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Improving hydrological model optimization for riverine species

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ABSTRACT

Hydrological indicators such as duration, frequency, magnitude, rate and timing of flow events are used to evaluate and, in models, predict the response of aquatic species to hydrological conditions. Hydrological models are generally optimized without considering specific species preferences by minimizing overall differences between observed and simulated flows using common hydrological objective functions. We hypothesize that hydrological models optimized to implicitly consider species' flow preferences will yield more reliable predictors.

To test this hypothesis, we developed a flexible evaluation method in which the hydrological model was optimized for different objective functions. We tested this concept for benthic invertebrates and selected seven species-relevant hydrological indicators as well as four objective functions based on commonly used hydrological performance criteria. Model parameterizations for these cases were assessed on their ability to reproduce an indicator-based performance criterion developed by applying feature scaling to the indicators. The results show that three indicator-based objective functions performed up to 14% better than the standard hydrological performance criterion KGE. When optimizing for individual or multiple indicators, we found that it is important to consider that other indicators are compromised. An evaluation of this trade-off showed a considerable range in indicator values and implausible indicator depictions.

We conclude that optimizing hydrological models to depict species preferences most effectively requires consideration of different objective functions that are based on hydrological indicators. Doing so, instead of simply optimizing to standard hydrological objective functions, can yield a rewarding result in terms of a more species-tailored model parameterization and, ultimately, a better prediction of aquatic species.

1. Introduction

The presence or absence of riverine species is related to environmental variables (Hering et al., 2006), and these relationships can be used to analyse how changes potentially influence the occurrence of species. Such variables are related to climate, land use, hydrology and substrates, which act at various scales (Kail et al., 2015; Kiesel et al., 2015; Schröder et al., 2013). The hydrological flow regime is one of the most important variables affecting the diversity and distribution of riverine biota (Schmalz et al., 2015).

To specify and quantify these dependencies, flow time series are translated to indicators that describe aspects of duration, frequency, magnitude, rate and timing of certain flow events (Poff et al., 1997). These indicators are related to species presence and/or absence to establish the response of aquatic species to hydrological conditions. Relationships have been identified for fish, macroinvertebrates, aquatic primary producers and riparian species (Lytle and Poff, 2004; Poff and Zimmerman, 2010). These relationships can be used to analyse how changes might influence the occurrence of various species.

Hydrological models are utilized to depict and predict discharge time series from which hydrological indicators are calculated (Carlisle et al., 2010). Usually, models are optimized for commonly used hydrological objective functions (Shrestha et al., 2014), of which several contrasting functions are deployed in parallel within hydrological research. Model optimization for different objective functions emphasizes different phases of the hydrograph (Pfannerstill et al., 2014b) or nitrate time series and duration curves (Haas et al., 2016). In previous studies that linked hydrology to species response, models were usually optimized for commonly used hydrological objective functions (Guse et al., 2015b; Kiesel et al., 2009). Depending on the

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chosen objective function, calculating species-relevant hydrological indicators from a standardized optimized model will lead to differences in the aforementioned indicators. Shrestha et al. (2014) analysed the ability of hydrological models, optimized in a standardized manner, to depict hydrological indicators. Even though the models performed well (Nash-Sutcliffe-Efficiency 0.71–0.87), some hydrological indicators were not simulated adequately. The authors attributed this mainly to the "lack of explicit consideration of these indicators in model calibration", as supported by Vis et al. (2015) and Murphy et al. (2013).

One option to improve hydrological model optimization for riverine species is a targeted and species-tailored model optimization. It is unclear how significantly the depiction of species-relevant hydrological indicators would improve if they were included in hydrological optimizations. This is especially applicable for enhancing species-specific simulations where hydrological indicators are used to link hydrological simulation and species occurrence. This leads to the following question: how large are the differences between simulated and observed indicator values when hydrological models are optimized directly for hydrological indicators instead of commonly used hydrological performance criteria?

Poff and Zimmerman (2010) have shown that the importance of hydrological indicators is species-specific, meaning that certain indicators are sensitive for one species, or group of species, but not necessarily for another species because of each species' hydrological preferences. In order to acknowledge species preferences, it is necessary to be able to optimize for different combinations and importance levels (weights) of indicators. If multiple hydrological indicators are included as objective functions in the model optimization process, the modeller is faced with the challenge of selecting the 'best trade-off solution' (Efstratiadis and Koutsoyiannis, 2010). This means that, depending on which indicator the model is optimized for, model performance will decline for other indicators (Gupta et al., 1998; Reusser et al., 2009; van Werkhoven et al., 2008; Vrugt et al., 2003). The magnitude of this trade-off depends on how different the selected indicators are and how well the model is able to simultaneously depict these indicators in one parameter set (Guse et al., 2014; Pfannerstill et al., 2014b; Sawicz et al., 2011; Shamir et al., 2005). It is important to know the magnitude of this trade-off in order to tailor the optimization for the preferred species. This leads to the following question: how much are certain indicators compromised when optimization is carried out for other indicators?

Answering the above research questions would considerably improve model optimization for riverine species. Therefore, we formulated two objectives for this study: (1) To evaluate the improvements associated with using a hydrological model optimized for hydrological indicators instead of hydrological performance criteria alone and (2) to evaluate the trade-offs of optimizing for different hydrological indicators.

2. Materials and methods

2.1. Study area

The developed methods were applied to the Treene catchment (Fig. 1). The catchment is well known from previous studies and it has a rich data basis (Guse et al., 2014, 2015b; Kail et al., 2015). The Treene is a sandbed river partly covered by gravel, located in the northern German lowlands with a maximum elevation of 80 masl. The Treene catchment has a size of 481 km^2 at the outlet Treia. It is dominated by agriculture and pasture (approximately 80% of the area), while forest and urban areas have a minor contribution (Guse et al., 2015a). The hydrological regime is governed by groundwater processes (Guse et al., 2014; Pfannerstill et al., 2014a, 2015) and by drainage flows due to the high presence of agricultural areas (Kiesel et al., 2010). High flows occur during autumn and winter months, and low flows occur during summer months. Typical and diverse fish and macroinvertebrate communities exist and the river is in a good saprobic state (Kail et al., 2015).

2.2. Model description and parameterization

The SWAT model (Arnold et al., 1998) in SWAT3S (Pfannerstill et al., 2014a) was used to simulate the hydrological processes in the Treene. SWAT3S was successfully applied to the Treene catchment (Guse et al., 2016; Haas et al., 2015) and in the Kielstau-subcatchment (Pfannerstill et al., 2015, 2014a). SWAT3S is characterized by a flexible groundwater structure, i.e., two storages that can be independently controlled for groundwater flow into the stream and a third storage that may be used to account for percolation into geologic formations that are not connected to the stream. Similar to the original SWAT model, SWAT3S divides the catchment into subbasins, which contain a stream channel and are further divided into Hydrological Response Units (HRUs), a spatial entity of unique soil, land use and slope. For each HRU, the processes of evaporation, surface runoff, infiltration, lateral flow, soil moisture, groundwater flow of two aquifers, and potential losses to a deep aquifer are simulated on a daily time step. Water leaving the HRUs via surface runoff, lateral flow and groundwater discharge are received in the stream channel where the water is routed to the catchment outlet.

2.2.1. Default model

The uncalibrated default model was compared with the optimized models described herein. The model was parameterized using a 25 m-resolution Digital Elevation Model (LVA, 1992–2004), a vector-based land use map (GeoBasis-DE/BKG, 2013), and a 1:200,000 soil map (BGR, 1995–2014). Climate data for the 13 subbasins of the Treene were derived from seven precipitation, two temperature, two wind speed, one solar radiation and four humidity stations (DWD, 2016; Fig. 1). The Thiessen Polygon method was applied to interpolate precipitation data at the subbasin level. Channel geometry was taken from satellite images (Google Earth, 2016) and field observations. Sowing, fertilization, harvest and tillage data followed standard German agricultural practices (KTBL, 2009). Tile drains were implemented according to the methodology prescribed by Guse et al. (2014), where HRUs with slopes smaller 1.25%, with agricultural land use patterns and soils prone to water logging were classified as 'drained'.

2.2.2. Definition of parameter space for optimization

Based on the hydrological information presented in previous studies of this catchment (Guse et al., 2016; Haas et al., 2016), ten model parameters were selected to be modified during optimization (Table 1). These parameters influence the major hydrological processes of snow accumulation and snowmelt, surface runoff, soil moisture, and groundwater. Model runs were carried out 20,000 times based on Latin Hypercube Sampling of the parameter space, shown in Table 1, as described in Pfannerstill et al. (2014b).

2.3. Optimization

For each model run, the herein defined and newly developed objective functions were calculated.

2.3.1. Hydrological indicators and normalization

The first objective functions are based on individual hydrological indicators (Poff et al., 1997). Since they are known to be inherently co-correlated (Olden and Poff, 2003), and to minimize the effects of redundancies among indicators on modelling results, we selected seven hydrological indicators representing all aspects of the hydrological flow regime (Table 2, Kakouei et al., 2017).

These seven indicators were calculated for the observed time series and the simulated time series using the R package EflowStats (Henriksen et al., 2006). Indicators have different units and values (Table 2), and the standard deviation of some indicators from the model