

Estimating the impacts and uncertainty of changing spatial input data resolutions on streamflow simulations in two basins

X. Zhang, G. Hörmann, N. Fohrer and J. Gao

ABSTRACT

The impact of different grid resolutions of spatial input data on modelled river runoff are investigated using the simple rainfall-runoff model KIDS (Kielstau Discharge Simulations) in PCRaster modelling language for two watersheds – Kielstau and XitaoXi. In this study, the grid-based spatial data are aggregated to coarser resolutions to support the multi-resolution, multi-calibration and multi-site analysis for grid-scale investigations. Daily streamflow is simulated and model parameters are calibrated at each spatial resolution. The study suggests that re-calibration is critically needed when the grid resolution is changed. Altering grid sizes has an apparent impact on the parameter distribution patterns. Resolution uncertainty bands obtained by the overlapping hydrographs generated with different resolutions of input data are reported with a sufficient coverage of the observations for both basins. The analysis of model efficiency in terms of IC-ratio (a ratio between the input grid area and the catchment area) indicates that coarser resolutions with an IC-ratio of <0.001 may be used as an effective alternative for conducting preliminary analyses in streamflow simulation for the Kielstau basin. The modelling outputs are more sensitive to the spatial distribution of input data at the XitaoXi watershed, showing that accurate input data are required to achieve optimum modelling performance.

Key words | grid size upscaling, hydrological modelling, IC-ratio, parameter sensitivity, resolution uncertainty

INTRODUCTION

Distributed hydrological models, as well as process-based models, deal with the interactions of their spatial patterns and processes on a variety of scales. Grid resolutions are often used in spatially explicit models to account for detailed watershed heterogeneity, such as spatial information on topography, soil and vegetation properties. The scale and resolution issues become more significant as physically based models are more widely used. In the first instance, the choice of an appropriate scale is considered to be aimed at attaining optimal model performance.

Many researchers have investigated the issues that are related to the impact of resolution on model parameters and the predictions of catchment modelling. As the higher

resolution database usually represents better landscape information required in model application, several studies found that the finer grid size gave more accurate results (Quinn *et al.* 1991; Moore *et al.* 1993; Wolock & Price 1994; Bruneau *et al.* 1995; Kuo *et al.* 1999). However, a large effort to improve model performance by increasing data discretization level is mostly not justified when above a certain threshold of resolution. Zhang & Montgomery (1994) examined the effect of digital elevation model (DEM) grid size on the portrayal of the land surface and hydrologic simulations. Elevation data gridded at 2, 4, 10, 30, and 90 m scales significantly affects computed topographic parameters and hydrographs. The result revealed

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that the 10 m grid size provides a substantial improvement over 30 and 90 m data, but 2 or 4 m data provide only marginal additional improvement for the study areas. Vazquez *et al.* (2002) and Vazquez & Feyen (2003) demonstrated that different input data resolutions with the MIKE SHE model code (Refsgaard & Storm 1996; DHI 1998) lead to significant differences in both effective parameter values and model performance. They found that an acceptable compromise between accuracy of model predictions and computational time was reached when using a grid size of 600 m for the Gete catchment in Belgium. A subsequent study with the same hydrologic code focuses on the impact assessment of different DEM gridding methods on basin runoff modelling (Vazquez & Feyen 2007). Bormann (2006) indicates that an aggregation of input data for the calculation of regional water balances using TOPLATS type models (Famiglietti & Wood 1994) does not lead to significant errors up to a grid size of 300 m. Shrestha *et al.* (2006) evaluated the model performance by comparing observed discharge against simulated discharge for a range of IC-ratio values. The IC-ratio is defined as the ratio of the input forcing resolution to catchment size (Equation (1)):

$$\text{IC-ratio} = \frac{C^2}{A} \quad (1)$$

where C [m] is grid cell size and A [m²] is catchment area.

The IC-ratio range 0.05–0.1 is found to be the optimum performance range when considering the data and resource demands of distributed models.

A possible reason for this could be that highly resolved data often contain redundant information, therefore a higher data resolution does not always produce a better modelling result. Furthermore, the benefit of increased data resolution strongly depends on the applied model philosophies and catchment specific characteristics. Beven (2001) described the problem of scaling as the difficulty of applying a hydrological model to a particular catchment with its own unique characteristics. Bormann *et al.* (2009) investigated model sensitivity to data aggregation using different catchment models. They concluded that aggregation effects are partly model and case study dependent. The results showed that high quality of input data is more

important than high spatial resolution of data for the calculation of regional water balances. With regard to the quality of input data, it is a highly subjective terminology as it should be appropriate to the resolution of model disaggregation and the scales of hydrological significance patterns such as topography, forcing data spatial discretization, etc.

Additional challenges arising from the scaling issues in hydrological modelling are the induced predictive uncertainty (Shrestha *et al.* 2006). A number of recent studies provided evidence of the effects of input data on model sensitivity and uncertainty. Lindenschmidt *et al.* (2005) conducted an uncertainty analysis for different degrees of model complexity in scale discretization and compared them at different basin scales. This indicated that the model sensitivity increases with the discretization level since the inclusion of additional processes brings with it additional parameters and data input. Hebel & Purves (2008) assessed the impact of scaling on models from different resolution, and concluded that tested models had clear dependencies on scale, terrain roughness and variations of parameter thresholds. Bogena *et al.* (2005) focused on model uncertainty analysis in the simulation of groundwater recharge at different scales.

In summary, choosing an appropriate resolution is a key task in hydrology (Hebel & Purves 2008). The scaling dilemma exists when approaching better model performance with higher resolution data: the limited effect to bring more accurate results after a certain resolution threshold and the massive demand of storage capacity and computer time required by high resolved data (Vazquez *et al.* 2002; Omer *et al.* 2003; Cullmann *et al.* 2006). Even when a detailed database is preferred, it is not always available for every catchment of interest.

Despite the efforts in literature to investigate the impact of data resolution, it is still a difficult task to find a suitable solution for different hydrological models or different sites. This is not only because results are mostly not transferable, but also as the assessment will usually demand the considerations of various aspects such as data assessment, parameter errors and modelling uncertainty. Therefore, this study elaborates the effects of grid aggregation on the streamflow simulation, parameter estimation and modelling uncertainty for model application in two case studies. The hydrological model in this study is set up with a GIS-based dynamic

modelling language PCRaster (Van Deursen 1995; Wesseling *et al.* 1996). River runoffs are simulated for two watersheds: the small lowland Kielstau catchment (51.5 km²) in Germany and the medium-sized mountainous XitaoXi basin (2,271 km²) in China. With regard to the scale issues, previous studies using PCRaster based models, such as Zhao *et al.* (2009), examined the impacts of spatial data resolution on discharge simulation for the XitaoXi basin. It concluded that an aggregation of input data does not lead to significant errors up to a grid size of 1 km. However, it did not address explicitly either the effects on parameter behaviour or the assessment of model uncertainty. Furthermore, discussion about the results comparison between small and medium-sized watersheds is not common in previous publications. In this paper, we intend to inspect how the modelling process is affected by changing input data resolutions (grid upscaling) in terms of the effective parameter values and of the modelling performance in the two watersheds. Thus the objectives of this study are: (1) to simulate daily stream flow at different grid resolutions for Kielstau and XitaoXi watersheds using a hydrological model (namely the Kielstau Discharge Simulation (KIDS) model) in PCRaster; (2) to examine the grid-size impact on effective parameter values; (3) to assess the extent of modelling uncertainty caused by varying resolutions; (4) to compare the model efficiency at changing input data resolutions for the

two watersheds in terms of the IC-ratio, and therefore to investigate the suitable resolution level for runoff simulation.

DATA, MODEL AND METHODS

The study sites

We consider two catchments in this study including the Kielstau basin in Germany and the XitaoXi basin in China. These two basins are the subject catchments of a Sino German integrated geohydrological study.

Kielstau is a lowland watershed in Northern Germany, with a drainage area of 51.5 km² (see Figure 1(a)). As the development of the landscape was mainly influenced by the Saale and the Weichselian ice ages (Eggemann *et al.* 2001), the whole catchment is rather flat, with a maximum altitude difference of about 52 m. Wedged between the North Sea and the Baltic Sea, the Kielstau catchment is characterized by moderate temperature and oceanic climate with soft moist winters and cool rainy summers. Snowfall is rare and occurs on average 20–25 days per winter. Mean annual precipitation is about 800 mm, and actual evaporation is approximately 400 mm (Schmidtke 1995). Land use is dominated by agriculture (55.8%) and grassland (26.1%). The geological underground of the basin is dominated by

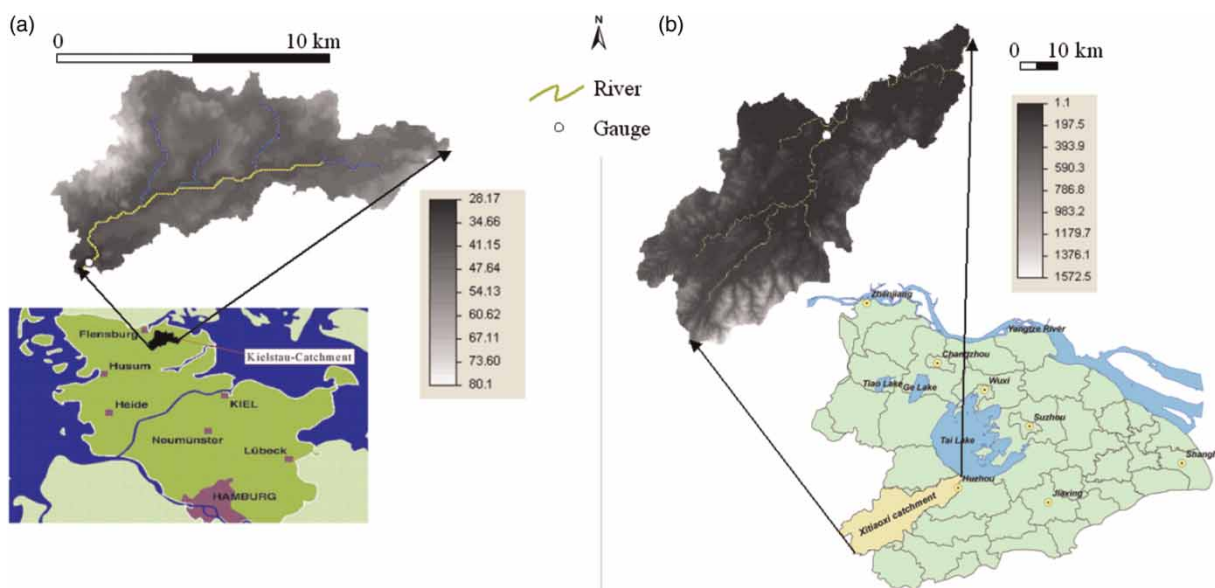


Figure 1 | Geographic location and elevation map for (a) the Kielstau basin and (b) the XitaoXi basin.

pleistocene deposits, resulting in a wide variety of soil types and soil forms in this small area. Soils mainly consist of Podzol, Gleysol and Luvisol formed in the Saale and Weichsel ice ages, among which Gleysol belongs to the major wetland soil types (Sponagel 2005). These are heavy soils having high field capacity and containing large percentages of clay and silt, which contribute to forming numerous scattered wetland areas in the watershed. A large fraction of wetland area (estimated as 30% of land surface area (Trepel 2004)) and the near-surface groundwater level are observed in this region. Dynamics of near-surface groundwater are generally determined by precipitation, and when close to the river by stream water level as well. Groundwater levels in the riparian wetland are in most cases higher than those in the river. The interaction between surface water and groundwater is thus active, especially in the riparian wetland area for this region. During flood events, a reversion of the flow direction could happen if the close-to-river groundwater level is lower than the stream water level (Springer 2006).

The second study watershed XitaoXi is a 2,271 km² sized mountainous basin, which is located in the semitropical monsoon zone in Southern China (see Figure 1(b)). It is one of the major sub-basins that drains into Taihu Lake. The spatio-temporal variations in precipitation and evaporation distributions are statistically significant. Average precipitation in the watershed is 1,466 mm annually, with 75% of rain falling between April and October (Gao *et al.* 2006). The annual rainfall gradually decreases from the southwest mountain area of 1,800 mm to the northeast plains of 1,200 mm. Average evaporation from water surface ranges from 800 to 900 mm annually. Evaporation intensity from the southwest to the northeast has shown an increasing trend (Zhang *et al.* 2006). The XitaoXi basin is characterized by three different topographic areas from southwest to northeast. The upper reaches in the southeast part are a mountainous area, with elevations over 600 m accounting for about 15% of the total basin area. The following section is a 150–600 m high hilly region in the central part of the XitaoXi basin, which accounts for 40% of the total area. The rest of the northeast part turns into a flat outwash plain with a low hydraulic gradient. The dominant soil types are red soil and rocky soil. These soils tend to have limited water storage capacity. In the XitaoXi region, 63.4% of land use is forest and grass and 20% paddy rice

land (Wan *et al.* 2007). Most portions of the river discharge are assumed mainly from the saturation excess surface runoff, with limited influence from the deeper, regional groundwater (Xu *et al.* 2007).

The Kielstau and XitaoXi watersheds have quite different hydrologic characteristics in catchment scale, topography, soil properties, land use and weather conditions (Zhang *et al.* 2009). These features also illustrate their noticeable differences in the extent of catchment heterogeneity. The mountainous XitaoXi basin is more heterogeneous in catchment spatial features than the small flat Kielstau watershed. These two areas thus provide a good dataset to compare the impacts of different grid-scales.

KIDS model description

The KIDS model (Hörmann *et al.* 2007; Zhang *et al.* 2007) is a simple rainfall-runoff model developed in PCRaster modeling language. It was first used for practical purposes to facilitate water resource management in the Kielstau basin. The main advantage of the KIDS model in PCRaster is its flexibility of model structure complexity in lumped or physically distributed models. It is basically driven by DEM and meteorological input data, and then simulates river discharge in given river basins. To fit model results to local conditions, it also allows the extension of the model with additional inputs such as soils and land cover as submodels (Zhang *et al.* 2008, 2011). All derived models form the KIDS model ensembles. The model is spatially distributed and space was originally discretized at a 50 m by 50 m grid size for Kielstau and 200 m by 200 m for XitaoXi using the best available resolution data.

In the framework of the KIDS model, runoff is calculated on each grid cell based on the water balance equation (see Equation (1)), taking into account interception, precipitation, evapotranspiration, and the flows to other compartments. We use ‘mm’ as the unit of measurement for all the water amount expressions included in equations of this paper, and calculate with a daily time step. The model is a simplified approximation of complex water cycles, with detailed calculation steps stated below:

$$S_t = S_{t-1} + P_t - ET_t - I_t - Q_{o,t} - Sp_t \quad (2)$$

where S is the soil water content, t is the modelling time step (daily), P is precipitation, ET is evapotranspiration, I is interception, Q_o is surface runoff (overland flow) and Sp is a lumped term of water seepage loss.

Precipitation and potential evapotranspiration are required as input data. The model calculates interception from vegetation layer, with the parameter 'Im' as shown in Equation (3). Surface runoff 'Qo' is calculated according to Equation (4). It describes saturation excess overland flow and storage calculation on the basis of derived soil parameters such as field capacity and infiltration rate of soil water deficit. The parameter 'Sp' is the expression of water loss which comprises percolation or seepage, lateral flows and other aggregate model errors.

$$I_t = \min(P_t, Im) \quad (3)$$

where Im is the maximum interception amount of vegetation cover.

$$Q_{o_t} = \max\{[P_t - I_t - K_c(S_{fk} - S_t)], 0\} \quad (4)$$

where Q_o represents the surface runoff, K_c is the infiltration parameter, and S_{fk} is the wetness at field capacity.

The whole river basin is set up with one lump soil layer in the basic structure. The current soil map can be sub-parameterized or more soil layers can be added if required. Sub-surface flow is modelled as 1D bucket flow with a lateral flow rate parameter 'K_s' as Equation (5) shows. The value of parameter 'K_s' is set equal to zero in the basic model for both basins; however, it can be adjusted above zero for further modifications.

$$Q_{s_t} = K_s S_t \quad (5)$$

where Q_s is subsurface flow, and K_s is lateral flow rate.

The groundwater layer is represented as linear storage. Combining Equations (6), (7) and (8) yields the daily groundwater dynamics.

$$G_t = G_{t-1} + I_{g_t} - Q_{g_t} \quad (6)$$

$$I_{g_t} = \rho S_t \quad (7)$$

$$Q_{g_t} = K_g G_t \quad (8)$$

where G is groundwater storage, I_g is the inflow to groundwater aquifer, Q_g is the groundwater discharge to runoff, ρ is the water seepage rate from soil to groundwater and K_g is the groundwater outflow rate.

Runoff is then composed of three parts: surface runoff, lateral flow and groundwater discharge. The flow path is then derived from topography through a flow accumulation grid calculated in PCRaster. The routing of surface and sub-surface runoff water flows is modelled with the fully dynamic kinematic wave function (Chow *et al.* 1988).

The basic KIDS model and equations as described above represent a simple rainfall-runoff model. The basic model can be easily adapted for a wide range of hydrological modelling applications by means of integrating sub-modules into basic structure in order to take some specific influence factors into account. Considering the greatly differing hydrology of the two basins, the appropriate model structure for each basin is selected from the KIDS model ensembles respectively (Zhang *et al.* 2011): Model 'DW' for Kielstau – basic KIDS model with drainage (Equation (9)) and integration of wetland (Equation (10)); Model 'GLT' for XitaoXi – basic KIDS model with groundwater outflow threshold (Equation (11)), subsurface flow and land use-coefficient adjusted ET distribution.

$$D_t = K_d S_t + L_d \quad (9)$$

where D is the drained water volume, K_d is drainage factor, S is available soil water storage, L_d is the lateral inflow volume (lateral seepage from irrigation canals and drainage channels).

$$W_t = W_{t-1} + I_{w_t} - E_{w_t} - Q_{w_t} \quad (10)$$

where W is wetland water storage, I_w is the incoming water volume influenced by precipitation, interception and soil moisture, E_w is the water loss from wetland, mainly evapotranspiration, and Q_w is the wetland water seepage contributing to runoff.

$$Q_{g_t} = \text{Min}(K_g G_t, G_m) \quad (11)$$

where G_m is the maximum daily groundwater outflow or groundwater outflow threshold.

Owing to the general nature and flexible structure of the KIDS model, its application to any study area requires certain parameters to be identified for the particular basin. In the current model version, six main parameters need to be determined by calibration using daily discharge observations. Table 1 lists an overview of the calibration parameters with the upper and lower value ranges, which are decided based on a preliminary parameter sensitivity test (Zhang *et al.* 2009) and also considering empirical scales of physical parameters.

Table 1 | Description of parameters included in the KIDS hydrological model calibration procedure, with their upper and lower bounds

| Parameter (unit) | Range | Definition |
|-----------------------|-----------|---|
| I_m [mm] | 0–10 | Maximum water amount intercepted by vegetation cover |
| S_{fk} [mm] | 1–800 | Soil water storage capacity |
| K_c [-] | 0.01–0.6 | Soil infiltration parameter |
| ρ [-] | 0–0.5 | Water seepage rate from soil to groundwater |
| K_g [-] | 0.001–0.1 | Groundwater discharge rate to the river baseflow |
| K_d [-] in Kielstau | 0–0.01 | Water drainage rate from available soil water storage |
| K_s [-] in XitaoXi | 0–0.05 | Soil water percolation rate to river discharge |

Experimental data processing and analyses steps

To investigate the effects of varying resolutions on model simulation, we need to generate input forcing data with different grid sizes. The initial and finest dataset in this study is at $50 \times 50 \text{ m}^2$ resolution for Kielstau and $200 \times 200 \text{ m}^2$ for XitaoXi. It was used to acquire a set of experimental data set at different spatial resolutions, namely two, four, eight, 12 and 20 times coarser resolution, over the two study basins. Aggregation is carried out with an upscaling operation in the PCRaster system using averaged parameter values. Figure 2 shows an example of the data aggregation process with the basic spatial data of DEM over the Kielstau watershed at six different grid sizes. Other spatial data or system required map data are converted into coarser resolutions using the same process. The time series data (TSS files), including the daily precipitation data and streamflow data at all six spatial resolutions, are consistent with each other.

The resolution coarsening process results in the change of overall watershed area (Bruneau *et al.* 1995; Kuo *et al.* 1999), as is clearly illustrated in Figure 2. We adjust the border cells for forcing input data of rainfall and ET to keep the modelled area consistent, so that only the portion inside the watershed defined in $1 \times$ resolution data is considered in modelling. Other data and parameters are aggregated to different spatial resolutions in the PCRaster

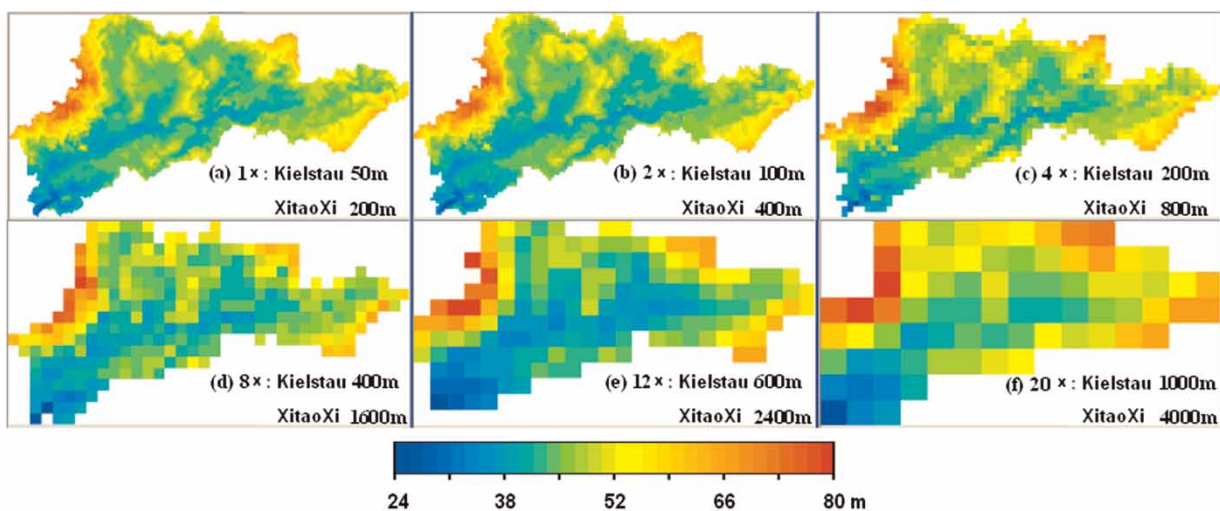


Figure 2 | An example of spatial data DEM over the Kielstau basin at resolutions of (a) $1 \times$ – grid size 50 m for Kielstau, 200 m for XitaoXi, (b) $2 \times$, (c) $4 \times$, (d) $8 \times$, (e) $12 \times$, (f) $20 \times$ and their corresponding grid sizes.

system based on the average cell value of continuous data or the most common value for categorical data. The grid cell aggregation process inevitably leads to loss of information and an increase in the errors in the data.

To facilitate model evaluation, three statistical criteria are used to evaluate the impact of model calibrations considering the strengths and weaknesses of each technique for their applications in watershed model evaluation (Gupta & Sorooshian 1998; Moriasi *et al.* 2007). They are the Nash–Sutcliffe (NS) coefficient (Nash & Sutcliffe 1970), the root mean squared error (RMSE), and the regression coefficient (r^2).

$$NS = 1 - \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (12)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}} \quad (13)$$

$$r^2 = \left[\frac{\sum_{i=1}^n (O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^n (O_i - \bar{O})^2} \sqrt{\sum_{i=1}^n (P_i - \bar{P})^2}} \right]^2 \quad (14)$$

where P_i and O_i denote the predicted value and observed value i , \bar{P} and \bar{O} are their means over the study time period, and n is the total number of simulation time steps.

With the establishment of required data at different resolution levels for the two catchments, a multi-resolution (MR), multi-calibration (MC) and multi-site (MS) test approach was conducted.

First, the model at the initial resolution level is calibrated to obtain optimal model performance based on daily streamflow data. The derived parameter values are directly transferred into other models at different resolutions for river discharge simulation. This is the MR test to analyse the model performance results as a starting step in the process. An automatic parameter estimation method is used for the KIDS model calibration. This software framework, developed by Schmitz *et al.* (2009), is suited for the PCRaster environment to assign the KIDS model files. It allows adding calibration algorithms by the user and evaluates

the objective function at randomly spaced points in the defined parameter space. For each calibration process it will generate 3,000 model simulations with different parameter values. The NS coefficient is used as the objective function to obtain a quick overview of model performance evaluation in this step. The optimal value of NS is 1.0 and the feasible range of variation is $-\infty < NS \leq 1.0$.

Second, models with the five coarser resolutions are subjected to identical parameter calibration process in the framework of the MC test. As each set of calibrated parameters is assigned with a NS value, we choose the parameter combinations whose NS value is higher than 0.5 ($NS > 0.5$) as the sample population for the parameter behaviour analysis. The parameter distribution pattern will be generated for each model by dividing the parameter sampling range into 20 equivalents. The results will then be compared to assess the relationships among effective parameter values and grid size. For the river discharge simulation, an optimal model behaviour can be obtained for all the grid sizes after calibration. This will yield a band of overlapping hydrographs generated from various input data resolutions in both catchments. Two measures are defined here to quantify the band width which represents model sensitivity or uncertainty of changing input data resolution (Abbaspour *et al.* 2004; Schuol & Abbaspour 2006). The first measure is referred as the R factor, the ratio of the average distance of the simulation intervals from different grid sizes and the standard deviation of the measured data, as Equation (15) shows. The other is the P factor, the percentage of measured data bracketed by the simulation uncertainty bounds (Equation (16)). The ideal situation is to have an R factor value close to zero, while at the same time to cover all the observation data within the simulation uncertainty bounds (P factor = 100%). The values of the P factor and R factor reflect the uncertainty of varying grid sizes after taking into account the discharge observations.

$$R \text{ factor} = \frac{\{\sum_{i=1}^n [(S_{\max} - S_{\min})_1 + (S_{\max} - S_{\min})_2 + \dots + (S_{\max} - S_{\min})_n]\} / n}{\text{stdev}\{Q1, Q2, \dots, Qn\}} \quad (15)$$

where S_{\max} and S_{\min} denote the maximum and minimal values for each simulated variables, n is the time steps of the selected flow period and stdev is standard deviation of the observed flows within the selected period.

$$P \text{ factor} = \frac{m}{n} \times 100\% \quad (16)$$

where m is the number of model time steps counted when the observed river discharge value is within the modelled simulation uncertainty bounds and n is the time steps of the selected flow period.

Finally, a MS evaluation test is also performed to investigate how the results differ between the small lowland Kielstau basin and the medium-sized mountainous XitaoXi basin. The MS test mainly includes an analysis of the model performances for the selection of an appropriate input data grid resolution in the context of IC-ratio. Shrestha et al. (2002, 2006) used the IC-ratio to investigate the effects of input data resolution on discharge.

Other results comparisons for the two study areas in the MR and MC analysis steps are considered as part of the MS test. Figure 3 describes the evaluation framework of the proposed MR-MC-MS test approach in this study.

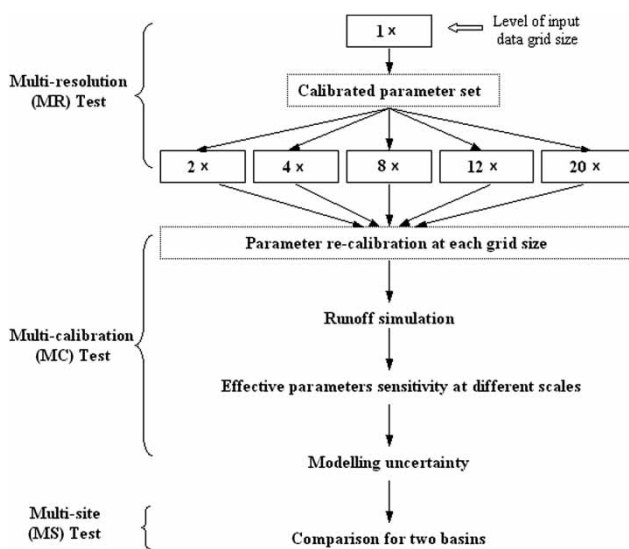


Figure 3 | Flowchart of the MR-MC-MS approach for the investigation of grid-scale issues.

RESULTS AND DISCUSSION

Multi-resolution test and multi-calibration test

The KIDS model performances at various resolution levels in the MR and MC tests are summarized by the NS index in Figure 4. The simulation results with the base-line data present acceptable accuracy – 0.8 NS value for 50 m Kielstau model and 0.75 for 200 m XitaoXi model. The result for Kielstau shows that the NS values (ranging between 0.74 and 0.79) at the four different spatial resolutions of 1x, 2x, 4x and 8x are similar to each other for both MR and MC tests. The NS values at 12x and 20x resolutions are significantly lower than those at the other four resolutions. However, different patterns of the behaviours in NS values are observed for the XitaoXi basin. It drops dramatically at 2x resolution (400 m grid size) even after calibration. All the calibrated (MC) results seem to have better NS values than the MR test. This indicates the necessity of parameter calibration, especially for the XitaoXi catchment as suggested by the larger gap between the NS values of the MR and MC test. The somewhat distinct model behaviours of the two basins are mainly due to the significantly large differences in the effect of spatial variability. The 51.5 km² small lowland Kielstau catchment is more homogeneous characterized in hydrometeorological features (such as topography, soil properties and spatial variation of precipitation) than the 2,271 km² mountainous XitaoXi basin. Model simulation and parameter estimation will be more sensitive to the upscaling grid cells operation

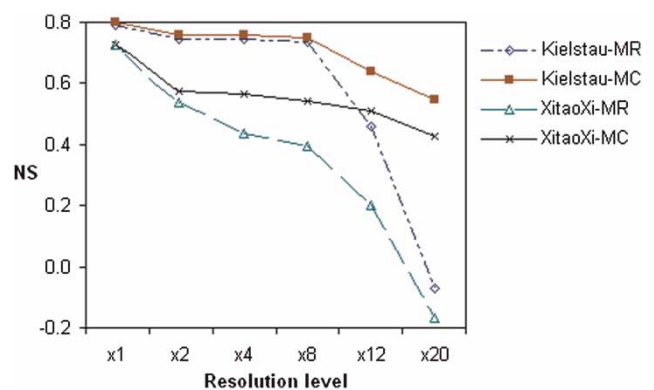


Figure 4 | Variations of model performance (NS) at different resolution levels for the MR and MC tests.

in XitaoXi, as the aggregation of input data causes important information losses for the runoff modelling.

Furthermore, Figure 5 illustrates that the outcomes of two other statistics RMSE and r^2 for the calibrated models also show similar patterns as the NS values in Figure 4. The evaluation analysis using three criteria reveals an acceptable agreement to compare simulated output with measured data. This combination of statistical indexes are

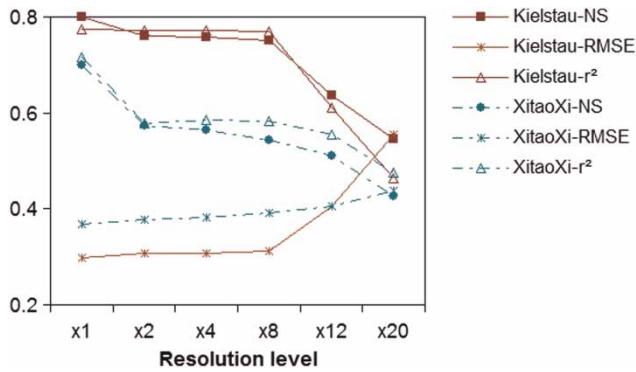


Figure 5 | Simulation results of NS, RMSE, r^2 of calibrated models for Kielstau (solid lines) and XitaoXi basins (dashed lines).

presented together to establish a platform for model evaluation in the MC test.

Parameter sensitivity

In this section we examine the change of parameter distribution patterns with different grid sizes using the random sampling techniques. It is automated model calibration with variation of random combinations of parameters rather than each parameter individually to perform the parameter sensitivity analysis. As the results show that some parameters (such as I_m , the maximum interception) have low sensitivity to varying input data resolution, we construct the probability distributions only for effective parameters. These are presented for the parameters including, S_{fk} [mm] the wetness at field capacity, ρ [-] water seepage parameter from soil to groundwater, K_g [-] groundwater outflow rate, K_d [-] drainage factor in the Kielstau catchment (Figure 6); and S_{fk} [mm] the wetness at field capacity, ρ [-] water seepage parameter from soil to groundwater, K_c [-] infiltration parameter, K_s [-] lateral flow rate factor in the XitaoXi

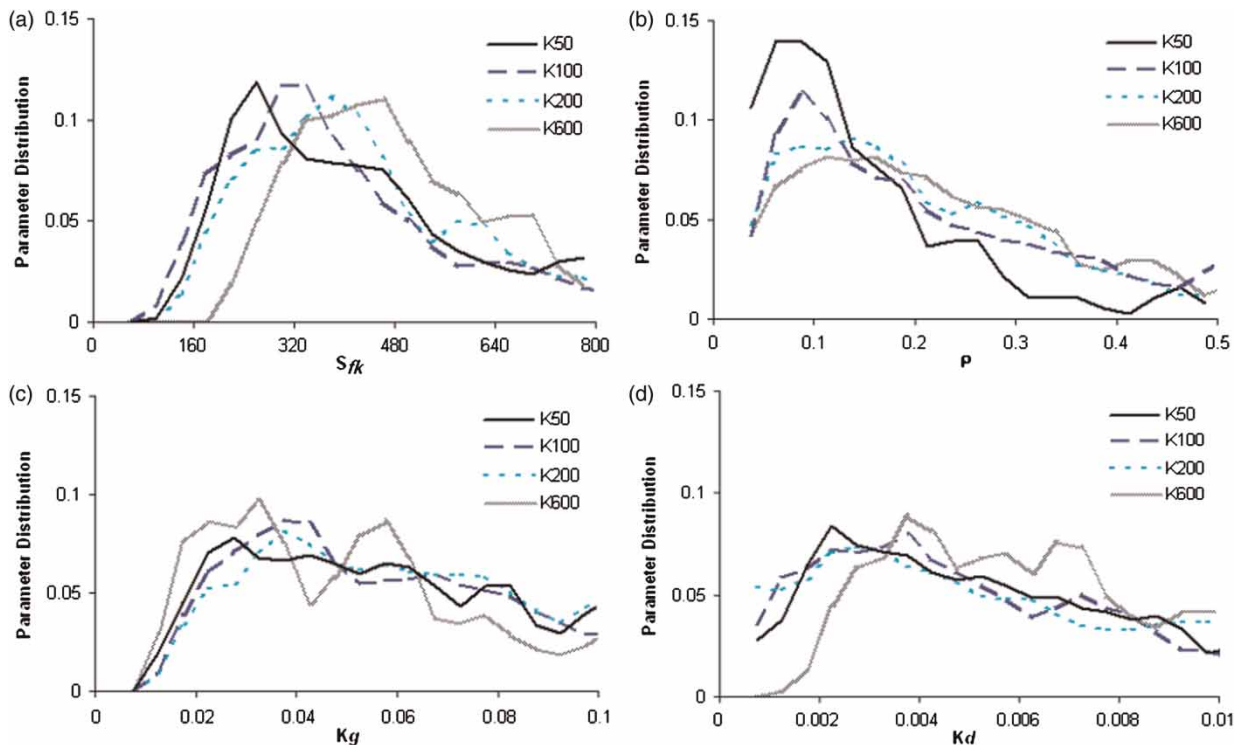


Figure 6 | Variations of probability distributions with different spatial resolutions for the effective parameters in Kielstau catchment.

catchment (Figure 7). Moreover, the result of models at four different resolution levels of $1\times$, $2\times$, $4\times$ and $12\times$ are selected in the plots for a better view of comparison. It suggests the models of K50, K100, K200, K600 for Kielstau, and X200, X400, X800, X2400 for XitaoXi. We designate a series of standard abbreviations for the modelling results using different resolution data in the two basins – ‘K’ is Kielstau, ‘X’ is XitaoXi, then followed by a number representing the grid cell size (50 means $50\times 50\text{ m}^2$ resolution).

As illustrations for the Kielstau basin in Figure 6, the distribution patterns are qualitatively similar for parameter S_{fk} , but with increasing peak values as the grid cells aggregate. As we can see from Figure 6(a), the peak value is around 240 for the K50 curve, which then increases to 480 for K600. Second, most of the distribution curves for models with finer resolution data (e.g. K50 model) are narrower and peakier than other models with coarser data input. This feature is especially apparent for parameter ρ : the lines become more flat as the grid size increases, which results in higher equifinality of parameter estimation. It indicates that the optimal parameter values become less

identifiable with upscaling resolutions, which will also introduce increasing parameter estimation uncertainty. Finally, while the model K50 derived parameter distribution curves are usually single well-defined mode (the desired result), coarser data derived curves become more multi-modal, such as the K600 curve for parameter K_g and K_d . However, differences between the curves for these two parameters are relatively small. For example, the dotted lines of K100 and K200 are very close to each other. It suggests that the parameters K_g and K_d are not so sensitive to input data resolution as the other parameters such as S_{fk} and ρ .

Similar conclusions are also applicable to the XitaoXi basin, as observed in Figure 7. Concerning the limited influence of groundwater layer in the modelled area of the XitaoXi basin, the parameter K_g reveals low sensitivity to resolution and therefore is not included in this plot. It is noticeable that, with respect to the parameter Sc , not only the peak values of derived functions deviate from the optimal value of model X200, but also the curves become more smooth and flat with increasing grid cell sizes. The distribution functions of parameter ρ in the XitaoXi models

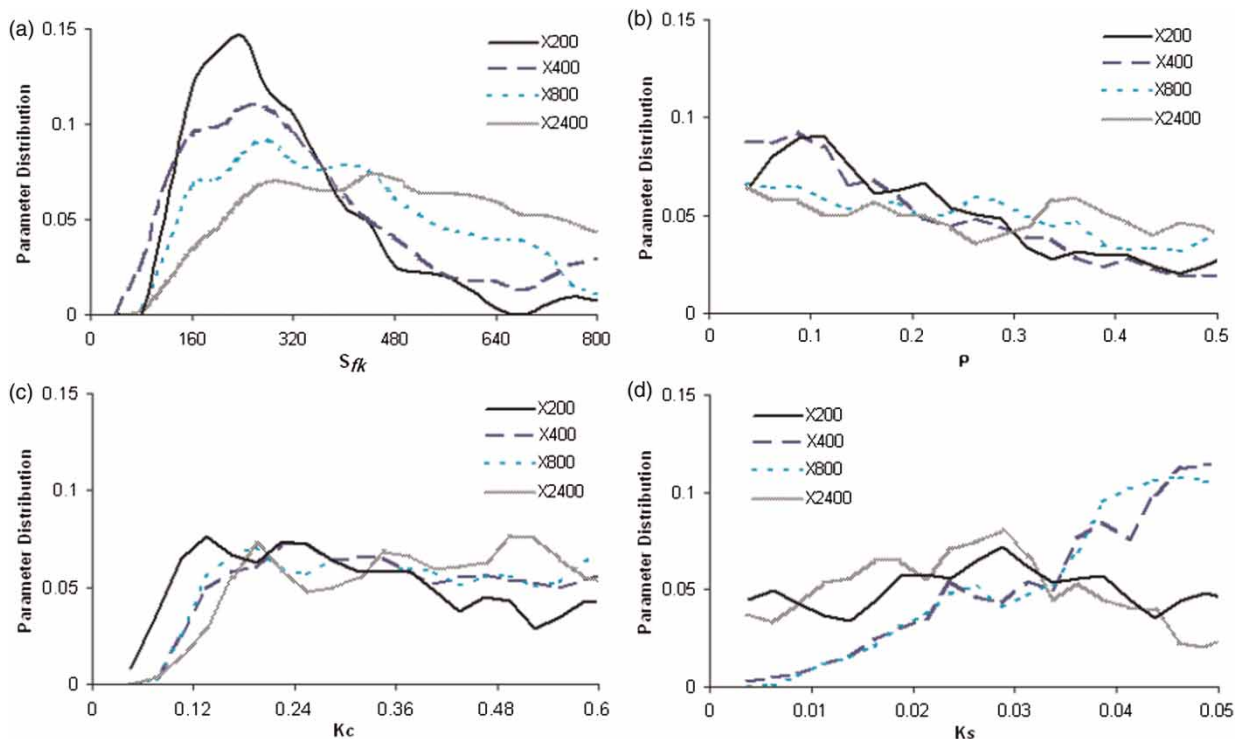


Figure 7 | Variations of probability distributions with different spatial resolutions for the effective parameters in XitaoXi catchment.

show less resolution dependency compared to those of the same parameter in Kielstau. This is consistent with the observations in the Kielstau area that high groundwater activities can affect the sensitivity of soil groundwater parameter ρ . The distribution patterns of the parameters K_c and K_s are unstable and their curves (e.g. the X400 X800 curves of parameter K_s) deviate much further away from that of model X200. The distinct differences among the distribution patterns obtained from various resolution levels show the parameters of XitaoXi are not so well identifiable as those of Kielstau, and exhibit more resolution dependency or sensitivity for the effective parameter in XitaoXi models.

Discharge simulation results and derived resolution uncertainty

The initial input data and the generated experimental data with five coarser resolutions are integrated into the KIDS model to simulate discharge in both study basins. The model yields different simulation results as the input data resolution changes. Overlapping the hydrographs obtained from different resolutions of input data produces a simulation band, which indicates the derived resolution uncertainty. Figure 8 (Kielstau catchment) and Figure 9 (XitaoXi

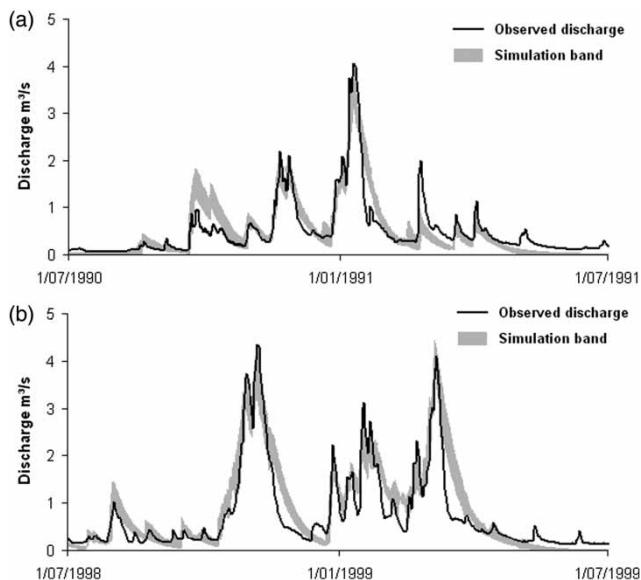


Figure 8 | Simulation bands showing the uncertainty intervals for the Kielstau basin using different resolution data with 50, 100, 200, 400, 600 and 1,000 m grid size in periods of (a) calibration, with R factor = 0.45 and P factor = 56.7%; (b) validation, with R factor = 0.41 and P factor = 53.9%.

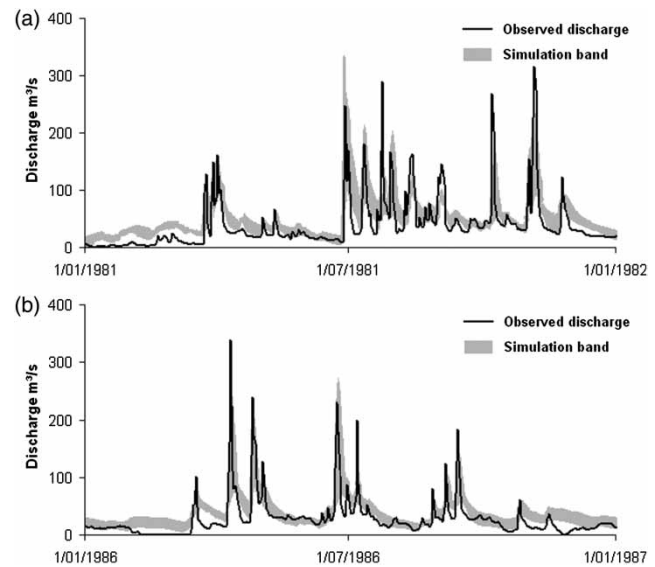


Figure 9 | Simulation bands showing the uncertainty intervals for the XitaoXi basin using different resolution data with 200, 400, 800, 1,600, 2,400 and 4,000 m grid size in periods of (a) calibration, with R factor = 0.50 and P factor = 53.4%; (b) validation, with R factor = 0.55 and P factor = 54.8%.

watershed) present time-series plots of observed streamflow data versus a simulated hydrograph band in the calibration and validation periods for a representative portion of the historical record. Figures 8 and 9 show that, in general, models can reproduce acceptable simulation bands centred on the observations with data at various resolution levels. In broad terms, the peak flows are better simulated, while the low flows are mostly underestimated for Kielstau and overestimated for XitaoXi. The quantitative measures of the R factor and P factor are also calculated for both basins. The R factor indexes, which depict the average width of the simulated hydrograph bands along the observations, are 0.45 (calibration) and 0.41 (validation) for Kielstau, 0.50 (calibration) and 0.55 (validation) for XitaoXi. This exhibits moderately better simulation performance in the small Kielstau catchment, resulting in less spread of the uncertainty bands due to resolution changes. The values of P factor, the percentage of observations falling inside the uncertainty bands, are statistically meaningful (larger than 50%) and exhibit appropriate coverage.

The simulated runoff at different resolution levels is further demonstrated in Figure 10, where the discharges simulated by various resolution input data are compared with the discharge simulation by the finest resolution data

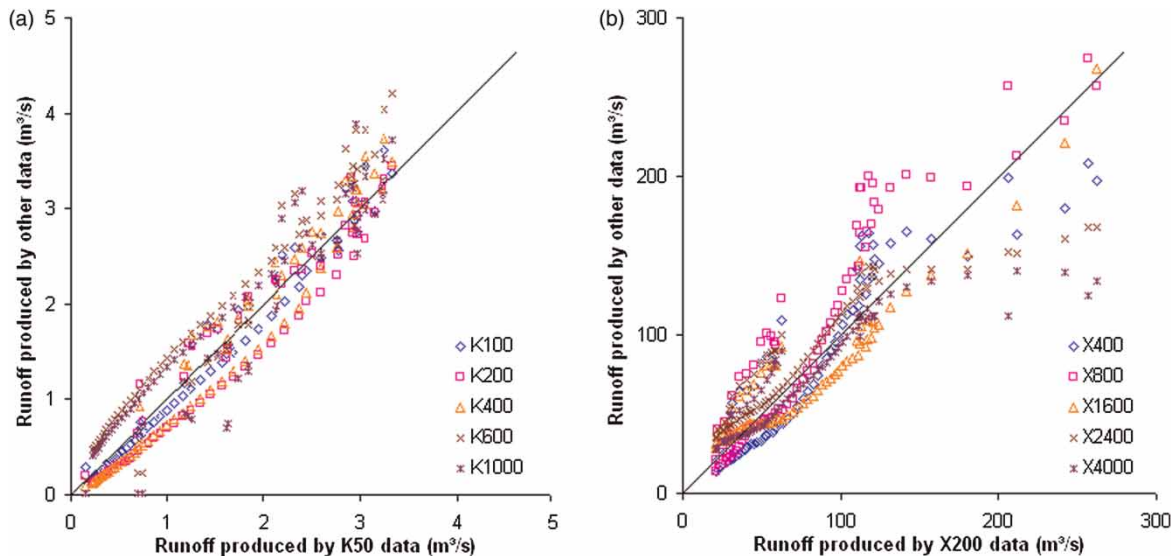


Figure 10 | Deviation of simulated discharge due to change in resolutions of input data at (a) Kielstau (51.5 km²) for the period of 10/10/98–20/12/98, (b) XitaoXi (2,271 km²) for the period of 10/06/86–20/08/86.

(K50 for Kielstau and X200 for XitaoXi) in a selected period representing the runoff simulations. From the deviated runoff simulations by other data we can see that using coarse resolution input data could give very different runoff to that obtained using fine resolution input data. It is especially obvious for large catchments, owing to the massive information loss caused by grid cell aggregation. The hydrograph peaks are particularly affected as shown in the plots of the XitaoXi catchment. Therefore resolution issues need careful consideration in discharge simulations.

Comparison of modelling efficiency in terms of IC-ratio

To compare modelling components or simulation results in different catchments is not an easy task (Beven 2002). It is difficult to find suitable indices for testing against forcing data resolutions and scale issues. The IC-ratio is proved to be a useful index for investigating the effects of input data resolution on discharge (Shrestha *et al.* 2006). All the tested spatial resolution levels for both basins in this study are expressed as the decimal IC-ratio ($0 < \text{IC-ratio} \leq 1$), where a lower value corresponds to a finer resolution of input for a given catchment. Concise information on the changes in the model performance in response to the altered resolution of forcing data using the IC-ratio index

is represented in Figure 11. The IC-ratio facilitates the comparison of responses at various scales of catchment size. Along with the model performances in NS values, the modelling time for each simulation at various resolution levels is also plotted on Figure 11. Since the modelling cost is likely to increase dramatically with an increase in resolution, the model running time is presented here to give an idea of the probably changed cost. Although the comprehensive cost is hard to be quantified, the optimum performance range can be appreciated from the curves in Figure 11, bearing in mind that there are huge data handling requirements and considerable model set-up costs involved when selecting a higher resolution.

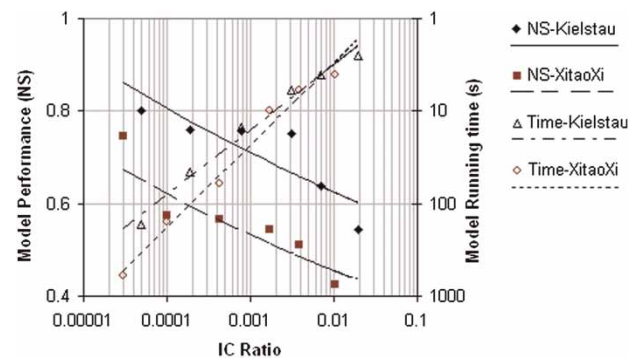


Figure 11 | Model performance versus simulation time at different scales expressed in IC-ratio for the Kielstau and XitaoXi catchments.

From Figure 11, model performance for Kielstau is found to be consistently good when the IC-ratio is lower than 0.001. That is noted to be the resolution range that can provide a satisfactory simulation result when considering the crossed cost curve. Comparatively, the simulation results for XitaoXi deteriorate significantly as the input resolution starts to become coarser. It suggests that coarser resolution hydro-meteorological datasets do not satisfy the need of runoff simulation in the XitaoXi basin. It is better to keep the current resolution level or even to try finer data. However, the cost may increase geometrically for that case, as the steepness of the time–cost curve is higher than that of the Kielstau catchment. The distinction in the result of both basins indicates that smaller, more homogenous-distributed catchment may be modelled successfully at a coarser scale but larger heterogeneous fields such as the XitaoXi basin need finer input data. This, in general, raised the point that it is preferred to investigate both the most appropriate data resolution and model representations that fit best the natural scales of hydrological significance (Shrestha *et al.* 2006). Based on the previous study on model structures (Zhang *et al.* 2011), we have applied different models to the Kielstau and XitaoXi basins which are considered to match the hydrological patterns, e.g. basin size, climate, underlying physiography, topography, land cover, drainage, etc. The results obtained in this study indicate that the best-fit input data resolution is not necessarily finer-resolution data but detailed enough to represent the river basin information in every model simulation. With respect to a further increase in resolution, it can be impractical in the case of the small homogenous Kielstau area, but beneficial for the heterogeneous XitaoXi basin.

In our effort to establish a data resolution criterion in different catchments with the proposed IC-ratio, it might be noted that the IC-ratio only accounts for the overall basin size but not any other basin features such as topography, shape or physiography. The two basins in this case have similarly elongated shapes which provide a good comparison base. For other basins it may provide an additional mode of complexity to the calculations and analysis when using IC-ratio, as it would only imply an approximation of the data requirements considering the catchment area.

CONCLUSION

Effects of spatial input data resolutions on daily discharge simulations using the KIDS models in PCRaster are investigated for the small (51.5 km²) lowland Kielstau catchment and the medium sized (2,271 km²) mountainous XitaoXi basin. The initial resolution data (50 × 50 m² for Kielstau, 200 × 200 m² for XitaoXi) are used as the base-line data (1×) and to prepare the experimental input data at various resolutions of 2×, 4×, 8×, 12× and 20×. Then, a MR, MC and MS methodology is employed to facilitate the grid-scale issues investigation. The following conclusions can be drawn from this study:

1. Models with the base-line resolution data can provide satisfying simulation results – 0.8 NS value for 50 m Kielstau model (K50) and 0.75 for 200 m XitaoXi model (X200). The MR and MC tests reveal that parameters calibrated at the finest resolutions cannot be directly applied to coarser resolutions. This is consistent with the statements in Beven (2001), Liang *et al.* (2004), and Bormann *et al.* (2009), that recalibration should be necessary when the input data resolution is altered. The importance of an appropriate calibration process is more distinctive for the larger XitaoXi basin, because of the higher parameter sensitivity and the greater information losses as the aggregation of input data. Therefore, a recalibration is generally required when the grid resolution is changed.
2. Six parameters for each catchment are calibrated to obtain a potentially optimal model performance at each spatial resolution. The analysis of resolution effect on parameter behaviour shows that most of the parameters inspected are scale dependent. The distribution function curves of these effective parameters are generally well-defined single modes with easily identifiable peak values for finer resolution data (e.g. K50 and X200 models). As grid size increases, the parameter distribution curve becomes smoother and more multi-mode style. The results obtained are more or less consistent in the findings for both Kielstau and XitaoXi. However, the larger deviations in parameter distribution patterns in XitaoXi models represent higher parameter sensitivity to grid resolution, which demonstrate more resolution dependency for the effective parameters.

3. The overlapping hydrographs generated with different resolutions of input data indicate the resolution uncertainty derived in the current study range. The grid cell size selection will generally lead to predictive uncertainty. The results of two quantitative measures (with R factor <1 and P factor $>50\%$) illustrate that representative uncertainty intervals can be obtained with a sufficient coverage of the observations for both basins. However, modelling with coarser resolution input data could produce different simulation results. This impact is particularly significant for the peak-flow simulations in the larger XitaoXi catchment. It indicates the importance of resolution selection and quality of input data at the scale of hydrological significance while taking both the basin geography and model framework into account.
4. There is a choice to make regarding the required resolution of hydro-meteorological input data. The challenge is to determine a scale, above which sufficient information for accurate modelling of basin runoff can be provided, and at the same time with acceptable modelling cost. We proposed here a possible solution with a sound basis of the IC-ratio, for investigating suitable resolution in different catchments. Our results suggest that coarser resolutions with an IC-ratio <0.001 may be used as an effective alternative for conducting preliminary analyses in discharge simulation for the Kielstau basin. In contrast, it is recommended to use the current fine resolution data at the XitaoXi catchment in order to achieve sufficient accuracy of model outputs, or even finer data to improve the situation.
5. The analysis of scaling effects in this study evaluated whether data aggregation is a useful regionalization tool or whether it leads to an unacceptable loss of information. The results of this study indicate that the aggregation procedure of input data cause changes in the simulation results for both study basins but at different extent. For the small lowland Kielstau catchment the grid aggregation up to 800 m grid size ($8\times$ basic above) has a slight information loss that leads to affected simulation results, while applying 400 m grid size ($2\times$ basic above) or more for the mesoscale XitaoXi basin causes a significant decrease in modelling efficiency. In this case, when the accuracy of the Kielstau model using coarser data, e.g. K200, is sufficient for applied

uses, the time and effort of pursuing finer data are saved as a benefit of this approach. Meanwhile in the opposite way, if the XitaoXi model with finer data, such as X50, would provide significantly better results than the X200 simulation, the costs of obtaining input data and spending additional computation time at that scale should be weighed against the benefit of a more accurate result. In this context, the aggregation approach in some watersheds (such as the Kielstau catchment) is adequate to capture the essential basin variability, but for the XitaoXi catchment, the scale of hydrological significance is of critical importance to improve model efficiency. The test of different grid sizes in hydrological modelling could be a meaningful tool for practical model applications, especially in data scarce regions.

Finally, we should caution that some of the results obtained in this study, in particular those concerning the comparison of resolution issues between the two study sites, might be model structure, spatial data resolution, model performance criteria and catchment specific, and the uncertainties associated with model structures are not explicitly considered. Therefore, it is critically required to test the validity of the results obtained here with other models or in other watersheds in the future.

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