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Analysing spatio-temporal process and parameter dynamics in models to characterise contrasting catchments

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Abstract

The relevance of hydrological processes varies in space and time resulting in typical temporal patterns for catchments. Contrasting catchments moreover differ in their catchment metrics. Hydrological models claim to be able to reproduce typical temporal patterns of dominant processes using site-specific model parameters. Thus, patterns of temporal dynamics in dominant modelled processes and their corresponding dominant parameters are a fingerprint of how a model represents the hydrological behaviour of a catchment and how these process patterns vary between contrasting catchments.

In this study, we demonstrate how catchment metrics, modelled processes and parameter dominances can be jointly used to characterise catchments. We assess how catchment characteristics are represented in spatio-temporal process dynamics in models and how to understand the reasons for hydrological (dis)similarity among catchments along a landscape gradient. For this purpose, catchment metrics which characterise contrasting landscapes (lowland, mid-range mountain and alpine catchments) are related to dominant processes and parameters which were provided by a temporally resolved sensitivity analysis (TEDPAS) and simulations of a hydrological model.

Our study shows that the applied model is able to represent the different processes and their seasonal variability according to the specific hydrological conditions of the study catchments. By analysing catchment metrics, modelled processes and model parameters jointly, we show that the largest differences are identified for the alpine catchment, whilst similarities are found among the other catchments. Following a landscape gradient, high flow phases are dominated by different flow components. In contrast, the model shows groundwater dominance in low flow phases in non-alpine catchments while in the alpine catchment low flows in winter are mainly controlled by snow processes. The joint analysis of catchment metrics, temporal dynamics of dominant processes and parameters can therefore be used to better disentangle similarities and differences among catchments from different landscapes.

1. Introduction

The relevance of different hydrological processes in controlling the hydrological system varies in space between catchments due to different characteristics in landscape and climate (Atkinson et al., 2002; Merz and Bloeschl, 2004; Bai et al., 2009; Jothityangkoon and Sivapalan, 2009; Köplin et al., 2012). Moreover, dominant processes are known to be variable in time due to seasonal variations in driving factors such as precipitation or radiation (Boyle et al., 2000, 2001; Shamir et al., 2005; Guse et al., 2016a). Thus, also the three catchment functions - partitioning, storage and release of water - are variable in space and time (Wagener et al., 2007; Sawicz et al., 2011).

In models, different hydrological processes are represented by storages and fluxes as well as by model parameters. Implicitly, complex hydrological models assume to be able to represent the hydrological behaviour in different catchments by site-specific identification of model parameter values and by emphasising or neglecting hydrological processes of major or minor relevance, respectively. It is still challenging in hydrological modelling how to reproduce the variability of process relevance in space and time, i.e. the spatio-temporal dynamics, accurately (Wagener et al., 2007; Hrachowitz et al., 2013; Melsen et al., 2016b). To investigate this, it is required to analyse the model capability to reproduce spatio-temporal process dynamics and how the controlling processes and parameters vary in contrasting catchments in different landscapes (Bai et al., 2009; Carrillo et al., 2011; Donnelly et al., 2016).

Contrasting catchments can be characterised by differences in specific metrics as typical statistical values such as mean annual precipitation or mean elevation (Wagener et al., 2007; Carrillo et al., 2011; Sawicz et al., 2011; Ali et al., 2012; Köplin et al., 2012). Catchment metrics vary between different types of landscape or climate as well as between seasons and also in different temporal scales. A set of catchment metrics can thus lead to typical fingerprints of hydrological behaviour (Wagener et al., 2007; Ali et al., 2012; Berghuijs et al., 2014; Donnelly et al., 2016).

Spatial process patterns are derived using a large set of catchments (van Esse et al., 2013; Gupta et al., 2014; Köplin et al., 2012; Markstrom et al., 2016). However, in detailed diagnostic model analyses, modelled process dynamics can be related to catchment characteristics using a small set of representative case studies to demonstrate the methodological approach (van Werkhoven et al., 2009; Euser et al., 2013; Herman et al., 2013b; Massmann et al., 2014; Melsen et al., 2016a). For this, complex hydrological models need to accurately reproduce the complexity of different process relevances in contrasting catchments. Diagnostic approaches have been proven suitable to identify the causes for hydrological similarity (Carrillo et al., 2011; Hrachowitz et al., 2013).

In several diagnostic model analyses, the modelled impact of spatial and temporal variations in dominant processes on the hydrological behaviour is highlighted (Reusser et al., 2009; Herman et al., 2013b,a; Guse et al., 2014; Pfannerstill et al., 2015; Guse et al., 2016b). A dominant process is here defined as the most relevant process in a model for a certain time period. The relevance of a certain process varies both in time and between different catchments resulting in differences in the relevance of the corresponding model components (Markstrom et al., 2016) as considered in flexible model structures (Clark et al., 2008; Fenicia et al., 2011; Euser et al., 2013; Coxon et al., 2014). A hydrologically consistent model needs to be able to simulate differences in dominant processes and to reproduce them in temporal parameter patterns in coincidence with the observed processes in the catchment (Pfannerstill et al., 2015; Donnelly et al., 2016). To reproduce both spatial and temporal dynamics, processes and their relevance need to be represented accurately in model structure and model parameters (Wagener et al., 2003).

A variation in the process relevance in time will inevitably result in a change in parameter sensitivity (van Werkhoven et al., 2008; Herman et al., 2013b; Pfannerstill et al., 2015; Guse et al., 2016a). Parameter sensitivity analysis is increasingly used to improve our understanding of how process dynamics behave in models. In the temporal dynamics of parameter sensitivity (TEDPAS) (Reusser et al., 2011), the sensitivity of model parameters is analysed for each time step. In this way, also the dominant processes in the model are derived for each day and based on this, temporal changes in dominant processes are precisely pointed out (Reusser et al., 2011; Guse et al., 2014). The resulting temporal patterns of dominant model parameters depend both on the model structure itself and on the hydrological characteristics of the catchment (Euser et al., 2013; Massmann et al., 2014; Fovet et al., 2015; Pfannerstill et al., 2015; Guse et al., 2016b). Several studies have shown that the relevance of model parameters and their sensitivity on modelled output changes in space and time and results in a typical fingerprint of how a model represents catchment processes (Reusser et al., 2011; Guse et al., 2014; Markstrom et al., 2016). While TEDPAS was already successfully applied in different catchments (Reusser et al., 2011; Guse et al., 2016b), an analysis of how different catchment characteristics affect temporal patterns of dominant processes and parameters is still missing.

In this study, it is investigated how spatio-temporal dynamics in processes and model parameters are related to typical catchment characteristics and in which aspects contrasting catchments behave similar. Thus, this study aims to analyse two points. First, we analyse how catchment metrics as typical characteristics of catchments are related to spatio-temporal variability of dominant processes and parameters. Based on this, we investigate whether a hydrological model that aims to be globally applicable is able to emphasise the dominant processes and their corresponding parameters in contrasting catchments.

Second, we investigate how spatial variability in catchment metrics, modelled processes and dominant parameters contribute to understand the (dis)similarity between catchments. Thus, catchment similarity is assessed based on data and model results, i.e. in modelled processes, as well as by looking at variations in parameter dominances in space and time. We intend to analyse how the understanding of process behaviour in models benefits from using parameter dominances for analysing catchment similarity. We hypothesise that by comparing all three types of information for contrasting catchments, similarities and differences between catchments and more specifically between the controlling processes can be derived.

These two points result in the following main research questions:

Can a universally applicable hydrological model represent the characteristics of contrasting catchments by typical dominant processes and parameter dynamics?

How do catchment metrics, modelled processes and dominant parameters contribute to explain similarities and differences between contrasting catchments?

2. Materials and methods

The methodical approach is described in Fig. 1. It is based on three pillars: data-based catchment metrics, modelled processes and dominant model parameters. We hypothesise that by comparing all three types of information for contrasting catchments, (i) it can be analysed how differences in catchment metrics are reproduced in temporal variations of both dominant processes and dominant model parameters and (ii) similarities and differences between the catchments can be derived.

[Figure 1 about here.]

2.1. Study catchments and catchment metrics

The study catchments can be classified along an elevation gradient from alpine catchments with high elevations via mid-range mountains to lowland catchments. To consider these catchment types, four catchments were selected for this study that are spatially distributed in Germany and cover different types of landscapes (Fig. 2). The Treene catchment is a typical lowland catchment which is situated in the North of Germany (catchment outlet Treia, 481 km^2). The Kinzig catchment belongs to the mid-range mountains (catchment outlet Hanau, 925 km^2). The Kinzig flows into the River Main in Central Germany. The Upper Saale catchment at the gauge Blankenstein (1019 km^2) is located in Southeastern Germany and used as an example for a mid-range mountain catchment. The Ammer is in southern Germany and is a typical alpine catchment and flows into the Ammer Lake. The gauge station Peissenberg (catchment size 299 km^2) is used for the model analysis.

[Figure 2 about here.]

We characterised our study areas by catchment metrics (Tab. 1) with respect to five categories: topography, land use, temperature, precipitation and discharge. For the dynamic variables - precipitation, temperature and discharge - monthly values and the seasonality index are shown for the period from 2000 to 2010. A higher seasonality index indicates a higher variability within the year (for further details see Coopersmith et al. (2012, 2014); Guse et al. (2016a)).

The elevation increases from Treene via Kinzig and Saale to the Ammer catchment. In contrast, the slope is slightly larger in the Kinzig compared to the Saale catchment. The mean slope of 1.3% assigns the Treene catchment to the lowlands. The Ammer has the highest elevation gradient of the four study catchments and largest slope class (see 75%-quantile in Tab. 1) which is much larger than in the other catchments. The Treene catchment is largely dominated by agricultural land. In contrast, the three other catchments are dominated by both agriculture and forest. The mean annual temperature ranges between 7.9°C (Saale) and 10.1°C (Kinzig). The largest seasonality in temperature was observed in the Saale catchment.

[Table 1 about here.]

2.2. Soil and Water Assessment Tool (SWAT)

A hydrological model was used to provide temporal patterns of different hydrological processes and of parameter sensitivities. The eco-hydrological model SWAT (Soil and Water Assessment Tool, Arnold et al. (1998)) was used in the modified version SWAT3s with three aquifers including two active ones (Pfannerstill et al., 2014a) named the SWAT model in the following. The SWAT model calculates the major hydrological processes. Model outputs are provided in a daily resolution for each subbasin as the finest spatially located unit. These subbasins are further spatially subdivided into hydrological response units (HRUs) based on same information in land use, soil and slope class.

The SWAT model distinguishes between a land and a water phase. At the land phase, the three typical catchment functions - partitioning, storage and release of water - are considered. Precipitation is partitioned into snow and rain. Storage changes are calculated for different soil layers and the three aquifers. Water is released via evapotranspiration and different runoff components. Actual evapotranspiration is calculated based on potential evapotranspiration and water availability on the current day. In addition to surface runoff, subsurface runoff components are included: Within the soil, lateral flow and artificial tile flow due to drainage activities are distinguised. Groundwater flow is released from the two active aquifers (fast and slow groundwater flow). All runoff components are summed up at each subbasin to calculate water yield. In the water phase, runoff is routed from one subbasin to the next. A modelling period from 1997 to 2010 was used in all catchments including a warm-up period of three years.

Twelve model parameters were selected in this study (Tab. 2) and described briefly below. To capture all relevant processes, we selected those model parameters that are expected to be of relevance in at least one of the catchments. For a more detailed description of the model parameters, we refer to Neitsch et al. (2011). Parameter ranges were selected based on experiences in other SWAT studies (e.g. Guse et al., 2014; Pfannerstill et al., 2014b, 2015; Guse et al., 2016b,a). Three snow parameters were included: The snowfall temperature (SFTMP) defines the temperature when snow falls, whilst snow melting is controlled by the snowmelt temperature (SMTMP). The third snow parameter (SNOCOVMX) expresses the lowest amount of snow which lead to a full snow cover. The curve number method (CN2) (SCS, 1972) is included in the SWAT model to regulate the amount of infiltrating water and thus the occurrence of surface runoff. Flow time of surface runoff, lateral flow and tile flow to the river is regulated by SURLAG, LATTIME and GDRAIN, respectively. The available soil water capacity (SOL_AWC) can be differentiated for each soil layer in the different soil types. The soil evaporation factor (ESCO) is used to parameterise a nonlinear function for contribution of soil water from different soil depths to evaporation. Fast and slow aquifers are differentiated in the SWAT3s model version. Three groundwater parameters were used. Retention time in recharging the first aquifer is controlled by the groundwater retention parameter (GW_DELAYfsh). Available water in the aquifers is partitioned into the two aquifers by the aquifer fraction coefficient (RCHRGssh). Subsequently, the baseflow retention factor (ALPHA_BFssh) regulates the timing of groundwater flow from the slow aquifer to the main river.

[Table 2 about here.]

The SWAT models for the Treene and Saale catchments were used as described in Guse et al. (2016b). For the Kinzig catchment, we used a 25-m resolution DEM (HVBG, 2001), the ATKIS vector land use map (BKG, 2013) and soil properties from a 1:200.000 soil map (BGR, 1999) as well as 13 rain gauges, two temperature and wind, four humidity and one solar radiation stations (see Kakouei et al. (2018) for details). The Kinzig reservoir was implemented in the model based on dam and reservoir properties and release rules. In the Ammer and Kinzig catchments, where elevation ranges exceed 500 m, we included elevation bands to differentiate precipitation and temperature in all subbasins in elevation distances of 50 m. For the Ammer catchment, global datasets on topography (SRTM DEM; (Jarvis et al., 2008; NASAJPL, 2013)) and soil (HWSD, 2009) as well as the ATKIS vector map (BKG, 2013) were used. Moreover, we implemented 13 rain gauges and five temperature gauges (see Kiesel et al. (2019)).

2.3. *Spatio-temporal dynamics in processes and model parameters*

In this study, the FAST (Fourier Amplitude Sensitivity Test) was used (Cukier et al., 1973; Saltelli et al., 2006) with the r-package FAST (Reusser, 2015). FAST provides the parameter settings for the 579 model simulations which are required to derive sensitivities for twelve model parameters. All model parameters are modified simultanously. For each catchment, identical parameter combinations were tested in model simulations covering the whole parameter space. These model simulations were used to derive spatio-temporal variations in both modelled processes and model parameters.

The model simulations were at first used to derive daily time series of different modelled hydrological components which were extracted for each of the 579 model simulations. Hydrological component is a more general notation including hydrological processes, state variables and other hydrological variables. As hydrological components, we have selected: Precipitation, snowfall, actual evapotranspiration, water yield, runoff ratio, surface runoff, lateral flow and subsurface flow. Water yield is the amount of water flowing from the land phase into the river. Daily model results for the selected hydrological components were monthly averaged for the entire modeling period for each model simulation. A monthly resolution was selected as appropriate temporal scale to detect typical fingerprints of catchment behaviour. Their variability was detected based on variations in parameter values within the model simulations.

Concerning model parameters, the temporal dynamics of parameter sensitivity (TEDPAS) (Reusser et al., 2011) calculate parameter sensitivities in daily resolution. Temporal variations in parameter dominance were increasingly investigated in recent years (Sieber and Uhlenbrook, 2005; Cloke et al., 2008; Guse et al., 2014; Haas et al., 2015; Pfannerstill et al., 2015) to extract the maximum information about parameter impact on hydrological behaviour of a model. TEDPAS uses directly model results and can thus be applied to all outputs which are provided by the model in a daily resolution (Guse et al., 2016a). Parameter sensitivity is expressed here as partial variance which is defined as ratio of first-order variance of a parameter divided by the total variance for this day. Guse et al. (2016b) suggested a monthly aggregation of the daily sensitivity to obtain easily interpretable patterns of typical parameter dynamics. In this study, daily time series of discharge were used to estimate parameter sensitivities. The dominant parameters to discharge were detected for each day and based on this, typical patterns of parameter dominances were characterised. For more detailed information about TEDPAS, we refer to Reusser et al. (2011) as well as to the initial TEDPAS study with the SWAT model in Guse et al. (2014).

3. Results

3.1. Spatio-temporal variability in measured preciptation and discharge

The four catchments were compared in terms of mean and variability (standard deviation) of two major hydrological variables, i.e. measured time series of precipitation and runoff, in a monthly resolution (Fig. 3). Mean annual precipitation in the Ammer catchment (1310 mm/a, Tab. 1) is much larger than in the three other catchments. Precipitation amount is significantly higher in summer in the Ammer catchment with a value about three times as large as in winter (see also Tab. 1), illustrating the highest variability in precipitation among the four catchments. In contrast, precipitation patterns are similar for the Treene, Saale and Kinzig catchments with low seasonal variations and a slightly higher precipitation in summer. In all catchments, precipitation variability is highest in summer and increases with increasing precipitation. Overall, seasonal precipitation patterns are similar for mean and variability in all catchments.

Runoff patterns are similar in Treene, Kinzig and Saale, with high values in winter and low values in summer. At the beginning of spring these three catchments are characterised by a strong decline in runoff ending up in a dry phase in autumn. The runoff time series of the Treene catchment is smoothest as indicated by the lowest standard deviation. Runoff variability for Saale and Kinzig is in particular higher in the winter period. This indicates a high retention in lowlands and a faster hydrological response in mid-range mountain catchments. The Ammer catchment is characterised by different runoff patterns compared to the other catchments. The highest runoff occurs from spring to summer and fluctuations throughout the year are lower compared to the other catchments. The lowest monthly average discharge occurs in January. Thus, in winter, runoff is lower than in the three other catchments.

The correlation between monthly precipitation and runoff is highest for the Ammer catchment with 0.71 for mean and 0.89 for standard deviation. High precipitation and high runoff coincide except in spring. The hydrological system is thus characterised by a fast runoff response to precipitation events (Fig. 3), whereas low precipitation in winter and storage in snow lead to minimum runoff values. In spring, precipitation is relatively low compared to runoff and snowmelt evokes an increase in water yield without additional high amounts of precipitation. The largest values in standard deviation were detected for both precipitation and runoff values in the Ammer catchment. Standard deviation increases in particular in high flow periods. Here, peaks in mean and variability in runoff coincide in their seasonal occurrence. High runoff variability in the Ammer catchment in August indicates a high contribution of surface runoff.

In contrast, for the three other catchments the correlations are negative for both mean and standard deviation with a value up to -0.53 in the correlation between the standard deviation of monthly precipitation and runoff in the Saale catchment. The largest variability in precipitation is detected in the Saale catchment in summer whilst runoff variability has its maximum in winter. Thus, variability in precipitation is related to the occurrence of intense summer events whereas runoff variability is controlled by the interplay between snow and rain-driven runoff processes. The negative correlation occurs due to a stronger retention in the catchment leading to a higher contribution of subsurface flow as well as to higher losses due to evapotranspiration.

[Figure 3 about here.]

3.2. Modelled hydrological components

Before presenting modelled patterns of temporal process dominance, model performance in the four catchments for the entire modelling period (2000-2010) is briefly summarised. These model performance values represent the median values of the model simulations within the sensitivity analysis. It was hereby not our goal to show the best results of a calibrated model. The information on performance criteria is added to provide a rough idea of how the model is performing and to demonstrate that the model can be used for our purpose. Median values of KGE are 0.73 (Treene), 0.72 (Kinzig), 0.61 (Saale) and 0.38 (Ammer) and of PBIAS 10.7 (Treene), 20.8 (Kinzig), -2.5 (Saale) and -9.3 (Ammer). Even though KGE values are not satisfactory for each model run, we assume that the general catchment behavior is represented realistically for each of the catchments (as shown in Fig. 4).

The average behaviour of different modelled hydrological components throughout the year is illustrated in Fig. 4 (above) to analyse how catchment characteristics are reproduced by the model. Snowfall is most relevant both in magnitude and duration in the Ammer catchment. At the beginning of the year, snowfall amounts in the Saale catchment are higher than in Kinzig and Treene catchments. In contrast, at the end of the year, snowfall is similar in Saale and Kinzig catchments.

Actual evapotranspiration shows a typical seasonal pattern driven by radiation. Its impact on seasonal runoff pattern is of relevance in summer and autumn and is highest in the Ammer catchment. However, the seasonal patterns for evapotranspiration are not controlling discharge patterns due to the large temporal variations in precipitation and snowmelt. The three other catchments (Treene, Saale, Kinzig) are characterised by high precipitation in summer but the highest discharge in winter. The high influence of actual evapotranspiration leads to these seasonal discharge patterns. Due to highest values of both precipitation and evapotranspiration in summer, no coincidence is observed between temporal patterns in precipitation and runoff. This is also shown in similar monthly patterns of runoff ratios in all catchments with the highest values in spring.

The runoff regime (median values for total water yield in Fig. 4) of the Ammer catchment shows two distinct peaks driven by snowmelt (March) and rainfall (August), respectively. Snow accumulation strongly buffers the hydrological response. The runoff regime of the other catchments is characterised by only one (less distinct) peak in March. This is mainly caused by the seasonal cycle of evapotranspiration and to a smaller extent also by snowmelt.

Regarding runoff components, surface runoff (in particular in early spring and late summer) and lateral flow (in spring and summer) are the major contributing runoff components in the Ammer catchment. In the Kinzig catchment, lateral flow is dominant throughout the entire year with low variability, while surface runoff and subsurface flow are important in winter. Similarly to the Kinzig catchment, lateral flow is relevant in the Saale catchment. However, in the Saale, the relevance of subsurface flow is higher, while surface runoff is of lower relevance. In contrast, the hydrological system in the Treene lowland catchment is controlled by subsurface flow in particular in winter, while the two other runoff components are of lower relevance.

All catchments show a typical hierarchical pattern of process occurrence (Yilmaz et al., 2008; Pfannerstill et al., 2015). In high flow phases, different runoff components from surface or fast-reacting subsurface up to groundwater in the Treene catchment dominate, while groundwater is dominating in the non-alpine catchments in phases of low flows. A higher variability occurs due to higher contribution of fast reacting runoff components such as it is shown when comparing winter discharge patterns between the four catchments.

[Figure 4 about here.]

3.3. Impact of parameter settings on modelled hydrological components

The variance in monthly values of the hydrological components throughout the year indicates how different parameter settings influence the relevance of these hydrological components (Fig. 4, below). High variance indicates high relevance of parameter settings which means that they highly modify the contribution of this hydrological component. In general, one would expect that the pattern of variances follows the pattern of medians as it is true for snowfall for all catchments. The impact of SWAT model parameter settings matches with the contribution of snowfall. However, there are quite a few exceptions for some hydrological components and catchments where high variances do not coincide with high medians. Variability in surface runoff is remarkably high in the Ammer catchment. The highest variance is detected in August and the highest median in March. Thus, the impact of parameter settings is higher in summer, whilst probably changes in snow parameters have a lower impact on the modelled amount of surface runoff. Variance in lateral flow is high in the Saale catchment and low in the Kinzig catchment. In contrast, median values are higher in the Kinzig than in the Saale catchment. Two distinct peaks of subsurface flow occurred in May and November in the Treene catchment while the median curve had only one prolonged peak in winter.

In consequence, variances for total water yield are remarkably different across the ensemble of catchments (Fig. 4, below). This implies more complex parameter sensitivity patterns for each catchment as expected by just looking at the average runoff regimes, where only the Ammer is markedly different. In the Ammer catchment the highest variability in water yield is detected in summer, while it is relatively low in spring indicating that processes in summer (e.g. evapotranspiration, rain-driven surface runoff) are more impacted by parameter settings than processes in winter (e.g. snowmelt). In the Treene catchment, monthly patterns for median and variance do not match since the highest variability is observed in May and November, while water yield has its highest values in winter. Thus, the temporal variability of groundwater and water yield is very similar in the Treene catchment showing that the groundwater parameter settings largely influence water yield. In contrast, in the Saale catchment median and variance of monthly patterns are similar. The variance in runoff ratio is high in April in the Treene and Saale catchments which is also the month with the highest runoff ratio, while it is constant throughout the year in the two other catchments. Thus, also the runoff ratio is strongly impacted by parameter settings in spring. Overall, variance in modelled hydrological components and thus the impact of parameter settings is lowest in the Kinzig catchment.

3.4. Monthly patterns of parameter sensitivity

Daily sensitivity results are aggregrated to mean monthly values of partial sensitivities for each model parameter (Fig. 5). This allows an easier interpretation of the typical hydrological behaviour for each catchment as suggested by Guse et al. (2016b). Regarding the three snow parameters (SFTMP, SMTMP, SNOCOVMX), sensitivity values and the number of months with a high sensitivity are increasing with the landscape gradient. In the Ammer catchment, snowfall temperature (SFTMP) is sensitive for a long period from early autumn up to late spring. Snowmelt temperature (SMTMP) in contrast is not relevant before winter times. The highest amount of snow in the Ammer catchment results both in the highest sensitivity values for snow parameters and in the largest duration of snow relevance (November to May). There are differences both in snowmelt and in the intensity and duration of the dominance of snow parameters. While the sensitivity values are higher in Kinzig compared to the Saale catchment, the duration of snow relevance is longer (one month) in the Saale catchment (Fig. 5).

The curve number (CN2) as representative for surface runoff in the SWAT model is only sensitive in summer in the Ammer catchment, whilst it is only of minor relevance in the other catchments. The highest relevance of lateral flow in Kinzig and Ammer is reproduced in the dominance of lateral flow lag time (LATTIME) throughout the year. While LATTIME is relevant throughout the whole year in the Kinzig, it is only dominant in the Ammer from May to November due to the high relevance of snow processes in winter. As evaporation parameter, ESCO is mainly relevant in the second half of the year, except for the Saale catchment where ESCO is of low relevance throughout the year.

The groundwater retention time (GW_DELAYfsh) is the major groundwater parameter in the non-alpine catchments in particular in the Treene catchment and is sensitive for the whole year. The aquifer partitioning (RCHRGssh) regulates the water distribution into the two aquifers and is sensitive in all catchments. RCHRGssh is relevant throughout the entire year due to high amount of water in both aquifers. Its lowest sensitivity values are detected in autumn in times of low discharge. In the two mid-range mountain catchments, RCHRGssh is in particular relevant for regulating water support in dry periods. Thus, its highest sensitivity is observed in summer before the dry phase in autumn. In the alpine Ammer catchment, groundwater flow is of minor importance. RCHRGssh has a low sensitivity in summer and is more relevant in winter times. While the non-alpine catchments are characterised by low flows in summer, the Ammer has the lowest phase in winter where water is retained as snow. The baseflow recession of the second aquifer (ALPHA_BFssh) is sensitive in summer and at the beginning of autumn in the non-alpine catchments. For these catchments, a typical sequence of groundwater parameter sensitivity can be derived. At first, GW_DELAYfsh is relevant at the beginning of the summer, followed by a high sensitivity of RCHRGssh. Subsequently, in autumn in the dry season, ALPHA_BFssh as the model parameter from the deepest zone becomes sensitive.

[Figure 5 about here.]

3.5. Monthly patterns of dominant hydrological components

In Fig. 6, the model parameter dominances are aggregated to explain the dominant hydrological components. All parameters of a certain hydrological component are summed up and compared with the mean monthly discharge values. In general, the process dominance patterns show three markedly different phases for the non-alpine catchments, while for the Ammer catchment only two phases can be detected.

For the Treene catchment, dominant patterns of hydrological components are typical for pluvial runoff regimes of lowlands with a high contribution of groundwater and low relevance of fast runoff and snow (Fig. 6). A dominance of groundwater was detected throughout the year with maximum relevance from April to June. Highest relevance of groundwater parameters occur in the transition between spring and summer, when they dominate over snow and evapotranspiration parameters. In contrast, the high impact of evapotranspiration in late summer reduces the relevance of groundwater parameters. This pattern is also related to water availability. In times of high water availability in spring when soils are close to saturation, the settings of soil and evapotranspiration parameters do not largely influence actual evapotranspiration. However, in summer when soil water content is lower, model parameters are more important to regulate the amount of available water for evapotranspiration. The runoff maximum in winter is driven by groundwater with contribution of snow but not from fast runoff components. The low relevance of fast reacting components could also be derived from low variability in runoff (Fig. 3).

The Kinzig catchment shows a pluvio-nivale regime with a rather small influence of snowmelt (Fig. 6). Snow parameters are relevant from December to March. From April to July, groundwater parameters dominate, whilst from August to November, a dominance of fast reacting and soil components is detected. Fast reacting components have the same level of high relevance throughout the year. In autumn, soil parameters become relevant to regulate evapotranspiration and soil water storage.

In the Saale catchment the dominance patterns also show the typical hydrological behaviour for pluvio-nivale regimes of mid-range mountain catchments. There is a strong influence of the snow component in the first four months of the year. Fast runoff components are slightly relevant during the year with low variability. Soil processes including evapotranspiration are in particular relevant in autumn (October). The groundwater component has the highest sensitivities in dry phases in summer. From late summer to winter, no component is highly dominant. This shows the balanced situation between different dominant hydrological components.

Finally, in the Ammer catchment with a nivale regime, a clear break between the dominance by snow and surface runoff can be observed between May and June. Thus, only two different dominant phases are detected. High runoff values occur from March to September with a comparably low impact of evapotranspiration. There is a direct transition to fast reacting runoff components due to high slopes with dominance from June to October, whilst there is no important phase of groundwater recharge as indicated in the low sensitivity of groundwater. Snow processes are relevant from November to May with a discharge peak in April evoked by snowmelt at the end of the winter.

[Figure 6 about here.]

4. Discussion

In this study, we presented three ways of deriving hydrological (dis)similarities between catchments. We detected how catchment characteristics are reflected in spatio-temporal dynamics of modelled processes and parameter sensitivities. In contrast to studies using a large set of catchments to classify them in a few groups (Köplin et al., 2012), we directly focused our analysis on four catchments to study the hydrological characteristics of typical landscapes in Germany.

Carrillo et al. (2011) have emphasised that signature-based catchment characterisation is a first approach to explain hydrologic behaviour. The comparison of catchment metrics among the four catchments disentangles similarities and differences between the catchments. Differences are prominent in the landscape structure resulting in a typical gradient from north to south. While the catchment structure is different for the non-alpine catchments (lowland vs mid-range mountains), the differences in the forcing by precipitation is small. This also results in small differences in the monthly discharge regime. Thus, the impact of precipitation on the total discharge regime is stronger than the impact of landscape structure. Thus, first insights for differences in the contribution of runoff components between the four catchments are already detected in catchment metrics, but to explain the overall hydrologic behaviour more detailed diagnostic analyses are needed.

Our study has demonstrated how different processes are reproduced in model applications for the four catchments. Modelled processes provide additional information which cannot be directly derived from measured time series of precipitation and discharge and resulting catchment metrics. It is shown that using monthly patterns of different modelled runoff components improves the understanding of hydrological behaviour and the explanation of similarities and differences between catchments. In the Ammer catchment seasonal dynamics in radiation impact discharge dynamics. Here, snowmelt is the governing hydrological process in the winter half-year in the alpine catchment due to low temperatures. Since surface processes are a driver for discharge, i.e. surface runoff and snowmelt, the strongest link between precipitation and discharge occurs in the Ammer catchment.

Seasonal process patterns in the Treene, Kinzig and Saale catchments are mainly driven by evapotranspiration in summer and by precipitation in winter. These results coincide with former studies demonstrating that high flows occur in phases of high precipitation and low demand for evapotranspiration whilst low flow phases are related to a high demand for evapotranspiration (Patil and Stieglitz, 2011; Guse et al., 2016a). A low relationship between daily precipitation and discharge is detected for the three non-alpine catchments, since they are controlled by subsurface flows (lateral or groundwater flow). However, the relationship between precipitation and discharge in the Treene lowland catchment with a strong dominance of groundwater flow is not lower compared to the two mid-range mountain catchments Kinzig and Saale which are also controlled by lateral flow. Thus, based on our study, we can state that the direct link between daily precipitation and discharge is low if subsurface processes dominate irrespective of the type of subsurface flow. As emphasised by Wagener et al. (2007), the interpretation of subsurface flow is more complicated due to less available data. More information than precipitation and total discharge is helpful to explain subsurface processes.

A core point of this study was to show how the analysis of temporal variations in dominant model parameters contributes to explain similarities and differences between catchments. Carrillo et al. (2011) showed by constructing linear regressions that only a few model parameters are connected to typical characteristics of nine catchments in the USA. In our study, we intensified the diagnostic analysis from the methodological point of view. As also shown by Donnelly et al. (2016), an analysis of different aspects of hydrologic behaviour in the model demonstrates whether the set of model parameters can reflect differences between contrasting catchments. While Donnelly et al. (2016) focused on flow signatures, our study used daily time series of modelled hydrological components and parameter sensitivity to investigate the relationship of model parameters and catchment characteristics. A couple of new insights were derived from these temporal sensitivity patterns:

An example for a model structure characteristic is the soil evaporation parameter ESCO which controls the contribution of soil water from deeper zones to the evaporation process. The more water evaporates from soil, the less is stored in the soil and thus the less is available in dry phases. Thus, ESCO is important in particular in the dry periods in autumn. Its temporal patterns of parameter sensitivity indicate the occurrence of dry conditions as a characteristic of the model structure. The temporal parameter sensitivity analysis in the four catchments shows that the relevance of model parameters varies between the catchments.

Although a similar behaviour in time is detected for snow and groundwater parameters, the relevance of those model parameters is different between the catchments. This is for example shown in the comparison of snow processes between the two mid range mountain catchments (Saale, Kinzig). In the Saale catchment, the duration of high relevance of snow parameters is longer than in the Kinzig catchment, while sensitivity values are higher in the Kinzig than in the Saale catchment. Different parameter settings as realised within the sensitivity analysis had a low impact on surface and lateral flows, since main factors controlling fast runoff such as slope, land use and precipitation were not varied throughout the analysis. Thus, the relevance of these fast occurring processes is not highly impacted by parameter settings, while subsurface processes are strongly controlled by parameter settings.

Subsequently, the criteria from the three groups, i.e. catchment metrics, modelled processes and dominant parameters, are jointly considered (Fig. 7). Each single criterion is presented as relative relevance in one catchment to derive typical catchment characteristics. A relative relevance is the value for one catchment expressed as the percentage of the sum of all catchments. The different criteria are weighted in font size according to their relevance in comparison with the other catchments.

[Figure 7 about here.]

The three-tiered analysis shows that major differences between the Ammer and the three non-alpine catchments are emphasised in the catchment metrics. As an alpine catchment, the Ammer is strongly impacted by topographical factors such as elevation and slope and by surface processes such as snow and surface runoff as well as the corresponding model parameters. Catchment metrics are mainly related to processes occuring at the land surface. Thus, the differentiation in terms of hydrological characteristics are more difficult between the three other catchments since they are mainly controlled by subsurface processes. The Treene catchment can be characterised by the large share of agricultural areas as well as by the dominance of groundwater and tile flow. The relevance of these subsurface processes becomes apparent by analysing the modelled processes. Hydrologic characterisation is even more complex for the two mid-range mountain catchments (Kinzig, Saale). Compared to Ammer or Treene catchments, Kinzig and Saale catchments are not characterised by the strong dominance of some criteria. A differentiation between both catchments is possible due to the distinct monthly patterns of dominant parameters. The larger the relevance of subsurface processes and the more similar the catchments are in their metrics, the more beneficial is the proposed three-tiered approach for a clear characterisation of contrasting catchments.

This gained knowledge can furthermore enable a more efficient and targeted model calibration. The presented model results of this study are derived with a rather complex hydrological model to appropriately represent the hydrological system with a high demand of computational resources. In future studies, it might be worth checking if a model with a lower complexity and simpler process depiction is still able to depict the system sufficiently (see (Wagener et al., 2003)).

5. Conclusion and outlook

In this study, catchment metrics, modelled processes and dominant parameters are jointly analysed in four catchments. Our study clearly shows that typical characteristics of the four study catchments are reflected in the relevance of hydrological processes and model parameters. Temporal dynamics in modelled proceses and parameters coincide with the regime types of the catchments and are a typical fingerprint of catchment characteristics. Thus, catchment characteristics, process dominance, temporal patterns of model parameters, and catchment regime type are closely linked. It is shown how a hydrological model represents different processes in contrasting catchments. The joint analysis of catchment metrics, modelled processes and parameter dominances enabled a clear identification of major differences and similarities between the catchments and contributed to explain causes of catchment similarity.

This approach was applied to contrasting catchments using only one model. In further studies, it would be interesting to apply this methodological approach with different hydrological models to derive similarities and differences in temporal patterns of modelled processes and dominant parameters in the same catchments.

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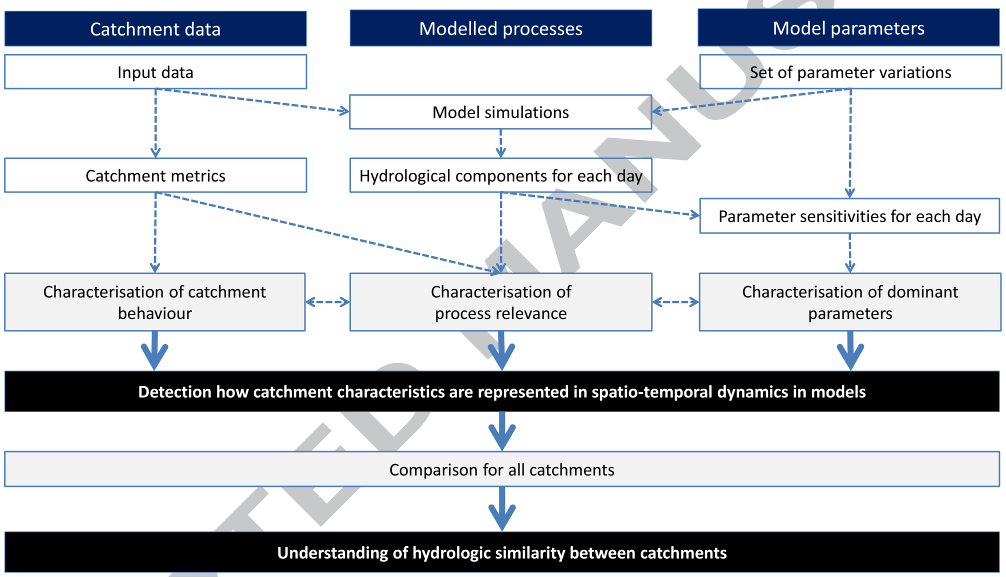

Figure 1: Proposed methodical approach with the three pillars. The aims of this approach are shown in black boxes.

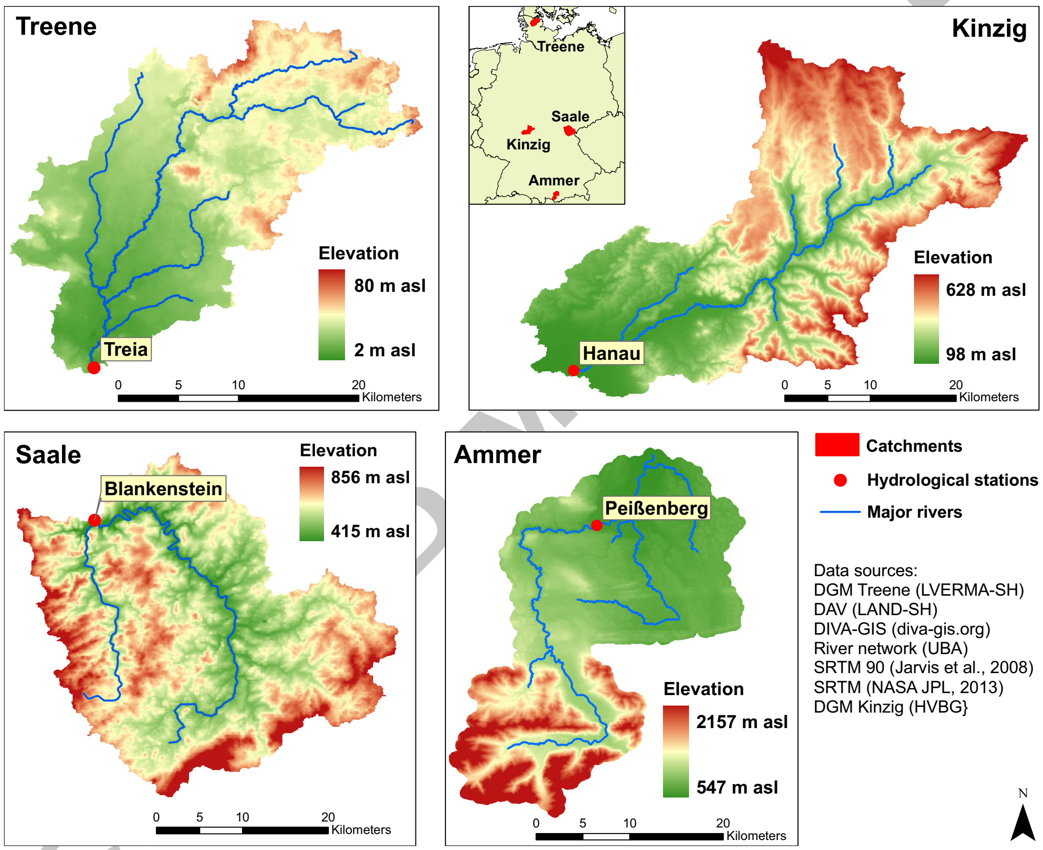

Figure 2: Elevation and outlets of the four study catchments and their location in Germany.

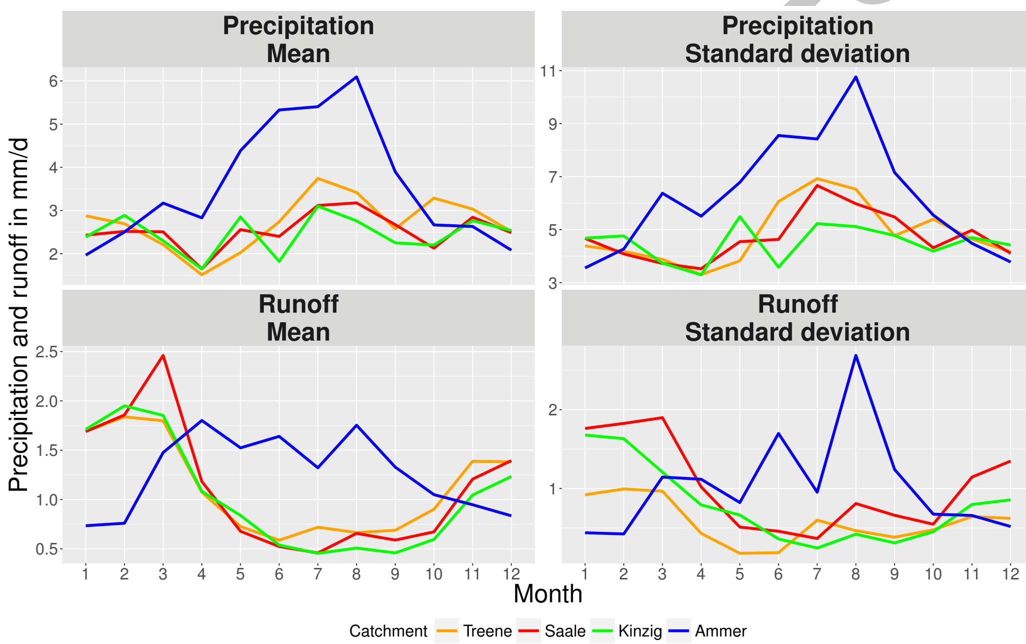

Figure 3: Monthly mean and standard deviation of runoff and precipitation for the four catchments.

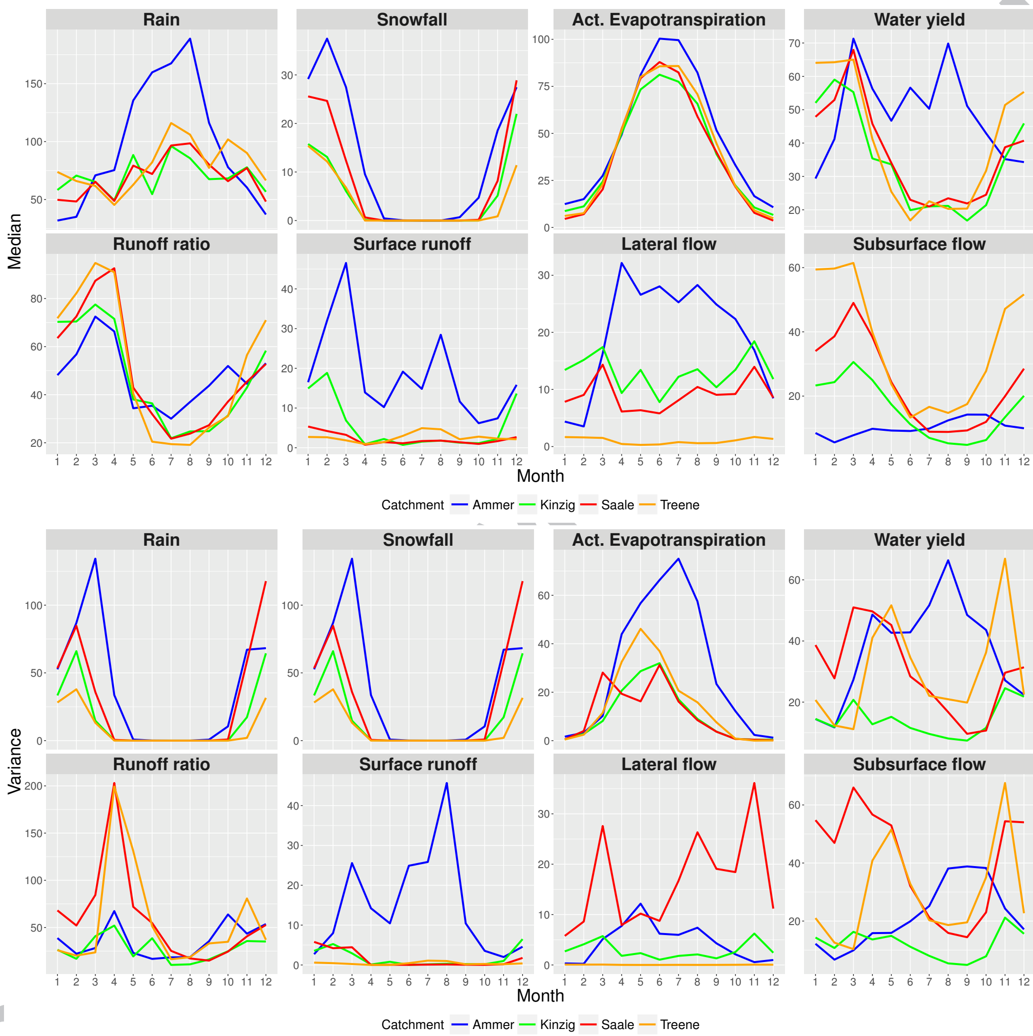

Figure 4: Monthly median (above) and variance (below) of different hydrological components [in mm] among all model simulations for the four catchments for the whole modeling period.

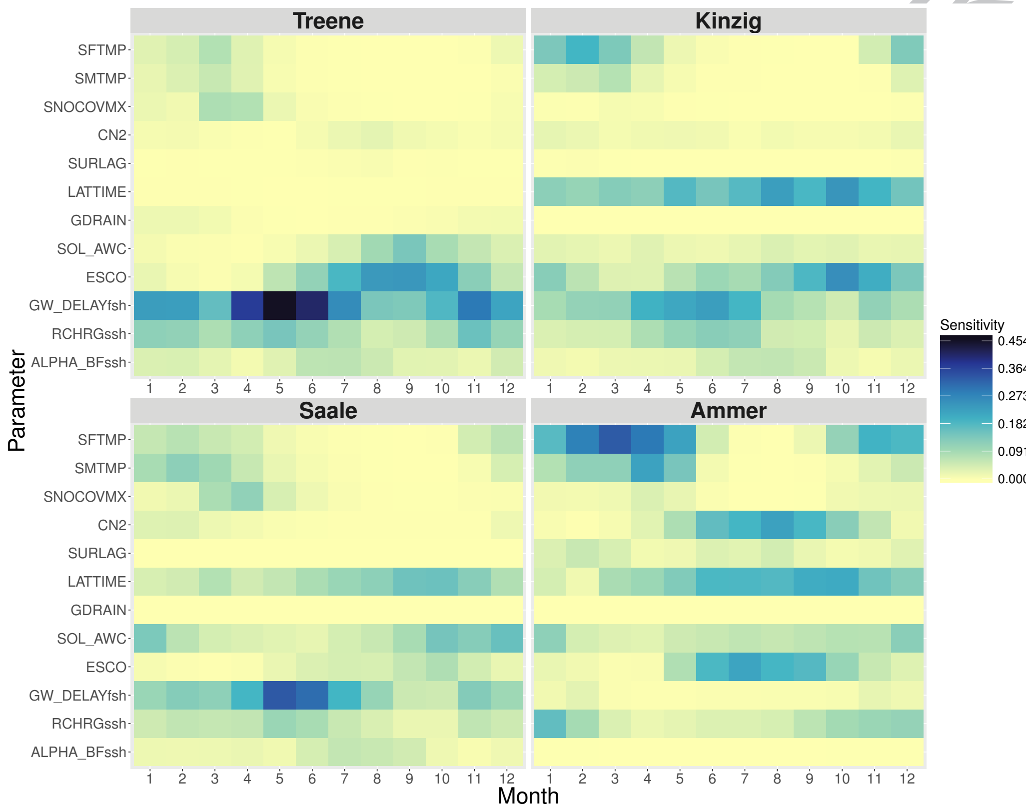

Figure 5: Mean monthly averaged parameter sensitivities for the four catchments. All sensitivity values of a parameter for a certain month were averaged for the entire modeling period. The parameter sensitivity is presented as ratio of partial variance of a certain model parameter to the total variance.

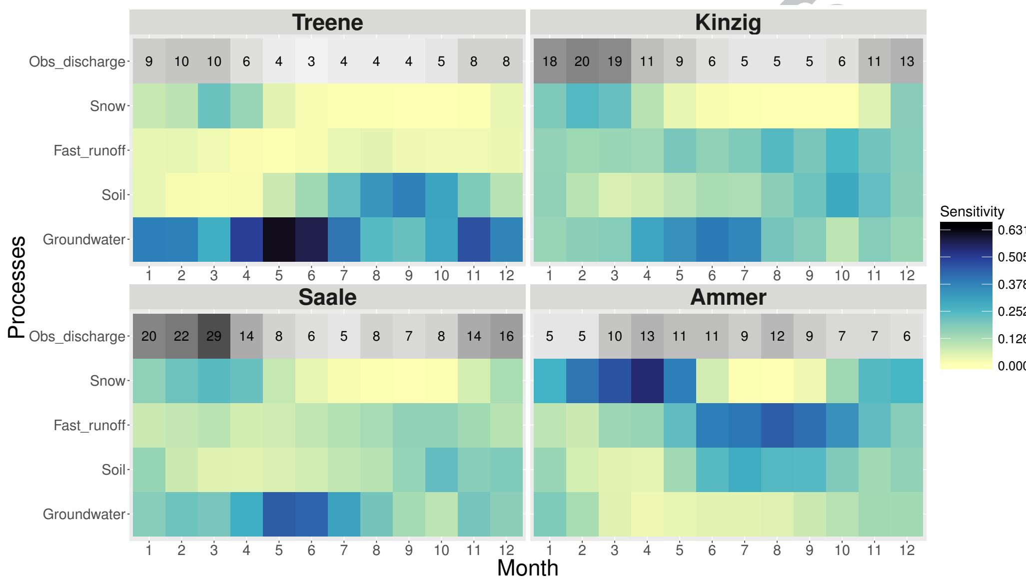

Figure 6: Aggregation of monthly averaged parameter sensitivities for four model components. The mean monthly measured discharges in m^3/s are labeled additionally in the first row with gray colour gradient.

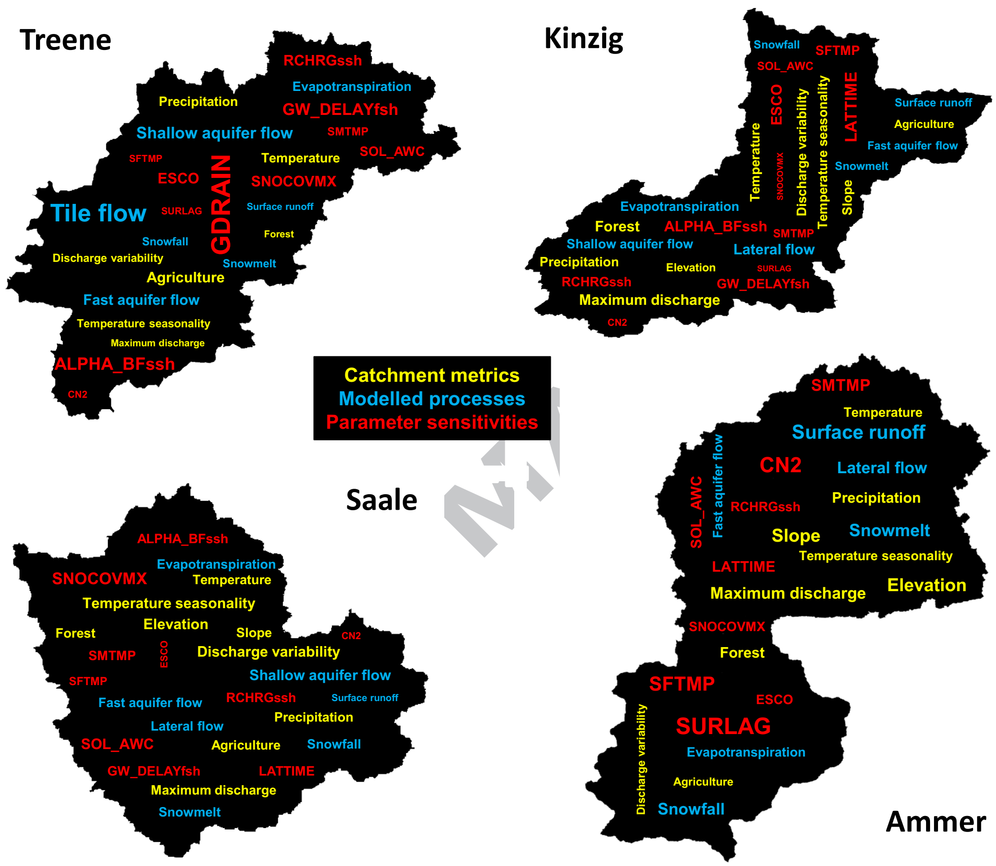

Figure 7: Word cloud of the catchment characteristics formed by the catchment borders based on catchment metrics (in yellow), modelled processes (in blue) and dominant parameters (in red). A higher font size shows a higher relative relevance of this criterion in a catchment. Please note that the relative relevance shows the relevance of a criterion in this catchment in relation to the relevance in the other catchments. For absolute values, we refer to the other figures and tables.

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Table 1: Characterisation of the four catchments. The numbers in brackets after the results indicate the month in which this value occurs.

Category [Unit]	Treene	Kinzig	Saale	Ammer
Catchment size at outlet [km2]	481	925	1013	602
Maximum elevation [m asl]	80	624	856	2157
Minimum elevation [m asl]	2	104	415	551
Mean elevation [m asl]	28.4	295.9	577.4	885.2
Mean slope [%]	1.29	10.37	8.81	21.70
Median slope [%]	0.93	8.23	7.65	11.20
75% quartiles of slope [%]	2.55	14.89	14.12	31.72
Land coverage by urban areas [%]	10	8	7	5
Land coverage by forests [%]	7	49	28	47
Land coverage by agricultural areas and pastures [%]	80	42	58	39
Mean annual temperature [°C]	9.3	10.1	7.9	8.3
Mean monthly temperature in the warmest month [°C]	17.8 [7]	19.1 [7]	17.2 [7]	17.2 [7]
Mean monthly temperature in the coldest month [°C]	1.5 [1]	1.0 [1]	-1.7 [1]	-1.3 [1]
Seasonality index of temperature	6.8	6.7	9.5	8.5
Mean annual precipitation [mm/a]	995	899	922	1310
Highest monthly average precipitation [mm]	116.0 [7]	94.1 [7]	104.8 [7]	188.9 [8]
Lowest monthly average precipitation [mm]	45.4 [4]	49.5 [4]	51.9 [4]	61.0 [1]
Ratio of highest and lowest monthly average precipitation	2.6	1.9	2.0	3.1
Seasonality index of precipitation	0.44	0.41	0.45	0.48
Mean discharge [m^3/s]	6.23	10.48	13.04	8.82
Maximum discharge [m^3/s]	34.9	165	168	237
Ratio between maximum and mean discharge	5.6	15.7	12.9	26.9
Highest monthly average discharge [m^3/s]	10.2 [2]	20.1 [2]	28.9 [3]	12.6 [4]
Lowest monthly average discharge [m^3/s]	3.2 [6]	4.7 [7]	5.4 [7]	5.1 [1]
Ratio between highest and lowest monthly average discharge	3.1	4.3	5.4	2.5
Seasonality index of discharge	0.38	0.47	0.50	0.31

Table 2: Lower and upper ranges of the twelve SWAT model parameters are provided as absolute range (r), additive (a) or multiplicative (m) value. More details of the model parameters are provided in the theoretical documentation of the SWAT model (Neitsch et al., 2011).

Parameter name	Abbreviation	Process	Range type	Lower range	Upper range
Snow fall temperature	SFTMP	Snow	r	-2.5	2.5
Snow melt temperature	SMTMP	Snow	r	-2.5	2.5
Minimum snow cover for 100% coverage	SNOCOVMX	Snow	r	1	50
Curve number	CN2	Surface runoff	a	-10	10
Surface runoff lag time	SURLAG	Surface runoff	r	0.8	4
Lateral flow lag time	LATTIME	Lateral flow	r	0.2	8
Tile flow lag time	GDRAIN	Tile flow	m	0.5	1.5
Available water capacity of a soil layer	SOL_AWC	Soil water	a	-0.02	0.1
Soil evaporation compensation factor	ESCO	Evapotranspiration	r	0.2	1
Groundwater delay time (fast aquifer)	GW_DELAYfsh	Groundwater	r	1	50
Aquifer fraction coefficient (slow aquifer)	RCHRGssh	Groundwater	r	0.2	0.8
Baseflow alpha factor (slow aquifer)	ALPHA_BFssh	Groundwater	r	0.001	0.2

Joint analysis of catchment metrics, modelled processes and parameter sensitivities

Spatio-temporal process and parameter dynamic is a fingerprint of catchment behaviour

Detection of (dis)similarities among four catchments from different landscapes

Improvement of process understanding in catchment and handling of processes in models

Applied hydrological model can reproduce dominant processes of contrasting catchments