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Hydrologic comparison between a lowland catchment (Kielstau, Germany) and a mountainous catchment (XitaoXi, China) using KIDS model in PCRaster

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Abstract. The KIDS model (Kielstau Discharge Simulation model) is a simple rainfall-runoff model developed originally for the Kielstau catchment. To extend its range of application we applied it to a completely different catchment, the XitaoXi catchment in China. Kielstau is a small (51 km^2) lowland basin in Northern Germany, with large proportion of wetland area. And XitaoXi is a mesoscale (2271 km^2) mountainous basin in the south of China. Both catchments differ greatly in size, topography, landuse, soil properties, and weather conditions. We compared two catchments in these features and stress on the analysis how the specific catchment characteristics could guide the adaptation of KIDS model and the parameter estimation for streamflow simulation. The Nash and Sutcliffe coefficient was 0.73 for Kielstau and 0.65 for XitaoXi. The results suggest that the application of KIDS model may require adjustments according to the specific physical background of the study basin.

1 Introduction

Recent years have seen a rapid development of various hydrologic models. With the ever-growing technology in remote sensing, data telemetry and computing, model development is striving how best to represent the heterogeneous characteristics of a watershed. Much of the growth in sophistication of hydrological modelling is attributable to the digital revolution of distributed models and the availability of geospatial data through the last hundred years (Vieux, 2004). However, as modelling and data power has increased there has been a concurrent debate in its disadvantage, e.g. the cost and time required in the collection of massive hydrological data. It is also argued that it can lead to more model uncertainty from the integration of more input data and the increasing number of model parameters, where it can affect the model prediction (Gupta et al., 2005). In some cases, simple model development like lumped models is sufficient in its own right (Silberstein, 2006; Li et al., 2009). They are still used for various applications, including the study of hydrological processes (Bingeman et al., 2007), estimation of runoff and catchment water balance (Xu, 1999), and assessment of land use and climate change impacts on runoff (Akhtar et al., 2008). Because lumped models have relatively few parameters, they can easily be regionalised to predict runoff. The modelling result is not therefore strongly depending on how sophisticated the model is. Another question concerning model application is whether a model is unique for each environmental problem. Even for a perfect model system, the unique properties of a location lead to a very important identifiability problem to decide the "optimal" model structure and parameter sets (Beven, 2001). As a result, computer models are needed that can easily be adapted to the problem under study. The KIDS model used in this study is such a flexible model, which is a simple rainfall-runoff conceptual model with the potential to be adjusted from lumped to distributed ones. It is programmed in the dynamic modelling language PCRaster (Wesseling et al., 1996). It was developed for the streamflow simulation in the Kielstau catchment, which is a very flat region with large area of wetlands (Zhang et al., 2007). The model structure was adjusted with integration of wetland representation for a better simulation result. To extend the range of the KIDS model application we

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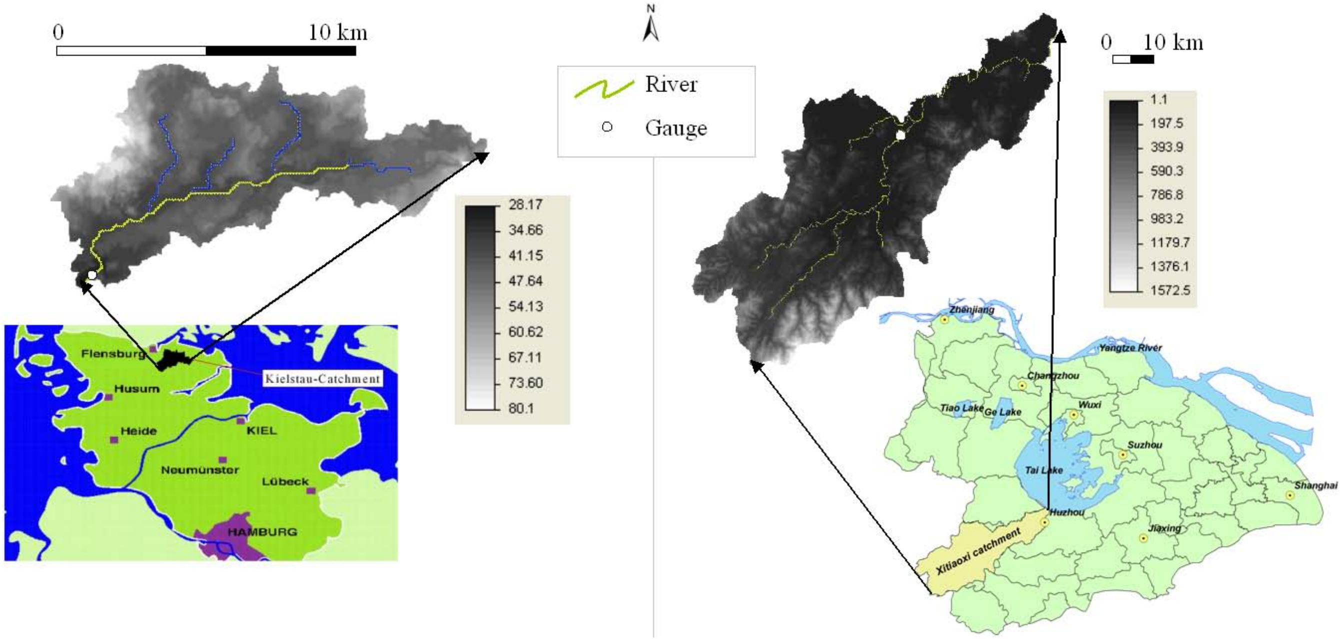

Fig. 1. Geographic location and GEM for the Kielstau (left) and the XitaoXi basin (right)

applied it to a completely different catchment, the mesoscale mountainous XitaoXi watershed in southern China. The goal of this study was to determine the applicability of KIDS model for modelling streamflow by comparing these two different watersheds in the hydrologic characteristics and modeling results. Specific objectives of this study were to: (1) analyse the unique features of the two catchments based on the available data, (2) compare the simulation results of the basic and adapted KIDS models, and (3) check the link between parameter estimation and hydrologic characteristics of the selected study basin.

2 Methods

The analysis framework includes three steps. First it is worth stressing the watershed and hydrometeorological characteristics for both large and small watersheds, by accounting for differences in topography, vegetation, soil properties, weather conditions and other important hydrologic features. With these considerations the KIDS model is then adapted to both locations for river discharge simulation. In addition, the problems of parameter estimation of the hydrology model for both catchments are discussed with focuses on the parameter sensitivity and its link to the unique catchment characteristics.

2.1 Site description

The study was carried out in the Kielstau and XitaoXi watersheds. Geographic location, catchment scale and the digital elevation map for both river basins are shown in Fig. 1. The Kielstau catchment is located in the region of Schleswig-Holstein, Northern Germany, and covers an area of about 50 km^2. The catchment has a rather flat relief, with maximum elevation difference of 55m. Soils are mainly consisting of Gleysol, Podsol and Luvisol, among which Gleysol belongs to the major wetland soil types (Sponagel, 2005). Most of the land in this catchment is used for agriculture (87%), forest and urban landuse share the remaining area. Average annual precipitation is around 860 mm, and evaporation around 400 mm (Schmidtke, 1999). A large fraction of wetland area and the near-surface groundwater level are observed in this region (Trepel, 2004), but there is no accurate mapping data for it. The interaction between surface water and groundwater is active, especially in the riparian wetland area for this region (Springer, 2006).

The second study watershed XitaoXi is a 2271 km^2 sized mountainous basin located in the semitropical zone in Southern China. It is a sub-basin of the Taihu Lake. In the XitaoXi region, 63.4% of land use is agriculture-used drought area and commercial forest, 20% paddy rice land. Average rainfall within the watershed is 1466 mm annually, and average evaporation from water surface ranges from 800 mm to 900 mm annually. The spatio-temporal variations in precipitation distribution and evaporation value are statistically significant (Gao, 2006). The dominant soil types are red soil and rocky soil. Since these soils tend to have limited water storage capacity, the highest fraction of the river discharge comes from surface runoff and interflow.

2.2 Data collection

Basic spatial data for the KIDS model included a digital elevation model (DEM) and meteorological data. Other inputs like soils and land cover are important input parameters to KIDS but optional, as it can be added as extended submodels to the basic model structure. Based on long-term climatic data (1983–1999) from some nearby weather stations, there was no considerable spatial variation around the Kielstau region (Zhang, 2006). The climatic data for Kielstau catchment was taken from the data set of the Flenburg station, 9km north from Kielstau basin (German Weather Service, Deutscher Wetterdienst, DWD). The DEM was provided by Landesvermessungsamt Kiel, and the LANU – Landesamt für Natur und Umwelt – has provided river discharge values from 1990 to 1999 (at the official Soltfeld gauge station). Other spatial data like land use, soil maps are from the BGR (Bundesamt für Geowissenschaften und Rohstoffe). Owing to the data limitation and the flat area, the model in Kielstau basin is set up with a completely lumped distribution of precipitation and evaporation (calculated with Penman-Monteith method).

In XitaoXi catchment, precipitation data are available from seven stations within the watershed area, and evaporation data are from two among the seven stations. Considering the spatial and temporal variation of the climate in this mesoscale mountainous area, we used sub-basin distributed rainfall and evaporation (measured with the Chinese pan standard method). The discharge data set from the Hengtangcun gauge station is available from 1978 to 1987. All data including soil and land use were provided by the Administrative Bureau of TaiHu Basin.

2.3 The KIDS model and model adjustments

The basic KIDS model is driven by meteorological input data and simulates river discharge in given river basins as a dynamic function of spatial information. It is composed of one lumped soil layer and one groundwater aquifer, where the flow from soil to groundwater is calculated according to Glugla (1969). Sub-surface flow is modelled as 1-D bucket flow and the groundwater layer as a linear storage. There are five important parameters contained in the basic module: "Intercp_max" (maximum interception amount of vegetation cover); "Inf_factor" (water infiltration rate of upper soil layer); "SWC" (maximum soil water capacity); "soil_gw_flux" (water seepage rate from soil zone to groundwater aquifer); "gw_factor" (groundwater discharge rate to the river baseflow). Runoff is calculated on each grid cell:

$$\text{Runoff} = P - \text{ETa} - I - \Delta S - \Delta\text{GW}$$

Where P is precipitation and ETa is actual evapotranspiration;

I is interception, $I = f$ (1"Intercp_max");

ΔS is storage change of soil water, $\Delta S = f$ ("SWC", "Inf_factor", "soil_gw_flux");

ΔGW is storage change of groundwater, $\Delta GW = f$ ("gw_factor").

Flow direction is then determined based on DEM, and channel flow is modelled with fully dynamic runoff routing using kinematic wave function. For more details see Hörmann et al. (2007) and Zhang et al. (2007).

In our previous study on model structure uncertainty (Zhang et al., 2008), we cited the method to build up the KIDS model ensembles in order to find out the "optimal" model structure for a specific location. Based on the result, we take the basic KIDS model and the optimized model structure for both basins to compare model simulation. For the Kielstau basin it is model "DW" with consideration of the influence of agricultural drainage and wetland fraction. The agricultural drainage is introduced as the water amount extracted from the available soil water decided with the new parameter "drainage_factor". Wetland fraction (12%) is modelled based on the soil map as additional water storage layer in the soil zone, which has unlimited water support for evaporation as its actual ET equals the potential ET. The modified model for the XitaoXi basin is "LTG", which is coupled with lateral flow process and groundwater outflow threshold, using spatial distribution of potential evaporation adjusted with landuse coefficients. As the behavior of rainwater tends to be more affected by lateral flow on slope area, another parameter "lateral_factor" is added to the XitaoXi model to generate lateral flow. The water amount recharged from groundwater to river base flow is here restrained by a groundwater outflow threshold, which represents limited influence on river discharge. Spatial distributed ETp adjusted with landuse coefficients referring to Gao et al. (2006), especially for drought area and paddy rice land of season changes. The adjusted KIDS models with submodels added accordingly, are expected to produce better simulations as presented further in the next section.

3 Results and discussion

3.1 Hydrometeorological comparison

As mentioned above, the two catchments in this study differ greatly in catchment scale, topography, soil properties, landuse and weather conditions. The analysis of long-term mean monthly precipitation shows a very distinct seasonal pattern in the XitaoXi basin, with 75% of rain falling between April and October (Monsoon). The average daily runoff of the XitaoXi river (35.09 m^3/s) is much higher than that of the Kielstau stream (0.45 m^3/s). The difference is significant as well when considering the different discharge area of the selected gauge stations for both basins. The runoff rate per unit area is 8.82 l/s/km^2 for Kielstau, and 23.02 l/s/km^2 for XitaoXi. The two watersheds also differ in streamflow response to summer rains. Runoff efficiency based on the ratio of monthly stream flow to monthly precipitation (Wu

Table 1. Nash and Sutcliffe coefficient NS for 5 year period model calibration and a 10 year period validation in the two watersheds.

	Kielstau		XitaoXi	
	Periods	NS	Periods	NS
Default	1990 to 1994	0.08	1979 to 1983	0.21
Calibration	1990 to 1994	0.70	1979 to 1983	0.61
Validation	1990 to 1999	0.73	1979 to 1988	0.65

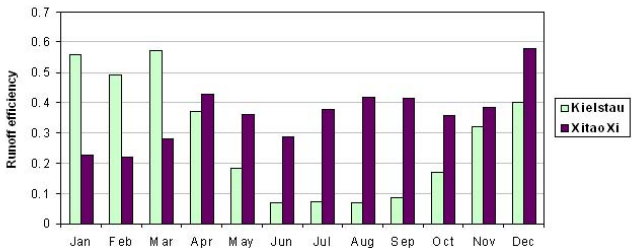

Fig. 2. Seasonal patterns of long-term monthly runoff efficiency (monthly streamflow to monthly precipitation) in the 10-year data periods: 1990–1999 in Kielstau and 1979–1988 in XitaoXi

and Johnston, 2008) is plotted in Fig. 2 for the two watersheds. Runoff efficiencies ranged from 0.08 to 0.58 in Kielstau basin and 0.22 to 0.58 for the XitaoXi catchment. The larger variations in runoff efficiency of the Kielstau basin might be caused by high evapotranspiration in the wetland area of the watershed and its capacity to impound surface runoff or to deter the streamflow events. The Kielstau and XitaoXi watersheds have quite different hydrologic regimes, thereby providing diverse data sets to test the adapted KIDS model used in this study.

3.2 Model simulation comparison

Runoff simulations were carried for the calibration period from 1990 to 1994 for the Kielstau and from 1979 to 1983 for the XitaoXi with the basic KIDS model and its optimal model version respectively. The resulting NS values (Nash and Sutcliffe, 1970) are listed in Table 1. The first results of the simulation using the default basic KIDS model yielded a low model efficiency of 0.08 for Kielstau and 0.2 for XitaoXi. With the adjusted model structure, the model efficiency improves significantly to an NS value of 0.73 for the validation period for model "DW" of the Kielstau basin and to 0.65 for model "LTG" of the XitaoXi basin. The result demonstrates that the selected submodels describe the hydrology of the catchment fairly well.

For the lowland Kielstau basin, the lateral flow may not be distinct due to the low altitude variance. Instead, the drainage ("D") reflects anthropogenic influence to some extent, with the evidence of large proportion of agriculture use in the local region and drainage pipes and ditches commonly seen in the field. Moreover, the wetland ("W") plays an important role in the local water cycle. It can increase the capacity of a watershed to impound surface runoff and to enhance evapotranspiration dramatically especially in summer and autumn seasons. The model performance shows that the influence of drainage and wetland fraction makes a great difference in model efficiency. For the mountainous XitaoXi basin, lateral flow ("L") is required as one of the dominating processes in sloping area. Spatial distribution of evaporation ("T") is adjusted with empirical coefficients applied to various land use types. This is an alternative to the very limited evaporation data from only two weather stations within the large-scale catchment. Groundwater outflow threshold ("G") is a simply set value to reduce water discharge to base flow. It indicates that the influence from the groundwater is limited. From the model performance assessment, the "LTG" model structure may better capture the hydrological mechanisms in the XitaoXi basin.

3.3 Parameter calibration

In the adapted model versions, six parameters need to be determined by calibration using daily discharge observations. As introduced before, five parameters are same for both study basins and one different: "drainage_factor" for Kielstau and "lateral_factor" for XitaoXi. Most of the parameters were adjusted on a trial-and-error basis, modifying parameter values within reasonable limits and selecting final values with maximum model efficiency.

The result of the parameter estimation is displayed in Figure 3. The flat response surface of parameters "intercp_max" and "soil_gw_flux" indicates low parameter sensitivity for both catchments. The optimum value of "swc" is much higher for the Kielstau than for the XitaoXi, which corresponds to large water storage capacity of the loamy soils in Kielstau. The sharp curves of the parameters "gw_factor" and "drainage/lateral_factor" for the Kielstau model suggest the influence of groundwater and drainage is important for streamflow simulation, but they are negligible for the XitaoXi catchment. Parameter identification problems will become easier to solve with more detailed information about the catchments that may be helpful to understand the uniqueness of location and its hydrological processes.

4 Conclusions

Performance of KIDS model simulation was carried out for a small flat and a large mountainous watershed in different climates. The differences between the two hydrogeological regions are significant in many ways like catchment scale, topography, geology, landuse, soil properties, and weather conditions. For the purpose of river runoff simulation, we analysed the unique features based on observations and existing data base, discussed the possible model adjustments that

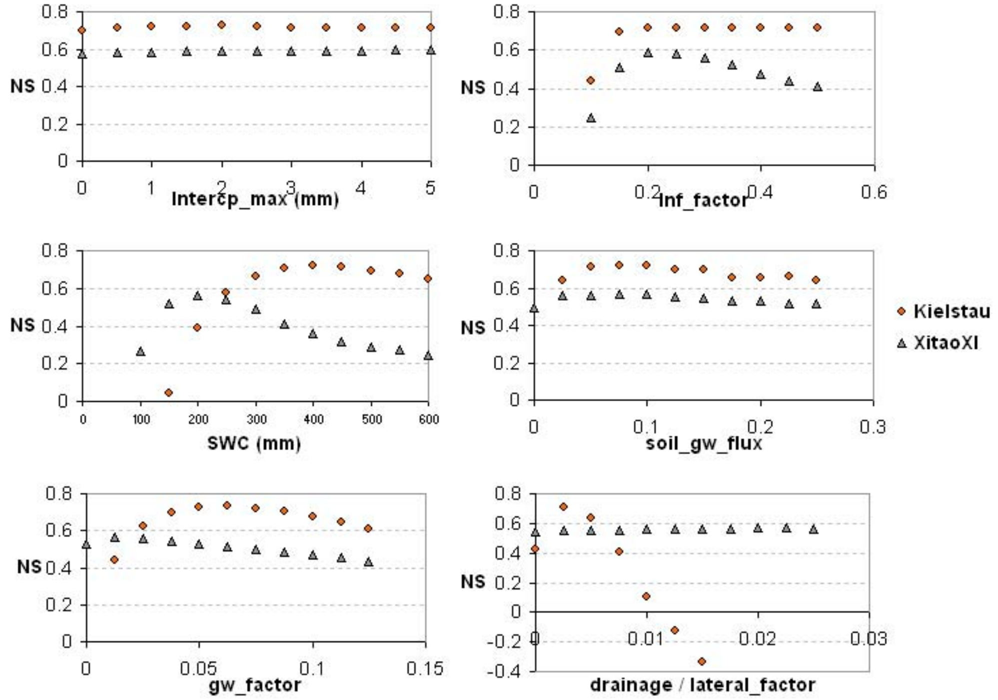

Fig. 3. Nash-Sutcliffe model efficiency with different, variable parameters in Kielstau and XitaoXi Watershed.

can improve simulations, and compared the results in model efficiency and parameter estimations. Overall, the simulation provided satisfactory agreement between observed and simulated discharge. The validated simulation reaches a NS value of 0.73 for Kielstau and 0.65 for XitaoXi. It proved the general applicability and flexibility of KIDS basic model and submodel ensembles with for specific features of study area. For the Kielstau catchment, lumped model is adequate for this small region and better model performance can be achieved when considering the influence of wetland. Based on the long-term climatic data, it exhibited substantially different flow trends in the Kielstau than in the XitaoXi catchment, with lower runoff efficiency during summer months. It suggests an important storage function of wetland and groundwater, and representative of the wetland components was necessary as added submodel. In the XitaoXi watershed we observed a significant impact of adjusted evapotranspiration for various landuse types and limited effects from groundwater. Owing to the larger catchment scale and distinct heterogeneity in topographic characteristics, more accurate geospatial data and distributed modelling are crucial for more accurate and reliable hydrologic predictions. The parameter calibrations in both case studies demonstrate the strong link between parameter estimation and the observed catchment features. This study stressed that, for simulating the hydrological behavior of a watershed, we should consider the unique features of the place much more explicitly (Beven, 2000), and adapt the models to the local situation.

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