al. (2014) (p.9 l.528 – 548, p.9 l.591 – 601). Therefore, we incorporated additional figures (Fig. 5, Fig. 6) which depict the model performance in the chapter dealing with result presentation and discussion of the TEDPAS application example. Furthermore, we make use of these figures and findings to highlight the requirement of model performance evaluation and the requirement to apply the newly developed verification framework to decide about hydrological consistency of models (p.10 l.591 – 601).

4. Another aspect which was considered for the revision of the manuscript refers to the remark of reviewer #2, who criticised shortcomings for the language and missing definitions of specific terms. We carefully screened the whole manuscript and introduced the terms of observed and simulated temporal process sequence (p.2 l.107 – 111, Fig. 1). To improve the readability of the manuscript, we consequently used these two terms throughout the entire manuscript to keep consistency. The meaning of this term is defined at the very beginning of the manuscript so that its meaning should be clarified now. Furthermore we shortened long sentences that were hard to read.

5. The last aspect refers to comments of Shervan Gharari, who criticised the usability of our hypotheses for the model verification. We revised the presentation of the results and discussion chapter by providing an additional figure (Fig. 06). This new figure considers the different temporal scales of the different hydrological processes. Thus, smaller time scales were selected for fast occurring processes such as surface runoff, while the time scale was longer for processes such as evapotranspiration or groundwater flow. For each analysed process, we zoom into the most relevant period to show calculated temporal parameter sensitivities and measured hydrological data such as precipitation and discharge. In our opinion, this figure supports the verification of each hypothesis. Due to the daily resolution, single events but also long lasting processes can be clearly analysed and used for the comparison with hypotheses about observed processes in the catchment.

Further minor revisions were made according to the minor comments of the two reviewers that were answered during interactive discussion. We hope that our explanations help to understand the way we revised all mentioned aspects and that our revisions meet your and the reviewer's expectations.

Best regards

Matthias Pfannerstill, also on behalf of the co-authors.

Literature:

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, 2014.

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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 analysed to identify the corresponding hydrological process. Based on these analyses it can be verified if the modelled hydrological processes match the observed processes of the real-world to ensure a reliable model application.

To achieve this, we present a framework that makes use of observed processes of 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. It is verified that the simulated processes match with observed processes of the catchment. Thus, we conclude that temporal dynamics of parameter sensitivity are helpful for verifying simulated processes of hydrological models.

1 Introduction

Discharge as a major output of hydrological models is controlled by different interacting processes. To investigate the reliability of model results, it is essential to understand how these processes are represented in models. It needs to be analysed whether the model behaviour is consistent with the hydrological processes in the catchment. These analyses are performed for the model structure, which is described by model equations and different model parameters.

Knowledge about the model structures is crucial to ensure appropriate simulation of hydrological processes (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 model structures is the comparison between simulated and observed discharge as a classical approach during model calibration. However, this comparison is not sufficient to evaluate the model structure. It is essential to investigate if the hydrological processes are simulated adequately. 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 structures. There is a need to diagnose, 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 a general framework for model accuracy verification as emphasised by Wagener et al. (2001) and Yilmaz et al. (2008).

The relevance of model structure analysis for hydrological models 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. Typical patterns of temporal parameter sensitivity can be used to identify 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 (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 nonlinear 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. To prove that the well fitted discharge was achieved for the right reason, there is the need to analyse if the hydrological processes are adequately represented by the model structure.

To fill this gap, this study aims to develop 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.

We demonstrate, how to (i) make use of observed hydrological processes of a catchment for (ii) comparison with TEDPAS results to (iii) verify appropriate process simulation of the hydrological model.

2 Methods

The general idea of the proposed framework is to make use of observed processes of the catchment and results of TEDPAS to verify hydrological models (Fig. 1). For this, all available information for the study catchment are gathered with respect to observed process occurrences (Fig. 1a). These process occurrences are ordered to a temporal process sequence, which describes the consecutive hydrological processes according to seasonal hydrological conditions. For further use, hypotheses about assumed process dynamics are derived from these observed temporal process sequence (Fig. 1b).

TEDPAS is then used to provide information about the model behaviour. Temporal parameter sensitivities are calculated for the hydrological model to obtain temporal dynamics of parameter sensitivity for the study catchment (Fig. 1c). The temporal dynamics of parameter sensitivity are interpreted to hydrological processes. Finally, consecutive hydrological processes that are simulated by the model are interpreted to a simulated temporal process sequence (Fig. 1d).

Since both sequences describe consecutive hydrological processes, the observed and the simluated temporal process sequence are directly comparable with each other. The appropriate simulation of the hydrological processes is then verified by comparing the observed temporal process sequence with the simulated temporal process sequence (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 methodical foundations of the proposed framework are described in detail.

2.1 Observed processes of the catchment

To achieve hydrologically consistent model results, the model should be able to simulate all relevant hydrological processes of the study catchment. To decide about appropriate process reproduction, the relevant hydrological processes of the study catchment and their temporal process occurrences need to be identified at the catchment scale (Fig. 1a). Previous field studies and analyses about specific hydrological characteristics of the study catchment provide valuable information. This information is utilised to get an overall view of the hydrological system.

2.2 Derived hypotheses

Finally, the observed processes are used to derive hypotheses about the observed temporal process sequence of the catchment (Fig. 1b). For this, observed processes are analysed to identify seasonal process occurrences, process dynamics and specific hydrological situations. To give an example, high flow conditions may be exemplarily attributed to winter months. During this season, high precipitation leads to saturated soils. As a consequence, hydrological processes such as surface runoff, tile drainage flow and fast groundwater flow are the dominant processes for discharge generation. These hydrological situations with specific hydrological process dynamics are then incorporated into hypotheses. At this point, it has to be emphasises that the incorporated hydrological information needs to be extracted from observed data of the catchment (Fig. 1a). In this way, real-world processes are considered for the verification framework.

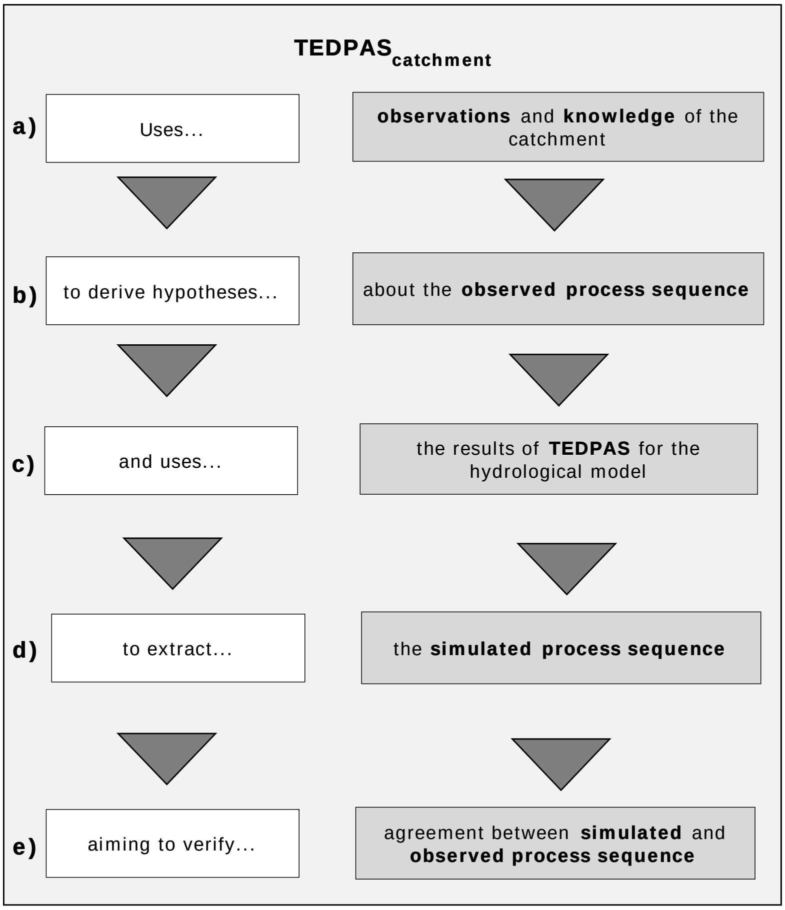

Figure 1. General idea of $\text{TEDPAS}_{\text{catchment}}$ as a verification framework. The framework integrates observed processes of the catchment (a) to derive hypotheses about the observed temporal process sequence (b) and the calculation of temporal parameter sensitivities with TEDPAS (c) to extract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

2.3 TEDPAS methods

Beside of considering the observed temporal process sequence, the simulated temporal process sequence is required for the application of the verification framework. For this, a suitable method that provides the simulated temporal process sequence needs to be selected (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), 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 presented framework for a TEDPAS-based verfication aims to provide insights into the modelled hydrological system in a high temporal resolution by using the generally available daily discharge. In general, TEDPAS is 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). 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 (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.

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

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); 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 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 $\text{TEDPAS}_{\text{catchment}}$.

The main assumption of the $\text{TEDPAS}_{\text{catchment}}$ is that the simulated temporal process sequence is represented by temporal parameter sensitivities 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.

2.5 Model verification by combining hypotheses and TEDPAS

TEDPAS provides the simulated temporal process sequence for the comparison with the hypotheses about the observed temporal process sequence. Consequently, the results of TEDPAS are used to verify an accurate process implementation. The hypotheses are accepted in the case agreement between simulated and observed temporal process sequence (Fig. 1e). For this case, 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 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 and mean annual temperature of 8.2 $^\circ\mathrm{C}$ (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 m 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). 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).

3.2 Derived hypotheses from observed processes

The observed processes of the catchment are used together with the concept of vertical water redistribution (Yilmaz et al., 2008) to derive hypotheses about the observed temporal process sequence (Tab. 1). The vertical redistribution of water after excess rainfall between faster and slower runoff

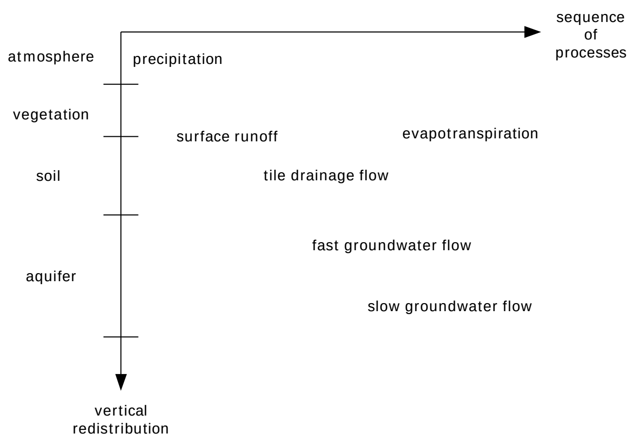

Figure 2. Schema of the process occurence and sequence after a precipitation event based on the concept of vertical water redistribution.

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 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 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 tile drainage flow is highly relevant in winter and of minor importance in summer (H2: 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 (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 of the fast reacting aquifer is active during high discharge periods in winter. This fast groundwater recharge is followed by 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 the 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 of the drainage for this 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 is decreasing. 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 (H6: evaporation at resaturation).

3.3 TEDPAS application

TEDPAS was applied to a hydrological model to obtain temporal parameter sensitivities, which are interpreted to specific hydrological process occurences. Based on this, a simulated process sequence 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 the following, the hydrological model is described, which was used to exemplarily show the application of TEDPAS for model verification. 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 a 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, several input data from the catchment were considered. The catchment specific input data for the model includes a soil map (resolution 1:200.000, BGR,

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

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). Spatial distribution of tile drainages and databases for soil and crops 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 that is based on regional interpolation (Oesterle, 2001) was used to fill gaps of needed data. 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 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 provides the dynamics of temporal parameter sensitivity for the analysed model. For this, the model parameters (Tab. 2) and their ranges were selected according to previous SWAT model studies (Guse et al., 2014; Pfannerstill et al., 2014a). 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 simulated temporal process sequence that is based on the parameter sensitivity. This simulated temporal process sequence is the core result of TEDPAS for the model verification. The sensitivity of parameters was assigned to the processes of surface runoff, tile drainage flow, groundwater flow, evaporation and soil water storage.

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

The agreement between the observed and the simulated temporal process sequence is determined with TEDPAS$_{catchment}$ by comparing both sequences with each other. The observed temporal process sequence of the study catchment is described with hypotheses according to the observed processes of the catchment. The temporal model parameter sensitivity that is investigated with TEDPAS is interpreted to a temporal process occurrence to derive the simulated temporal process sequence. Finally, both temporal process sequences are compared to verify the appropriateness of the model results with respect to observed processes of the study catchment.

4 Description and discussion of the results

TEDPAS was used to determine the simulated temporal process sequence 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 observed and simulated temporal process sequence, the results of TEDPAS as depicted in Fig. 3 were analysed in detail by having a close look at each parameter. For this, we selected appropriate time periods for each model parameter to clearly detect the coincidence between the derived hypotheses and simulated temporal parameter sensitivity (Fig. 4).

The impact of the model parameters controlling surface runoff (SURLAG and CN2) were 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 observed temporal process sequence, 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. 3 and Fig. 4).

All other parameters showed a characteristic temporal pa-

Table 2. 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	10000 - 45000	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

rameter 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 H1 and H2: 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. 4), where rising water tables are expected due to sufficient precipitation.

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 observed temporal process sequence as 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 is in accordance with 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_{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 clearly depicts the 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 ($ALPHA\_BF_{fsh}$, 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. The impact of the fast shallow aquifer is low, 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 hypothesised to be mainly relevant in winter (H4). Due to the low parameter sensitivity of the fast shallow aquifer, hypothesis H4 is partly verified.

The partitioning of recharge of the slow shallow and the deep aquifer ($RCHRG_{dp}$) was especially important at the beginning of recession phases (Fig. 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 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 observed processes of the study catchment since 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) 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, hypoth-

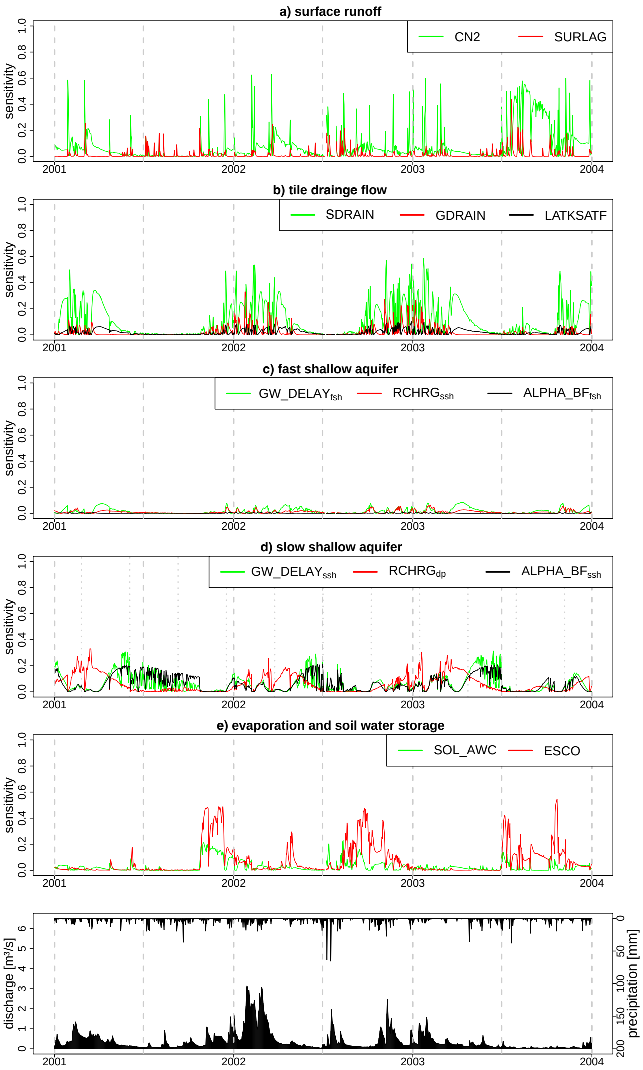

Figure 3. Temporal parameter sensitivities for all analysed model parameters. The parameters are ordered according to the processes of surface runoff (a), tile drainage flow (b), the process dynamics of the fast shallow aquifer (c) and the slow shallow aquifer (d), and the evaporation together with soil water storage (e). The observed discharge and precipitation are shown additionally from 2001 to 2004 in the last subplot.

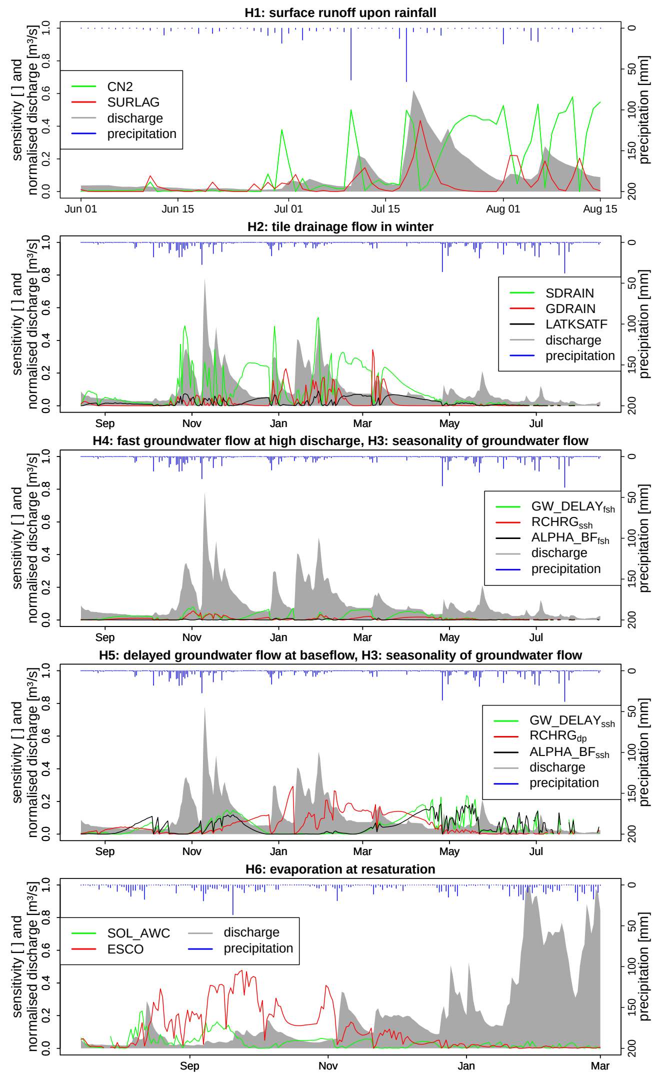

Figure 4. Periods of temporal parameter sensitivities for the verification of hypotheses about surface runoff (H1), tile drainage flow (H2), the process dynamics of the fast shallow aquifer (H3,H4) and the slow shallow aquifer (H3,H5), and the evaporation together with soil water storage (H6). Additionally, the observed discharge is shown together with precipitation for each subplot.

esis H6 is verified (Fig. 4).

Based on the verified temporal process sequence, we assume hydrological consistency for the hydrological process reproduction. 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 sufficient model performance for the calibration and validation period (Fig. 5). In addition, Pfannerstill et al. (2014b) confirmed the reproduction of discharge magnitudes for the validation and calibration period by extracting information about the ability of $SWAT_{3S}$ to simulate hydrologic characteristics appropriately (Fig. 6a and Fig. 6b). By joining the results of Pfannerstill et al. (2014b) with the results that were presented in this study, it is confirmed that $SWAT_{3S}$ is able to simulate the investigated hydrological processes adequately. This evidence is provided by satisfying model performance in reproducing daily discharge dynamics and magnitudes together with 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 build $\text{TEDPAS}_{\text{catchment}}$, which is a verification framework that makes use of observed processes of the catchment together with TEDPAS. In the following, it is discussed, whether the results of the presented verification framework provides diagnostic information for model verifications.

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 shown by abstracting our findings into a more general context. We hypothesise that $\text{TEDPAS}_{\text{catchment}}$ is applicable for any hydrological model in any catchment, which needs further demonstration.

Based on our analysis results of the model it was shown that there is the necessity to analyse the role of the model parameters. We interpret the results of the demonstration example to focus on the hydrological processes which are identified with daily resolution. Due to the daily resolution, the groundwater processes of the model were detected (fast and slow reacting aquifer). Despite of this clear separation of the two groundwater storages, the verification of dynamics for the fast aquifer was limited due to low parameter sensitivity of fast groundwater model component. Beside of this limited dynamic identification for the fast aquifer, each hypothesised process was detected for the simulated temporal process sequence. The case study results revealed a simulated temporal process sequence that is consistent with observed processes for the study catchment and in accordance with the concept of vertical water redistribution (Fig. 2). The simulated temporal process sequence exhibited the order with surface runoff as first process, followed by tile drainage. Finally, this simulated temporal process sequence continues with fast groundwater flow and slow groundwater flow (Fig. 3 and Fig. 4). However, the low sensitivity of the parameters for the fast shallow aquifer limits the verification to a small extent. Nonetheless, the temporal process sequence is identifiable. Consequently, the confirmation of the 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 mentioned that the confirmation of a realistic temporal process sequence is just one side of the coin. In the context of hydrological consistency, the hydrological model should be also able to reproduce common hydrological data (e.g. discharge). For this, we propose the combination of common model performance evaluation as it was exemplarily shown for the investigated model (Pfannerstill et al., 2014b) and our newly developed verification framework. Ideally, model performance evaluation and model verification should make use of all available data of the catchment.

In this study, $\text{TEDPAS}_{\text{catchment}}$ 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 $\text{TEDPAS}_{\text{catchment}}$ to evaluate the consistency of parameters and process structure using qualitative data. We used observed processes of the catchment, as well as the concept of vertical water redistribution (Fig. 2) to derive hypotheses for the model verification.

The results of this study show, 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 single 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 temporal dynamics of parameter sensitivities (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.

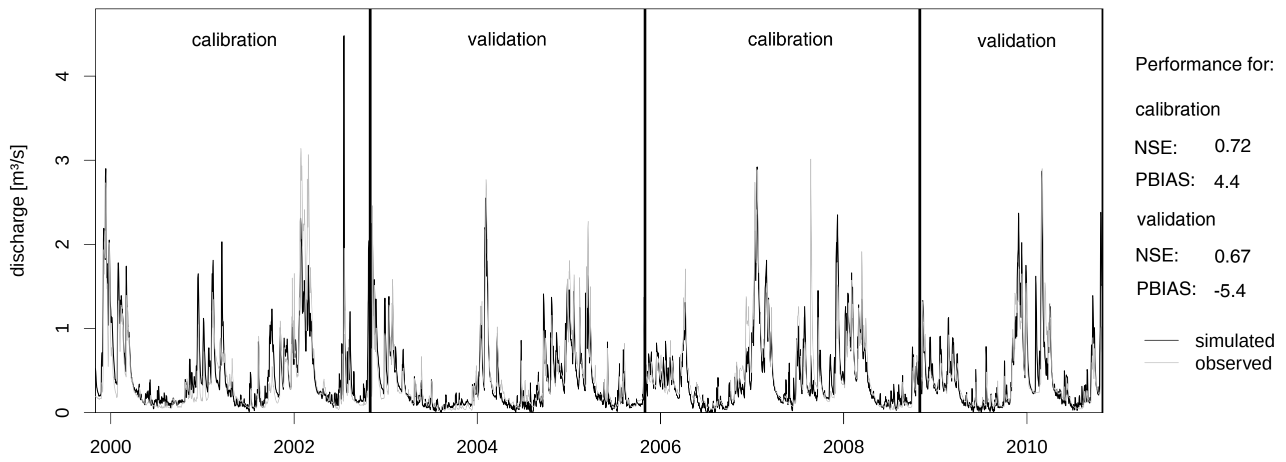

Figure 5. Daily Observed (grey) and simulated (black) discharge for the study catchment with model performance (Nash-Sutcliffe efficiency (NSE) and percent bias (PBIAS)) for the calibration and validation period after Pfannerstill et al. (2014b).

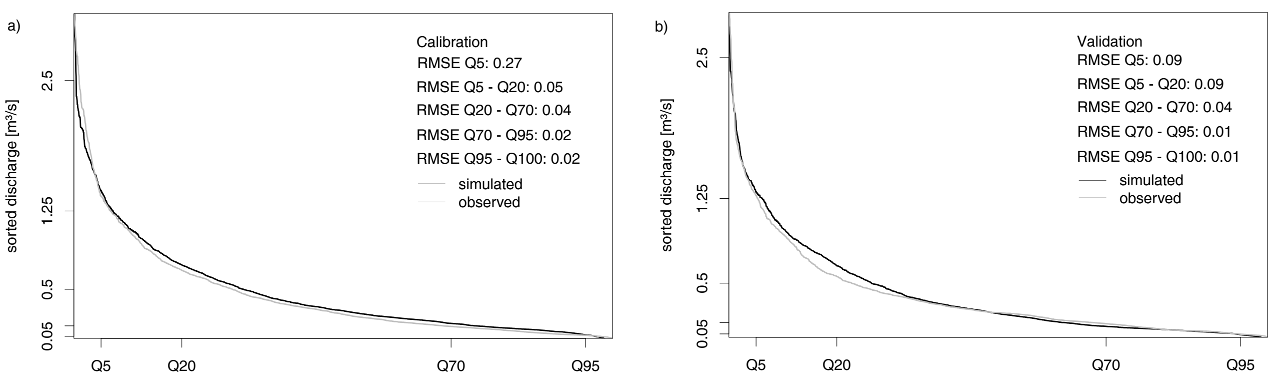

Figure 6. Flow duration curve of observed (grey) and simulated (black) discharge magnitudes for the calibration period (a) and the validation period (b). The model performance is depicted with root mean square error (RMSE) of the different flow duration curve segments according to Pfannerstill et al.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

The proposed framework for model verification requires (i) observations and knowledge about the catchment to (ii) derive hypotheses about the observed temporal process sequence. Contrary to observed processes of the catchment, TEDPAS is used to (iii) calculate temporal parameter sensitivities to (iv) extract the simulated temporal process sequence. Finally, the model verification is performed by (v) determining the agreement between observed and simulated temporal process sequences.
Based on our results, we propose TEDPAS as a method to provide relevant diagnostic information. TEDPAS is applied to analyse the temporal process sequence including all relevant hydrological processes.

The main outcomes of this study are:

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

– TEDPAS provides the simulated temporal process sequence of the whole model for the verification with the observed temporal process sequence.

We recommend the use of TEDPAS$_{catchment}$ 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.

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