

## Comments on the Editor's review on manuscript hess-2014-528

Dear Prof. Zehe,

We carefully checked the comments of the two reviewers, who recommended the publication of the manuscript after minor revisions. In the following, we will describe the revision of the manuscript by addressing each of the comments and recommendations step by step.

### Comments and recommendations of referee #1:

**Shervan Gharari: The revised manuscript has been improved significantly and it is much clearer now. To what I understood from the paper the work is as follow:**

- **The authors took a model and calibrated it.**
- **The authors studied and listed the way catchment seems to function in their view.**
- **The authors compared the way they perceived the catchment is working with calibrated model via sensitivity of the model parameters.**

We are glad that the revised manuscript points out more clearly our idea of how to verify process dynamics in hydrological models. Based on the given summary, we conclude that the most essential steps of our framework are much clearer now. However, there seems to be still some lack of clarity about the necessity of model calibration. We would like to emphasise that our verification framework with TEDPAS does not need a calibration. In our revised manuscript we integrated this aspect. The temporal parameter sensitivities are calculated to gain information of the temporally resolved behaviour of the model parameters. With this information, we perform a diagnostic evaluation of the hydrological model on the observed processes of the catchment (cf. P.2 l.129 – 139).

**Shervan Gharari: However in my point of view the paper can be written with better language. I would suggest the authors to make the paper more fluent.**

We took up this recommendations and carefully checked the language and for complicated sentences and had another proofreading. We identified that the methods chapters would benefit from reformulation and rewording. For this, we completely reworked the chapters of "Processes observed in the catchment" and "Derived hypotheses" (cf. p. 2-3, l. 155 – 184). Additional minor revisions for the whole manuscript are marked in bold within the manuscript.

**Shervan Gharari: I would rewrite many parts of the paper starting from the title; instead of the current title the authors can use a more revealing title such as “Verification of processes [in model XXX] using a temporal parameter sensitivity analysis” or “On the role of parameter sensitivity analysis for the process verification [for a model XXX]”. Just a simple example which I can point out is page 4 line 213. The authors wrote “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”. These sentences can be shortened and rewritten in the following ways “The sum of all partial variances cannot be higher than one by definition.” Or “Because of parameter interactions the sum of all partial variances fluctuates between 0 and 1 while it cannot be more than 1 by definition.”**

We thank the reviewer for providing suggestions of how to improve the title of the manuscript and additional suggestions of how to restructure sentences of the technical method chapter. According to these suggestions and after discussion with all authors, we would like to change the title of the manuscript to „Process verification of a hydrological model using a temporal parameter sensitivity analysis“. We think that this title summarises the content of the manuscript more clearly than the previous one. Furthermore, we revised the descriptions and definition of the partial variances according the reviewer’s recommendation (p. 4, l. 225 – 229). Furthermore, we reworded and shortened the beginning of the introduction (p. 1, l. 21 – 36). We think that this rewording leads to a clear definitions and improves the readability.

**Shervan Gharari: In my point of view the paper reads much better scientifically now and deserve to be published. However as I mentioned I think the paper will benefit a lot by smoothing the use of English language. As I am not a native speaker and my English skills might be poor I leave it to the Editor to decide.**

We agree with the reviewer and had a proof reading by another native speaker to improve several wordings within the manuscript. These changes are marked in the revised version of the manuscript in bold.

## Comments and recommendations of referee #2:

**Referee #2: In this new version, the manuscript has undergone some major and necessary improvements, which has eliminated the major issue of circular reasoning. My reading of the current version is essentially an implementation of the TEDPAS sensitivity analysis on an implementation of the SWAT model for a watershed in Germany. This is a useful case study, and may be worth publishing. The manuscript is generally well written, and the presentation of figures and tables is of good quality.**

We are thankful that referee #2 reviewed our revision of the previous manuscript version. Due to his short summary about the applied method, we conclude that the understandability of our idea for model verifications with TEDPAS has improved significantly. According to the reviewer's report, the major issue of circular reasoning has been removed by emphasising that our hypotheses were derived from observed processes of the catchment.

**Referee #2: The introduction can do with a better contextualization of TEDPAS in the contemporary literature. In particular, methods such as DYNIA and TIGER (as suggested by resp. the other reviewer and the editor) are relevant and even if not implemented can be used to sketch a broader picture of temporal sensitivity analysis.**

The recommendation about setting additional and contrary diagnostic model analyses into context was taken up at our revision of the manuscript. Of course, other methods such as DYNIA or TIGER are valuable methods to diagnose the model's behaviour, especially in the context of temporal analyses of model parameters and model performance. According to the recommendations of referee #2, we integrated and emphasised two aspects within the introduction. Firstly, we give a short and general introduction into parameter sensitivity analyses to finally highlight the value of temporally resolved parameter sensitivities (cf. p. 1, l. 53 – 61). Secondly, we discussed the role and aims of the different methods such as TIGER and DYNIA. In our opinion, both methods provide diagnostic information to detect model structure related deficiencies. Based on this possibility for model diagnostics, we propose a further interpretation of TEDPAS to diagnose the appropriateness of model structure in relation to real-world processes, which is the content of this current manuscript (cf. p. 2 l. 69 – 84).

**Referee #2: I can understand the angle of hypothesis testing used in the paper, but I think that it still sits a bit uncomfortable. The problem with many hypotheses including those put forward in the manuscript is that they are vague and either too straightforward or too hard to test. In this case, I think that one would struggle to find a hydrologist that would disagree with any of those listed in Table 1. Another problem with the hypothesis discourse is that it makes the language of the introduction rather heavy handed and difficult to read. It might be worth considering the hypotheses simply as key pieces of knowledge about the catchment processes, and TEDPAS as a powerful method to make sure that those are represented in the model? A more fundamental problem with the hypotheses is that they are qualitative. It would have been ideal if any hard data were available, for instance the start and end time of tile drainage contribution. The lack of such data makes building a strong argument difficult, and as a result the discussion is rather fuzzy. But I understand that this is outside the scope of the study.**

We can understand the reviewer's thoughts about the hypotheses that are used for our methodology. Certainly, we agree that hard data in terms of measured observations would be favourable to formulate hypotheses. However, despite of progress in measurement techniques the amount of hard data in addition to precipitation and discharge observations is generally still limited, especially for large catchments. We took up this point into the discussion of the manuscript to

highlight the value of hard data (cf. p. 9, l. 626 – 629). With our manuscript, we would like to encourage the reader to make sure that hydrological processes are implemented into the model reasonable in terms of real-world processes. According to our case study, we propose the application of the newly developed verification framework by using at least soft data. We see our work in the way of optimising the use of model results in diagnostic analysis as emphasised by Gupta et al. (2008). It is of course up to the modeller to integrate additional hard data to formulate hypotheses. Furthermore, we agree with the reviewer that the introduction needs revisions to improve the understandability. For this, we reworded and restructured the general idea about integrating catchment knowledge and observed processes (cf. p. 2-3, l. 155 – 184):

## 2.1 Processes observed in the catchment

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

## 2.2 Derived hypotheses

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

**Referee #2: The temporal sensitivity plots in figure 3 and 4 are useful, but I wondered whether it would be possible to add a stacked area plot showing the different contributions to streamflow, especially related to the flows mentioned in the hypotheses. I think that this could be a very intuitive visualization of how the model simulates the magnitude and timing of these flows (e.g., when tile flow contribution starts, peaks, and stops). As such, it may also help with a qualitative evaluation of the model.**

In our opinion, this recommendation of how to improve the information content of the temporal sensitivity plot is very helpful. We used averaged model output of hydrological components such as tile drainage flow, groundwater flow or evapotranspiration and integrated this information into figure 4 with an intensity band. This band of intensity supports the decision if the raised hypotheses can be verified. To give an example, high tile drainage flow can be assigned to phases of high discharge in winter and high temporal sensitivity. This finding emphasises that our hypothesis about tile drainage flow was verified. Based on the improved information content of figure 4, we see improved opportunities to evaluate the model qualitatively. The main improvement is related to the possibility of comparing temporal parameter sensitivity, discharge magnitude, and modelled discharge contribution of the analysed hydrological component

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

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**Abstract.** To ensure reliable results of **hydrological models**, it is essential that the models reproduce the hydrological process **dynamics** adequately. Information about **simulated** process dynamics is provided by looking at the temporal sensitivities of the corresponding model parameters. For this, the temporal dynamics of parameter sensitivity are analysed to identify the **simulated** hydrological **processes**. Based on these analyses it can be verified if the **simulated** hydrological processes match the observed processes of the real-world. We present a framework that makes use of processes observed in a study catchment to verify simulated hydrological processes. Temporal dynamics of parameter sensitivity of a hydrological model are interpreted to simulated hydrological processes and compared with observed hydrological processes of the study catchment. The results of the analysis show the appropriate simulation of all relevant hydrological processes in relation to processes observed in the catchment. Thus, we conclude that temporal dynamics of parameter sensitivity are helpful for verifying simulated processes of hydrological models.

**represented are essential. To determine if the model behaviour is consistent with the hydrological processes observed in a catchment, the model structure, i.e. the model equations and parameters, needs to be considered when evaluating the model output (e.g. Hrachowitz et al., 2014).** Model diagnostic analyses as proposed by Gupta et al. (2008) and Yilmaz et al. (2008) determine the appropriateness of process descriptions in the model structure. Thus, diagnostic methods help to detect failures in models and the corresponding components that need to be improved (Fenicia et al., 2008; Reusser and Zehe, 2011; Guse et al., 2014). As stated by Yilmaz et al. (2008), a systematic approach **to analysing the adequacy of model structures** is needed since the processes **occurring in a catchment** are not always represented appropriately within hydrological models (Clark et al., 2011). There is a need to assess if the model structures and the simulated processes are consistent with observed hydrological processes within the catchment (Gupta et al., 2012). This is a step towards establishing a general framework for model accuracy verification (Wagener et al., 2001; Yilmaz et al., 2008).

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

**Temporal parameter sensitivity analyses detect periods in which a certain parameter or a set of parameters controls the model output (e.g. Massmann et al., 2014).** This

## 1 Introduction

**Discharge, one of the major outputs of hydrological models, is controlled by a number of interacting processes. However, a simple comparison of observed and simulated discharge, which is often the only criterion used for model calibration and evaluation, does not take into account the underlying processes that shape the hydrograph. For a more profound assessment of the reliability of model results, a deeper understanding of how these processes are described in the model and a more detailed analysis of how well the corresponding real-world processes are**

information can be obtained by TEMporal Dynamics of PA-  
parameter Sensitivity (TEDPAS, Sieber and Uhlenbrook, 2005;  
Reusser et al., 2011; Guse et al., 2014; Haas et al., 2015).

**In contrast to other temporally resolved sensitivity anal-  
yses, which were applied on performance metrics (van  
Werkhoven et al., 2009; Herman et al., 2013), TEDPAS  
detects dominant model parameters by analysing their  
sensitivity on the modelled discharge in a high temporal  
resolution. Thereby, it helps to explain the model's be-  
haviour by detecting the temporal dominance of individ-  
ual model components. Reusser et al. (2009) used TED-  
PAS in combination with TIGER, a temporal model per-  
formance analysis (Reusser et al., 2009), to characterise  
the types of errors in the output of hydrological models  
(e.g. the simulation of discharge). Wagener et al. (2003)  
analysed parameter variations over time to reproduce ob-  
served hydrological data. Both approaches have in com-  
mon that they focus on the link between model perfor-  
mance and deficiencies of the model structure. However,  
the capabilities of TEDPAS for examining model struc-  
tures have not been fully exploited yet.**

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

In this context, Guse et al. (2014) used TEDPAS and TIGER  
to detect which component of a hydrological model was re-  
sponsible for poorly simulated baseflow in dry years. Al-  
though the **temporal variability of the parameter sensitiv-  
ity** was reasonable, the model performed poor for several per-  
formance 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 ground-  
water processes. The analysis of Pfannerstill et al. (2014b)  
showed that the modification improved the simulation of  
the discharge with respect to different performance metrics.  
**However, an analysis of the hydrological processes and  
their representation by the model structure are required  
to prove that the simulation of discharge was improved  
for the right reasons (Kirchner, 2006).**

**Therefore, this study aims at developing** a method that ver-  
ifies appropriate process simulation of hydrological models  
using TEDPAS and observed hydrological processes of the  
study catchment. Based on an application example, we pro-  
pose 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) use observed hydrological pro-  
cesses of a catchment for (ii) comparison with TEDPAS re-  
sults to (iii) verify **that processes are adequately simulated  
by a hydrological model.**

## 2 Methods

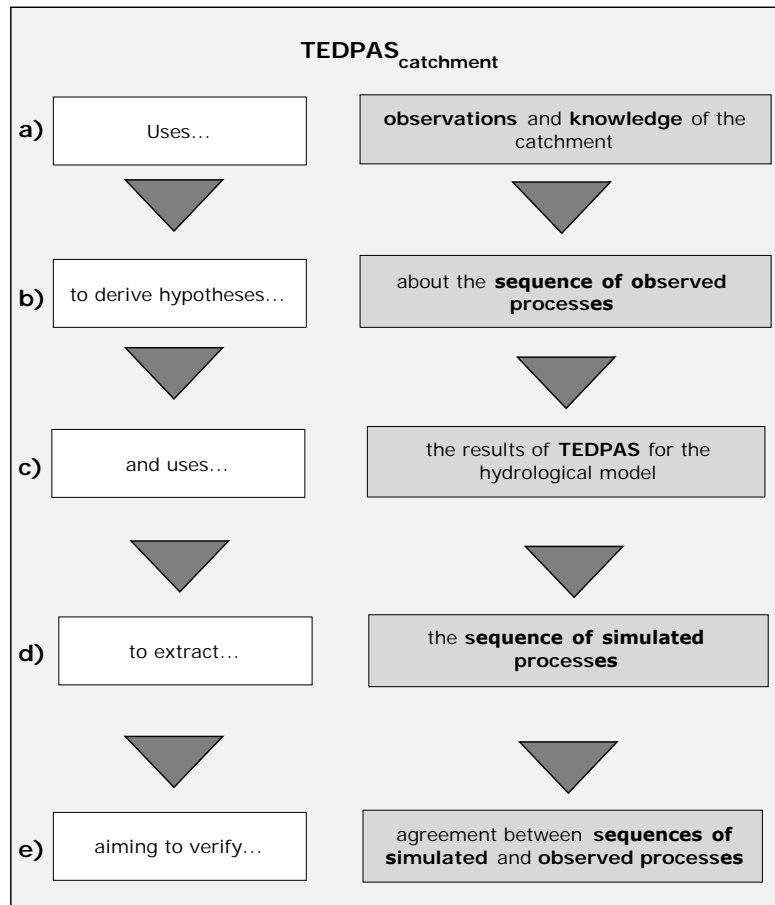
The general idea of the proposed framework is to make use  
of processes **observed within** the catchment and results of  
TEDPAS to verify hydrological models (Fig. 1). For this,  
all available information **about processes occurring in the  
study catchment is collected** (Fig. 1a). **These processes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

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

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

### 2.1 Processes observed in the catchment

To achieve hydrologically consistent model results, the  
model should be able to simulate all relevant hydrological  
processes of the study catchment. **Therefore, knowledge  
about observed hydrological processes is crucial to eval-  
uate the hydrological consistency of the model results.  
For this, all available information available from previ-  
ous field studies and general knowledge about hydrologi-  
cal characteristics of the study catchment needs to be col-  
lected** (Fig. 1a). This information is then used to identify  
**all relevant hydrological processes of the study catchment  
and the timing of their occurrence.**



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

## 170 2.2 Derived hypotheses

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

## 185 2.3 TEDPAS methods

TEDPAS was selected to provide the temporal sequence of simulated processes for comparison to the temporal sequence of observed processes (Fig. 1c). As shown in recent studies for several models with different complexity (Gupta et al., 2008; Yilmaz et al., 2008; Herbst et al., 2009; Reusser et al., 2009; van Werkhoven et al., 2009; Garambois et al., 2013; Herman et al., 2013; Pfannerstill et al., 2014b; Guse et al., 2014; Haas et al., 2015), a high temporal resolution is essential for proper diagnostic model evaluation. TEDPAS aims at improving the understanding of model dynamics and identifying temporal dynamics of parameter sensitivity. For each time step, the sensitivity of changes in the values of different parameters on the model output (e.g. discharge) is calculated (cf. Reusser et al., 2009; Guse et al., 2014). The presented framework for a TEDPAS-based verification aims at providing insights into the modelled hydrological system in a high temporal resolution by using the widely available

daily discharge. **However**, TEDPAS is **generally** applicable with or without measured data.

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

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

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

$V$  = total variance  
 $V_i$  = variance of parameter  $\theta_i$  (first order variance)  
 $V_{ij}$  = covariance of  $\theta_i$  (second order variance) and  $\theta_j$  and higher order terms

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

Readers are referred to Reusser and Zehe (2011) for further details.

## 2.4 Identification of simulated processes with TEDPAS

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

## 2.5 Model verification by combining hypotheses and TEDPAS

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

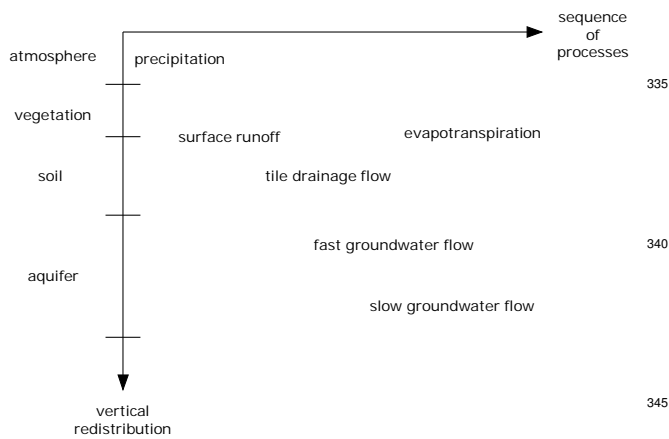
## 3 Framework application example

### 3.1 Catchment description

The Kielstau catchment comprises an area of about 50 km<sup>2</sup> and is located in the federal state of Schleswig-Holstein in North Germany. It is a subbasin of the Treene catchment to which TEDPAS has **previously** been applied by Guse et al. (2014) and Haas et al. (2015). The catchment is characterised by a maritime climate with a mean annual precipitation of 918.9 mm and mean annual temperature of 8.2 °C (Station: Gluecksburg-Meierwik, period: 1961 - 1990; DWD, 2012). As reported by Kiesel et al. (2010), the catchment has a high water retention potential. 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). **Decreasing tile drainage flow has been observed from April and May** before tile drainage flow stops during the relatively dry summer months (Kiesel et al., 2009).

Another main characteristic of the Kielstau catchment is the close interaction between river and groundwater, which is due to high groundwater water tables that are directly connected to the river (Schmalz et al., 2008). The near-surface groundwater is controlled by precipitation, especially in win-





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

ter (Schmalz et al., 2008). A more detailed description of the catchment can be found in Fohrer and Schmalz (2012).

### 3.2 Hypotheses derived from observed processes

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

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

The amount of water that does not run off on the surface infiltrates into the soil and is stored for a limited time **depending** on the soil water storage capacity. **As shown by Kiesel et al. (2009, 2010) and Schmalz et al. (2008), the storage capacity in the catchment is directly connected with tile drainage and groundwater dynamics.** In winter, groundwater tables are high, which results in a high potential for groundwater extraction through the tile drainages (Kiesel et al., 2010). Based on the observations of Kiesel et al. (2009), tile drainage flow **is expected to cause** peak flows in winter due to groundwater ponding and a high soil water content. Consequently, we hypothesise that the tile drainage flow is highly relevant in winter and of minor importance in summer (H2: tile drainage flow in winter).

High groundwater tables are **one of** the most important **hydrological** characteristic in the study catchment. During win-

ter 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 summer, the extent of groundwater-surface water interactions decreases,** but groundwater storage remains the main contributor of flow to the river (Schmalz et al., 2008). Based on these assumptions, we hypothesise a high relevance of fast groundwater flow in winter and high relevance of the slow groundwater flow in the beginning of summer (H3: seasonality of groundwater flow).

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

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

### 3.3 TEDPAS application

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

#### 3.3.1 Model description and setup

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

The water balance is driven mainly by the processes of pre-

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

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

precipitation, evapotranspiration, runoff, soil water percolation, drainage and groundwater flow. Runoff is routed through the main reaches of the subbasins to the catchment outlet. A detailed description of process implementation and the theory about the SWAT model can be found in Neitsch et al. (2011). **Catchment-specific input data is required to set up the model, including a soil map (resolution 1:200.000, BGR, 1999) and a digital elevation model (resolution 5 m; LVerMA, 1995). The data on land use and crop rotations used in this study was derived from two mapping campaigns during the cropping seasons 2011/2012 and 2012/2013 (Pfannerstill et al., 2014a, b).** The spatial distribution of tile drainages and databases for soil and crops were obtained from Fohrer et al. (2013, 2007).

Precipitation data 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<sub>3S</sub> 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<sub>3S</sub>.

### 3.3.2 Model simulations

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

2015). Based on the parameter variation set that was generated with FAST (Reusser, 2012), TEDPAS required 687 model runs.

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

### 3.4 Process verification of SWAT<sub>3S</sub> with TEDPAS<sub>catchment</sub>

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

## 4 Description and discussion of the results

TEDPAS was used to determine the **temporal sequence of simulated processes** by analysing the temporal sensitivities of the different model parameters (Fig. 3). The results show that the impact of the different parameters on discharge changed remarkably over time (Fig. 3). To determine the agreement between **the temporal sequences of observed and simulated processes**, the results of TEDPAS shown in Fig. 3 were analysed in detail for each parameter. For this, we selected appropriate time periods for each model parameter **and averaged model output of hydrological components to test the derived hypotheses against the temporal parameter sensitivity** (Fig. 4).

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

Parameter name	Abbreviation	Process	Range	Type
Curve number	CN2	SR/SW	-15 - 15	as
Surface runoff lag coefficient	SURLAG	SR	0.2 - 4.0	r
Available soil water capacity	SOL_AWC	SW	-0.07 - 0.10	as
Tile drain lag time	GDRAIN	DF	0.5 - 2.0	m
Distance between two tile drains	SDRAIN	DF	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 <sub>fsh</sub>	GW	1 - 15	r
Recession fast shallow aquifer	ALPHA_BF <sub>fsh</sub>	GW	0.3 - 1	r
Percolation slow shallow aquifer	RCHRG <sub>ssh</sub>	GW	0.65 - 0.80	r
Delay slow shallow aquifer	GW_DELAY <sub>ssh</sub>	GW	15 - 60	r
Recession slow shallow aquifer	ALPHA_BF <sub>ssh</sub>	GW	0.0001 - 0.3000	r
Percolation deep aquifer	RCHRG <sub>dp</sub>	GW	0.1 - 0.4	r

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 **temporal sequence of observed 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 **and single surface runoff events** (Fig. 3 and Fig. 4). **Additionally, it is clearly shown that these events are connected to high amounts of daily precipitation.**

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

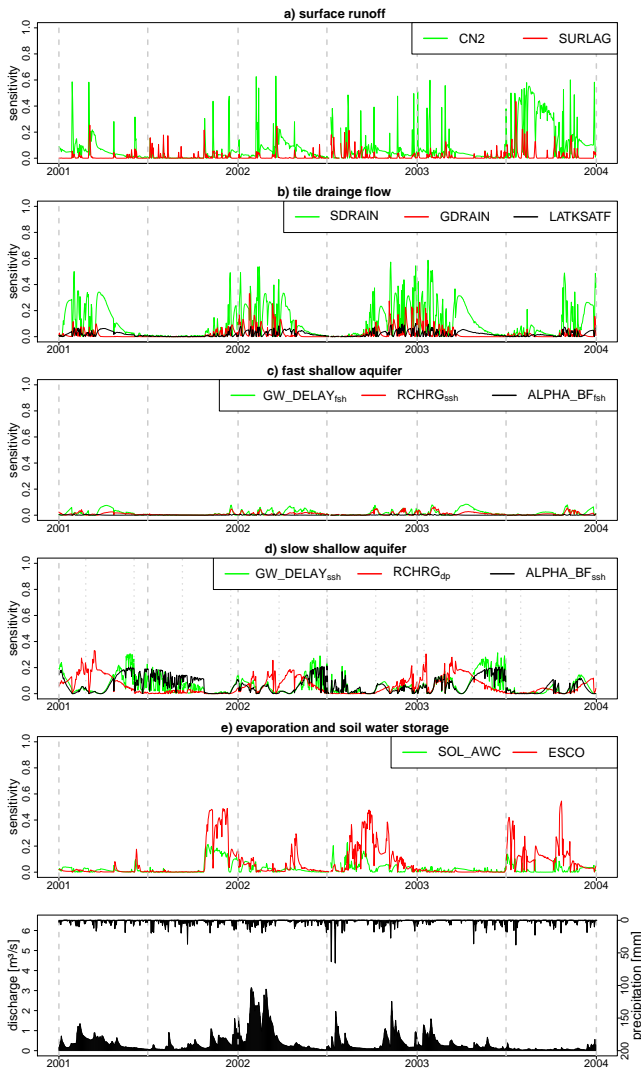
The low impact of the tile drainages **during low flow periods** can be further explained by the groundwater dominance, which is the next step in the **temporal sequence of observed processes that is** described by the concept of vertical water redistribution (see Fig. 2). The high impact of groundwater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

Additionally, there is a clear separation for the relevance of the fast and the slow shallow aquifers. The time delay for

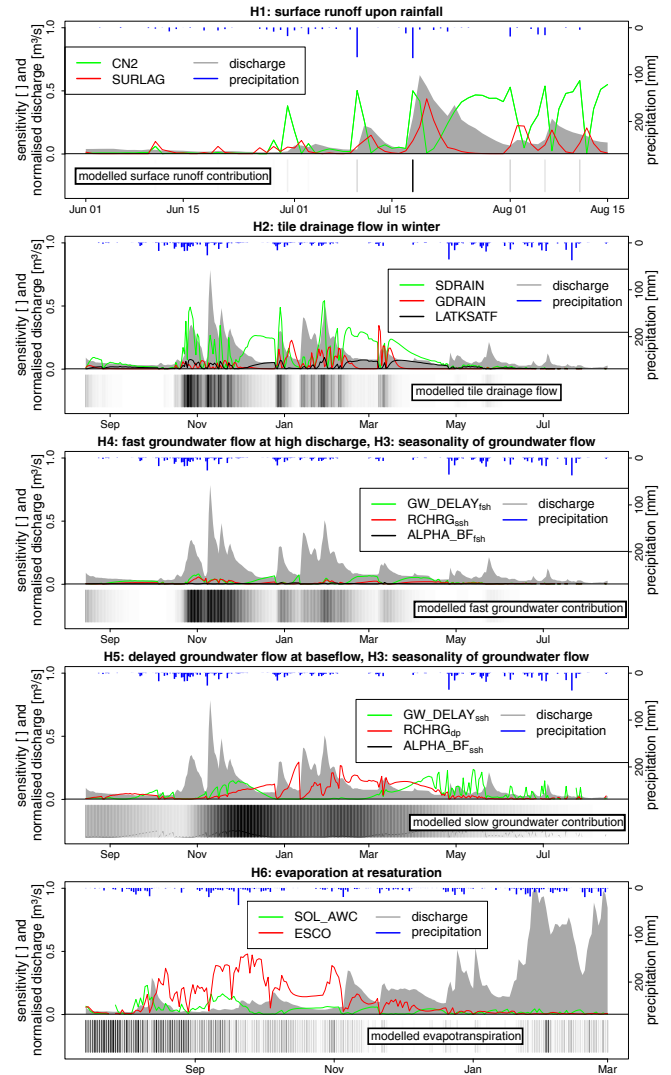
recharge of the fast shallow aquifer (GW\_DELAY<sub>fsh</sub>) becomes less relevant **when** the influence of the time delay parameter of the slow shallow aquifer (GW\_DELAY<sub>ssh</sub>) increases. This result clearly depicts **the fast shallow aquifer recharge** at high discharge with fast groundwater contribution (ALPHA\_BF<sub>fsh</sub>), followed by a delayed slow shallow aquifer recharge at recession phases with slow groundwater contribution (ALPHA\_BF<sub>fsh</sub>, H3, H4, H5). Consequently, the low flow during dry periods is controlled by flow from the slow shallow aquifer to the channel (Fig. 4). This finding supports hypothesis H3, which expects a high relevance of the slow shallow aquifer parameters in the beginning of the low flow period in summer but low relevance in winter.

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

The partitioning of recharge of the slow shallow and the deep aquifer (RCHRG<sub>dp</sub>) was particularly important at the beginning of recession phases (Fig. 3 and 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 **recharges 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



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



**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 evaporation and soil water storage (H6). Additionally, the normalised observed discharge and modelled hydrological output (averaged and normalised, intensity from low (white) to high (black)) and the precipitation are shown for each subplot.

study catchment as the recharge to the fast shallow aquifer is intended to be more important during wet phases with fast groundwater recharge (H3, H4). In contrast, the slow shallow aquifer controls the slow recharge before recession phases (H3, H5).

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

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

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

## 5 Relevance of TEDPAS for model verifications

TEDPAS is a central method for model diagnostics and the verification of models (Fig. 1). We **developed** TEDPAS<sub>catchment</sub>, which is a verification framework that **uses** processes observed in a catchment **in combination** with TEDPAS. In the following, it is discussed **if the** presented verification framework provides **useful** diagnostic information for **the verification of hydrological models**.

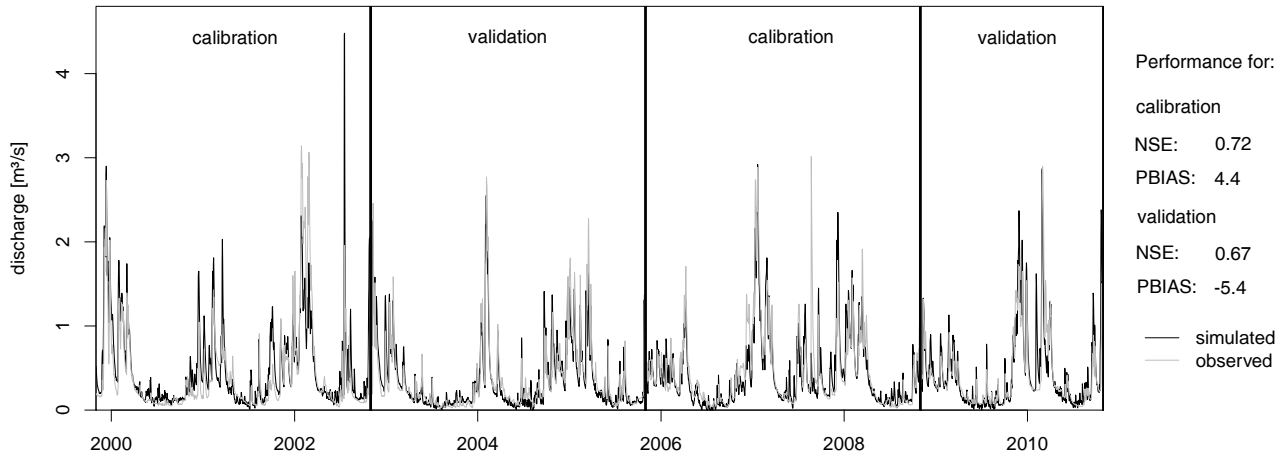
In this study, we exemplify the analysis of a model in regard to the hydrological consistency and the hydrological processes within a catchment. The general application of this framework is **discussed** by abstracting our findings into a more general context. We hypothesise that TEDPAS<sub>catchment</sub> is applicable **to** any hydrological model in any catchment.

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

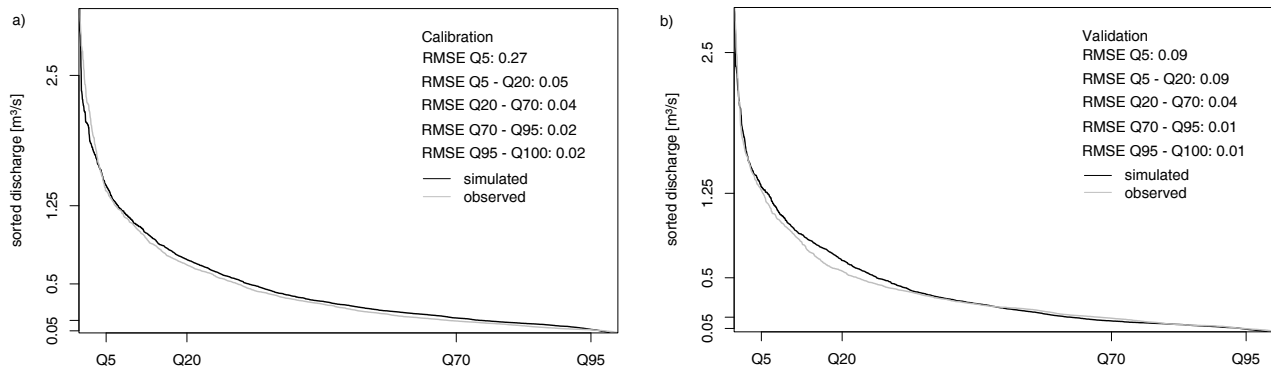
However, it has to be **pointed out** that the confirmation of a realistic **temporal sequence of processes** is just one side of the coin. In the context of hydrological consistency, the hydrological model should be also able to reproduce commonly available hydrological data (e.g. discharge). For this,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

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

**Regardless from the kind and amount of available data**, this study shows that TEDPAS is needed for the extraction of comprehensive model diagnostic information. The application of TEDPAS in our demonstration example revealed



**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).

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 TEDPAS as a verification method in model diagnostics. As shown in Fig. 1, we propose five aspects that need to be considered for model diagnostics and the verification of models.

The proposed framework for model verification requires (i)

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

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

The main outcomes of this study are:

- TEDPAS<sub>catchment</sub> provides diagnostic information for the verification of the consistency between the **temporal sequence of observed and simulated processes**.

The **temporal sequence of observed processes** is derived from qualitative knowledge of the catchment, and the concept of vertical water redistribution.

- TEDPAS provides the **temporal sequence of simulated processes for comparison against the temporal sequence of observed processes**.

We recommend the use of TEDPAS<sub>catchment</sub> 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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