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Distributed hydrological modeling in a large-scale watershed of Northern China: multi-site model calibration, validation, and sensitivity analysis

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Abstract

Model calibration is a complex task for large watersheds, especially for those in a heterogeneous mountain environment where multi-objective calibration strategy is essential. That may improve a model's capability to capture the spatial variations of the internal hydrologic variables. This study used the physically-based distributed hydrologic model, MIKESHE, to contrast a lumped calibration protocol that uses data measured at one single outlet to a multi-site calibration method which employed streamflow measurements at three separate stations within the large Chaohe River basin in Northern China. The results showed that, the single-site calibrated model was able to sufficiently simulate the hydrographs for two of the three stations (Nash-sutchliffe coefficient of 0.65–0.75, and correlation coefficient 0.81–0.87 during the testing period), but model performance was poor at the third station (EF only 0.44). By using the multi-site measurements model calibration reached a compromise between the different stations, the model reasonably representing the hydrographs of all three stations with EF ranging from 0.59–0.72. The modeling calibration results suggested that the dominant hydrological processes varied across the large watershed with upstream area dominated by slow groundwater and middle- and down-stream areas dominated by relatively quick interflow. We conclude that to account for the different hydrological process of watershed with large heterogeneity, it is necessary to employ a multi-site calibration protocol to reduce prediction errors.

1 Introduction

Spatial variability of land surface characteristics is widely recognized for understanding the physical/hydrological, biological, and other related process in watershesds (Becker, 1999). It is critical to take into account the spatial variability for modeling watershed hydrology and for understanding watershed hydrological processes (Beven, 2001; Blöschl et al., 1995; Merz and Bárdossy, 1998; Anquetin et al., 2010). This is particular true for the application of large-scale watershed due to more diverse hydrological conditions (Sivapalan, 2003) and for the application of the mountainous watershed where it usually exhibits great heterogeneity in geology, topograph, soil, vegetation, and climate (e.g. Weingartner et al., 2003; Gurtz et al., 1999; Smerdon et al., 2009).

Compared with lumped hydrological model, distributed hydrological model provides a comprehensive approach for characterizing spatial variability of watershed, and is able to simulate spatial distribution of water-related variables. Though numerous hydrological models have been developed in either distributed or lumped framework to simulate watershed hydrology, lumped hydrological models are usually precluded in the case of the applications of ungauged watershed as a result of the significant changes between watershed conditions (Knudsen et al., 1986; Sahoo et al., 2006), whilst distributed hydrological models specify data and parameters for a network of grid of points, enableing the spatial variability of watershed well characterized (Refsgaard, 1997). Nevertheless, to obtain an internal consistency of results, it is also required to carry out a careful model calibration for distributed hydrological model. A few of researches revealed that hydrological model which was calibrated only against the discharge measurements of watershed outlet did not perform well for the internal variables simulation (such as the discharge, unsaturated water content, and water table of the other sites) (e.g. Ambroise et al., 1995; Refsgaard, 1997). This calls for a rigorous calibration and validation procedure for distributed hydrological models (Freer et al., 2003; Moussa et al., 2007).

Researchers have long recognized the needs of multi-objective framework (multi-site, multi-variables, as well as multi-criteria) in distributed hydrological modeling (e.g. Ambroise et al., 1995; Andersen et al., 2001; Khu et al., 2008; Dai et al., 2010). Bergström et al. (2002) suggested that the model calibrated against more measured variable rather than runoff only can greatly increase confidence in the physical relevance of the model. Vázquez et al. (2008) adopted a multi-criteria protocol which included different statistical, analytical and visual criteria to calibrate the model. They also suggested that multi-criteria calibration protocol enhanced the physical consistency

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of model prediction. Several researches have specifically summarized the merits of multi-objective framework (Madsen, 2003). Generally, in addition to reduce the uncertainty and modeling bias (Kuczera et al., 1998; Dai et al., 2010), it was believed that multi-objective strategy better constrain calibration process, and is able to unlock the equifinality of distributed hydrological models to a certain degree (e.g. Mroczowski et al., 1997; Seibert et al., 2000; Andersen et al., 2001; Bergström et al., 2002; Khu et al., 2008; Dai et al., 2010). Khu et al.(2008) have also stressed the benefits of multi-objective strategy to decision support framework.

Numerous watershed hydrologic models exist in the literature, such as the SWAT model (Cao et al., 2006; Zhang et al., 2009; White and Chaubey, 2005), HBV model, ModSpa model (Moussa et al., 2007), Wetspa model (Shafii and Smedt, 2009) and the GWLF model (Li et al., 2010). MIKESHE, as the first generation of distributed hydrological model, has shown its great appeals for a wide range of hydrologic applications (Graham and Butts, 2005; Lu et al., 2006; Zhang et al., 2008; Dai et al., 2010; Wijesekara et al., 2012). With an increasing application of MIKESHE in the watersheds around of the world, it was increasingly required to test the model's simulation capability with a strict model calibration and validation procedure. In order to reduce the redundant information between the related multi-site measurements, Khu et al. (2008) classified the multi-site groundwater measurement before applying the MIKESHE to the Danish Karup catchment. Anderson et al. (2001) employed MIKESHE to simulate watershed hydrology as well. Although nested multi-site measurements were employed in that research, the model well simulated the distributed results. Feyen et al. (2000) introduced multi-site measurements in MIKESHE model evaluation, too, however, the multi-site measurement were only used for model validation rather than calibration.

This study tested the MIKESHE model in the large scale watershed of Northern China, Chaohe watershed by using multi-site calibration protocol. The watershed is of mountainous topography with the elevation ranging 159 to 2218 m, being one of headwater areas of Miyun Reservoir that supplies near half of drinking water for Beijing of China (Jia and Cheng, 2002; Yang et al., 2007). It is said that 60 percent of reception water of Miyun Reservoir was originated from the Chaohe Watershed (Sun et al., 2008). Due to the increased population and climate change, the reception water of Miyun Reservoir has decreased greatly over the past decades (e.g. Li and Li, 2008; Sun et al., 2008; Ma et al., 2010), which is especially true since 1999, as successive dry years has caused the average annual reception water only $2.51 \times 10^8\,m^3$ (Li and Li, 2008). There is an urgent need to understand the hydrologic processes and take an adaptive watershed management to cope with the emerging water resource issues in the watershed. Considering the complex characteristics of the large mountainous watershed with high heterogeneity with respect to soil, vegetation, and climate (Sivapalan, 2003), the MIKESHE model was chosen for this study. The objectives of this study are to (i) assesse the applicability of MIKESHE model in the large-scale watershed of Northern Chian; (ii) understand the spatial controls on watershed hydrology of Chaohe watershed; and (iii) examine the benefits of multi-site calibration protocol for modeling analysis.

2 Methods

2.1 Watershed characteristics

The Chaohe watershed has an areas of around 4854 km^2 with elevation ranging from 159 m to 2218 m a.s.l. (Fig. 1) with 80 % classified as mountainous topography. Two large mountain ranges, Yanshan Mountain and Yinshan Mountain intersect with the watershed. The substrate of the watershed is made of granite, gneiss, and lime rock, which is mainly overlain by brown soil with varied depth. The upstream area of the watershed is adjacent to the Inner-Mongolia Plateau, therefore, the upstream of the watershed is characterized by deep soil, whereas the middle- and down-stream area is by thin soil. Due to severe weathering process, the soil across the watershed is represented with a high degree of gravel content. Temperate continental monsoon climate dominates the watershed. The average annual precipitation is around 494 mm, 80 %

of precipitation falling from June to September. The watershed is well covered by vegetation, with vegetation coverage as high as 80 %. Land use is mainly dominated by grassland, shrubland and forestland that mainly consists of mixed broadleaf-conifer forest. In addition, cropland, residential area, and bare area account for a certain percent of the watershed.

We have acquired daily rainfall records from seven rain gauges (Fig. 1) and daily streamflow records from three hydrological stations of the watershed, i.e. the outlet station (Xiahui) and the other two internal hydrological stations (i.e. Daiying and Dage) (Fig. 1). Meteorological data is not registered in the watershed, therefore, data recordes of national meteorological base-stations around the watershed were introduced, which was further used for estimating potential evapotranspiration according to Penman-Monteith equation (Allen et al., 1998), and arithmetic average statistic of the estimations was used for modeling analysis. DEM of the watershed (resolution of 30 m) was acquired from International Scientific & Technical Data Mirror Site, Computer Network Information Center, Chinese Academy of Sciences (http://datamirror.csdb.cn). And land use of 1999 were interpreted according to remote sensing TM images, which was used to represent surface condition of the watershed for the study period. In addition, soil dataset of the watershed was derived from HWSD (The Harmonized World Soil Database). According to FAO-90 classification system, 10 soil units were found in the watershed, Calcaric cambisols, Haplic Luvisols and Calcic Luvisols accounting for much of the watershed.

2.2 Model construction and parameterization

We have used MIKESHE to simulate hydrology of the Chaohe watershed. MIKESHE is a fully distributed physically-based hydrological model. It covers the major processes of the hydrologic cycle and includes process models for evapotranspiration, overland flow, unsaturated flow, groundwater flow, and channel flow and their interactions. Detailed model description can refere to the literatures (e.g. Refsgaard and Storm, 1995;

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Graham and Butts, 2005). We have applied MIKESHE in arid regions in Northern China (Zhang et al., 2008).

MIKESHE uses a network of regular grids to discretize the horizontal plane of watershed. Choice of grid size depends on several factors, such as the degree of heterogeneity of the hydrological parameters and the boundary conditions, and the extent of the flow domain defined by computational limitations (Feyen et al., 2000). Considering the large scale modeling domain of Chaohe watershed, grid size of 2 km × 2 km was used in the analysis, which was comparable to the grid size of the researches of Andersen et al. (2001) and Khu et al. (2008). Our preliminary analysis suggested that the application of the grid size of 2 km × 2 km is able to greatly enhance the computing speed, whilst retaining the capability of representing the long-term streamflow variation of the watershed. According to field investigation and experience, we have specified seasonal dynamic of vegetation properties (LAI and root depth) for each land use, however, vegetation growth over years was ignored in the model construction. Overland flow is calculated by solving the diffusive wave approximations of the Saint-Venant equations. Parameters of Manning's number (M) and detention storage (D) were all subject to model calibration, and both were specified with uniform spatial distributions. Unsaturated flow was simulated with simplified gravity-flow procedure, which has been approved greatly reducing the computing time, while preserving the modeling accuracy to a certain degree. Given that most area of the watershed was of mountainous topograph with shallow soil profile, groundwater table for lower boundary of the unsaturated zone (Bnd_UZ) was specified with a uniform depth of 1.5 m. Parameters of saturated hydraulic conductivity in unsaturated zone (K_s) and bypass fraction (B_p) in three dominant profiles were subject to model calibration, whilst parameters of the other profiles were unchanged in calibration process. In order to keep the number of free calibrated parameter as small as possible, a dependent relationship was further specified between the K_s of the three dominant profiles. As a result, only parameters of one profile have freedom in calibration process, whereas parameters of the other two were assigned with a specific relationship. Due to the lack of data on geo-hydrological

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information of the watershed, saturated flow of the watershed was simulated by using simple linear reservoir method which accounts for the interflow, the baseflow and the percolation from interflow reservoir. Parameters of specific yield (S_p) and time constant (T) in both interflow and baseflow reservoirs were all subject to model calibration. Except to the initial values of K_s which was specified according to the estimation of Pedotransfer function by using soil physical properties, the other parameters were initialized according to literature or experience.

2.3 Model calibration, validation, and sensitivity analysis

Parameter adjustments made during the calibration process were carried out manually by trial and error method. Two kinds of calibration protocol were taken in the analysis (i.e. the single-site calibration and multi-site calibration). In the first protocol, the model was calibrated against the discharge measurement of watershed outlet (i.e. Xiahui station). Streamflow data for 1991–1995 and 1996–1999 were used for the model calibration and validation, respectively. Both time periods experienced wet, dry and normal climate, representing a wide range of hydrologic conditions. In order to test the capability of the model in simulating the behaviors of internal hydrologic variables (e.g. Refsgaard, 1997; Feyen et al., 2000), multi-site validation test was introduced as well, in which the previously calibrated model was tested against the discharge measurements of Daiying and Dage stations for 1991 to 1999 for model validation.

In the second protocol, the model was calibrated against multi-site discharge measurements simultaneously (i.e. Xiahui, Daiying, and Dage). Though few of authors argued that multi-site model calibration should employ independent multi-site measurements (Migliaccio and Chaubey, 2007), the fact is that independent multi-site measurements are rarely available for model testing, which causes that, in most of case, it remains a common practice of using nested multi-site measurements (e.g. Andersen et al., 2001; Moussa et al., 2007). In our modeling analysis, on the basis of the calibrated model of the first protocol, parameters sets were further adjusted against the other two site discharge measurements simultaneously (i.e. Daiying, and Dage) for the period of 1991 to 1995 for model calibration. The aim of the process is looking for an optimal parameter set which is able to yield satisfied modeling results for all hydrological stations. As such, the model was run for the period of 1996 to 1999 for model validation. Both single-site model calibration and multi-site model calibration was initialized by running the model for 1990 for warming up exercise.

In order to detect the differences of hydrological processes due to the watershed spatial variability, sensitivity analysis was carried out by manually altering parameter values in the parameter range which was specified by referring to the literatures and our previous modeling experience. The contribution of each parameter to affecting hydrological process was evaluated according to its influence on model performance.

2.4 Model performance criteria

Three numerical measures were employed for evaluating the goodness of model performance. In addition to root mean square error (RMSE) (1), correlation coefficient (R) (2) and Nash-sutchliffe coefficient (EF) (3) (Nash and Sutchliffe, 1970) were employed as well. Correlation coefficient indicates the strength of a linear relationship between observed and calculated discharge, whilst Nash-sutchliffe coefficient measures the ability of the model to simulate variation of the hydrographs for a particular river gauge station. Optimal values for RMSE, R and EF are 0,1 and 1, respectively. According to the previous studies (e.g. Henriksen et al., 2003; Moussa et al., 2007), four performance levels were defined with respect to both EF and R (see Table 1). As for RMSE, it was exclusive in the definintion of the performance level, as we believed that the RMSE between different stations are incommensurable due to their different contributing area, and it does not make sense to evaluate RMSE for different stations by using a uniform criteria.

$$\text{RMSE} = \frac{1}{n}\sqrt{\sum_{i}^{n}\left((Q_{\text{s},i} - Q_{\text{o},i})^2\right)} \quad (1)$$

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$$R = \sqrt{\frac{\sum_i (Q_{s,i} - \overline{Q_o})^2}{\sum_i (Q_{o,i} - \overline{Q_o})^2}} \quad (2)$$

$$\mathrm{EF} = 1 - \frac{\sum_i (Q_{s,i} - Q_{o,i})^2}{\sum_i (Q_{o,i} - \overline{Q_o})^2} \quad (3)$$

In which, $Q_{s,i}$ and $Q_{o,i}$ represents the simulated and observed daily discharge for day i ($m^3 s^{-1}$), respectively; $\overline{Q_o}$ is the mean of the observed discharge in test period ($m^3 s^{-1}$).

3 Results and discussions

3.1 Single-site model calibration and validation

Comparison of discharge simulation by single-site calibration protocol with the measurement of Xiahui Station was displayed in Fig. 2a. Table 2 has shown the performance measures of the simulation. The RMSE of Xiahui station was 18.1 during the calibration period, whilst it was improved during validation period with the RMSE of 12.3. The simulated daily streamflow showed a more flashy response than that of the measurements, especially during the year of 1999, and the recession limbs of the hydrographs were generally underestimated by the model (Fig. 2a). However, the model generally represented the dynamic variation of the streamflow with acceptable the EF (0.72 and 0.75), and the R (0.85 and 0.87) for the calibration and validation period, respectively. According to the performance criteria (Table 1), both EF and R indicated that the model generally performed well in simulating hydrograph of Xiahui station.

The well model performance for the Xiahui station was mainly attributed to the satisfied modeling results with respect to the high flow and median flow simulations. This

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could be explained by the facts that EF statistic takes more weights for peak flow simulation (Henriksen et al., 2003) and it is easier to gain an acceptable simulation result when the model was run for large stormflow events, whilst the model run for the dry period with low flow is likely to be affected by various source of errors. Examining the scatter plot of model simulation against the measurement, it was found that, the model generally underestimated the streamflow of flow regime ranging 1 to 10 $m^3 s^{-1}$ around, whilst over-predicted when the flow regime was lower than 1 $m^3 s^{-1}$ around. The systemic underestimations of low flow suggested that there existed errors on ground water simulation. Refsgaard (1997) also reported underestimation of baseflow and the authors attributed the poor model performance to the biased simulation of internal groundwater divide. More detailed analysis on modeling errors would be given in the section of errors analysis.

Multi-site model validation results were presented in Fig. 2b, c. Similar to the results for the Xiahui Station, model performance for the Daiying and Dage stations was much better during the validation period than that of the calibration period (Table 2). Though flashed response appeared in the hydrograph simulation of the Daiying and Dage stations, too, the model showed somewhat difference between the Dage and the other two stations with respect to low flow simulation. Specifically, the underestimation of the Dage station was more obvious (Fig. 2c) than that of the Daiying and the Xiahui stations (Fig. 2a, b). The RMSE of the Dage station (being 4.08 and 3.76) was smaller than that of Xiahui and Daiying stations, however, it did not imply a satisfied modeling result, as the smaller value of RMSE of the Dage station was mainly attributed to its smaller drainage area compared to that of both Xiahui station and Daiying station. On the contrary, it was suggested that the model behaved poorly for the Dage station than it did for the Xiahui and Daying stations, the EF of the Dage station being 0.44 and 0.52 only for the calibration and validation period, respectively (see Table 2). The model performance of the Daiying station was quite similar to that of Xiahui station, R being 0.81 and 0.86, and EF being 0.65 and 0.73 for the calibration and validation period, respectively (Table 2).

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The similar model behavior between the Daiying and the Xiahui stations was largely due to similarity of drainage area. Whilst the different model behavior between the Dage and the other two stations was explained in part by the high spatial variability of Chaohe watershed, especially with regard to the variability of the unsaturated zone and saturated zone properties, which also was an indication that the up-stream and the down-streams areas of the watershed differed in the hydrological processes. Though a spatially distributed soil profile has been accounted for in model construction, a uniform parameter value was specified for the saturated zone. This might not be realistic and be inconsistent with the characteristics of the watershed. Since the northern of the Chaohe watershed is adjacent to the Inner Mongolia Plateau, the northern part of the watershed is commonly characterized by high soil water storage capacity due to the deep soil profiles, which caused much of water stored in the unsaturated zone available for recharging the groundwater and discharge the river flow subsequently. However, in the middle and downstream area of the watershed, the thin soil profiles resulted in small soil water storage in the unsaturated zone and less recharge to the saturated zone, and consequently flashy streamflow accordingly. The different hydrological process also could be identified according to the sensitivity of the model to the parameters. Detailed analysis on the discrepancy of dominant hydrological process is given in the section of sensitivity analysis.

3.2 Multi-site model calibration and validation

The unsatisfied modeling results for the Dage station in the single-site protocol called for a multi-site calibration protocol (Fig. 3). By increasing the value of K_s only from 2e-006 to 4e-006 which was supposed to be able to increase the soil water storage capacity of upstream area of the watershed, the hydrograph simulation of the multi-site calibration protocol displayed less flash response than that of the single-site calibration protocol. However, low flow remained underestimated for the three stations (Fig. 3). The model performance of the multi-site calibration protocol was similar to that of the single-site protocol in terms of R. However, the performance in terms of EF was improved

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greatly for the Dage station during the calibration period, whilst it was decreased for the Xiahui and Daiying stations, the EF during the calibration period for the three stations being 0.59, 0.69 and 0.61, respectively (see Table 2). The improvement of EF for the Dage station was mainly because that the pseudo flashed response was improved and that the hydrograph simulation was improved greatly during the wet periods of high flow conditions (see Figs. 3c and 4). The poor model behavior for the Dage station with respect to low flow simulation indicated that, in addition to the errors on K_s, there were the other sources of errors on representing watershed variability. The degraded model performance for the Xiahui and Daiying stations was because that a pseudo high water storage capacity was specified for the downstream area of the watershed, which was inconsistent with the lower soil water storage capacity of this area in reality as a result of the thin soil profiles.

3.3 Sensitivity analysis

Sensitivity analysis revealed the differences of the dominant hydrological processes across the watershed. Generally, the model was insensitive to the parameters of ET and overland flow, but was sensitive to the parameters of unsaturated zone and saturated zone modules (Table 3). This indicated that process of ET and overland flow were less important in affecting streamflow generation of the watershed, whilst unsaturated flow and saturated flow played an important role. Nevertheless, the weight of the role that the sensitive parameters played in affecting hydrological process varied between the different stations.

Examining the relationship between the parameters and the model performance in terms of EF, it was found that, with the T_interflow increased from 0 to 5 which means an increase of time for water flowing through the interflow reservoir to the next, the model was improved greatly for the Dage station, the relative change in EF as high as 25 %, whereas it got worsen, even, for the Xiahui and Daiying stations (Fig. 5a), the relative change in EF being 11 % around. As such, the increase of time for water seeping down into the baseflow reservoir (i.e. the increase in the T_percolation) induced

EF decreased by 13 % for Dage station, whilst EF increased by 5 % for Xiahui and Daiying stations only (Fig. 5B). The variation of EF for the Dage station in response to T_interflow and/or T_percolation suggested that prolonging the process of water replenishing the streamflow and/or reducing the time of water recharging baseflow reservoir was able to improve greatly the model performance of the Dage station, which was also an indication that streamflow of Dage may be mainly replenished by relative slow groundwater; whereas as both Xiahui and Daiying stations displayed less sensitivity to the T_interflow and T_percolation, we assumed that streamflow of the Xiahui and Daiying station was mainly replenished by the relative quick interflow.

Sensitivity of the other parameter indicated the differences of the dominant hydrological process between the stations as well. When reducing the volume of water released by aquifer (i.e. altering the Sp_baseflow from 0.62 to 0.1), the model performance degraded greatly for Dage Station with EF decreased by 11 %, whilst EF was almost invariant for the Xiahui and Daiying stations (Table 3). This indicated that streamflow generation of the Dage station was actually more affected by groundwater compared to that of Xiahui and Daiying stations. The decrease in time for water flowing through the baseflow reservoir (i.e. change in T_baseflow from 72.21 to 20) caused the EF of Dage station decreased by 7 %, whereas it seem has no influence for the Xiahui and Daiying stations (see Table 3). Both sensitive model behavior in response to Sp_baseflow and T_baseflow for the Dage station confirmed that groundwater has actually exerted more influence on hydrological process of the Dage station, whereas it was less influential for that of Xiahui and Daiying stations.

We found that soil parameters of the unsaturated zone were all influential. As specification of UZ zone defined the soil water storage capacity, which directly affected the water available for recharging groundwater and replenishing the river flow. The influence of the unsaturated zone was usually as significant as that of the saturated zone. The change in saturated soil water conductivity (K_s) from 4e-007 to 1e-008 m s^{-1} caused the EF of the Dage station sharply decreased, with the EF value being −1.1 only, whilst it remained as high as 0.5 for the Xiahui and Daiying stations. Again, the

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change in lower boundary of UZ (Bnd_UZ) from 1.5 to 0.5 induced the EF of Dage station changed from 0.59 to −3.23, whilst the EF for Xiahui and Daiying still as high as 0.56. The distinct model behavior between the stations suggested that, compared to the Xiahui and Daiying stations, unsaturated water content seems more influential in affecting hydrological process of the Dage Station. This was in line with the assumption that a high water storage capacity existed in the upstream area of the watershed. It was acknowledged that an linear relationship between UZ parameter and the EF response was not derived in the analysis. We assumed that this may be explained by the impacts of parameter interaction.

Parameters of ET were generally less influential in affecting hydrograph simulation of the watershed. However, when contrasting the three stations, the Dage Station displays a certain degree of variation of EF in response to the ET parameters especially in terms of C1, C2, and Aroot. This was explained by the fact that runoff generation of deep soil profile was easily affected by the evapotranspiration process, and specification of ET parameters was vital important for ET estimation, ET partition, and runoff generation accordingly. For the Dage Station, due to the deep soil profile of the drainage area in reality, the modeling results of this station were, therefore, more sensitive to the altered calibrated ET parameters, presenting an obvious sensitivity to the changed ET parameters, whilst results of the other two stations were less sensitive due to the relative thin soil profiles in reality.

3.4 Potential source of errors

Modeling results were usually interfered by various sources of errors including (i) random and/or systematic errors in the input data; (ii) errors as a result of a non-optimal parameters set; (iii) mathematical errors in the model code; (iv) conceptual errors in the model; (v) numerical errors inherent in the solution algorithm; (vi) and interpretation errors of the predicted results (Feyen et al., 2000). Beven (2001) has also suggested that model uncertainties mainly resulted from the errors on model itself, errors on initial and boundary conditions, and errors on calibration data. In our modeling analysis,

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though calibration process was able to reduce the errors of non-optimal parameters set to a certain degree, two major source of errors remained existed in the modeling process, which included the errors on the specification of boundary conditions and the errors on model parameterization.

The errors on boundary conditions mainly referred to the incorrect representation of the groundwater divide. Owning to the lack of information on saturated zone, saturated flow of the watershed was simulated with the simplified linear reservoir method. However, the adoption of the method caused that the model was not able to represent the groundwater divide correctly, resulting in smaller drainage area and groundwater recharge. The incorrect representation of groundwater divide explained mostly the underestimation of the flow with the discharge of 1 to 10 $m^3 s^{-1}$ around.

The errors on model parameterization were mainly associated with the incorrect representation of the spatial variability of the hydro-geologic properties. As revealed by the sensitivity analysis, sensitivity of the model was different between the stations, which was an indication that it was necessary to apply spatially distributed parameters for accounting for the variability of the watershed. Though parameters of saturated zone were less influential in improving groundwater simulation of the Daiying and Xiahui stations, the linear relationship between the EF and the Sp_baseflow and *T*_baseflow for the Dage station (Table 3) implied that it was possible to further improve the model performance of the Dage station by adjusting the parameters of Sp_baseflow and/ or *T*_baseflow, which was an indication that the uniform parameter distributions especially with respect to Sp_baseflow and *T*_baseflow were inappropriate for accurately modeling the variation of the groundwater of the watershed. This also explained in part the reasons of the distinct underestimation of low flow simulation for the Dage station. Additionaly, the groundwater table for lower boundary of UZ (Bnd_UZ) which was critical important for determing the soil water storage capacity was specified with an uniform value as well. As the watershed was highly characterized by various depth of soil, the uniform specification of Bnd_UZ would naturaly lead to much of errors on representing soil water storage and affecting the interflow and groundwater simulation accordingly.

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Simulated flow for flow regime lower than 1 $m^3 s^{-1}$ generally show overestimations, suggesting model deficiency for simulating lowflows. Several authors suggested that over-predictions during dry period may be attributed to the artifact of MIKESHE that does not allow for a river/stream to dry out (Lu et al., 2006; Dai et al., 2010).

4 Conclusions

We have used physically-based distributed model, MIKESHE, to simulate the hydrology of a large-scale mountainous watershed of Northern China, Chaohe watershed. The single-site model calibration protocol well simulated the hydrograph of the downstream stations (Xiahui and Daiying) with the EF of 0.65–0.75 and the R of 0.81–0.87 for the testing period, however, it was failed to simulate that of the upstream station (Dage) as the model did not well represent soil water storage capacity of the upstream area of the watershed, EF only 0.44 for the calibration period. By using the multi-site model calibration protocol, the model behavior reached an compromise between the stations, the performance measures decreased a little for the Xiahui and Daiying station (EF being 0.61–0.72 and R 0.82–0.85 for the testing period, respectively), whilst it was improved greatly for the Dage station, the EF being 0.53–0.59 and R 0.77–0.80. We suggested that, due to the variation of unsaturated zone and saturated zone properties, especially with respect to that of K_s, Sp_baseflow and T_baseflow, the dominant hydrological process was varied across the different area of the watershed. Streamflow of the upstream area of the watershed was mainly replenished by slow groundwater, whilst it was mainly recharged by relative quick interflow for the middle- and down-stream areas of the watershed.

We concluded that, for large scale watersheds with high land surface heterogeneity, hydrological processes were complex as affected and/or controlled by the variability of soil, geology. To truly represent the spatial variation of watershed hydrology, it was necessary to employ multi-site measurements in model calibration. Multi-site model

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calibration protocol would greatly further reduce the modeling errors resulting from the inherent great spatial variability.

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Table 1. Performance criteria for model evaluation.

Performance indicator	Excellent	Good	Fair	Poor
EF	>0.85	0.65–0.85	0.5–0.65	<0.5
R	>0.95	0.85–0.95	0.85–0.75	<0.75

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Table 2. Modeling performance of MIKESHE in Chaohe watershed.

Station	Period	Single-site model calibration			Multi-site model calibration		
		RMSE	*R*	EF	RMSE	*R*	EF
Xiahui	1991–1995	18.06	0.85	0.72	19.07	0.85	0.69
	1996–1999	12.26	0.87	0.75	12.94	0.85	0.72
Daiying	1991–1995	17.48	0.81	0.65	18.35	0.82	0.61
	1996–1999	9.79	0.86	0.73	10.30	0.84	0.67
Dage	1991–1995	4.08	0.81	0.44	3.48	0.80	0.59
	1996–1999	3.76	0.80	0.52	3.78	0.77	0.53

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Table 3. The relative change in performance measures in response to the variation of each parameter of the Chaohe watershed.

Module	Parameter*	Unit	Xiahui			Daiying			Dage		
			RMSE	*R*	EF	RMSE	*R*	EF	RMSE	*R*	EF
SZ	Specific yield for interflow (Sp_interflow)										
	0.3	–	0.03	–0.01	–0.03	0.02	–0.01	–0.03	0.04	–0.03	–0.06
	0.2		0.02	–0.01	–0.02	0.01	–0.01	–0.02	0.02	–0.01	–0.03
	0.1		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	–0.01
	0.0874		**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	0.01		–0.01	0.00	0.01	–0.01	0.00	0.01	–0.01	0.01	0.02
	Time constant for interflow (*T*_interflow)										
	15	Day	0.05	–0.02	–0.05	0.03	–0.01	–0.04	0.02	–0.03	–0.02
	10		0.03	–0.01	–0.03	0.02	0.00	–0.03	0.01	–0.02	–0.01
	5.251		**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	1		–0.09	0.02	0.08	–0.05	0.01	0.07	0.06	0.03	–0.09
	0.1		–0.13	0.03	0.11	–0.08	0.01	0.09	0.16	0.04	–0.24
	Time constant for percolation (*T*_percolation)										
	15	Day	–0.07	0.02	0.06	–0.03	0.00	0.04	0.08	0.01	–0.12
	10		–0.06	0.02	0.05	–0.03	0.00	0.04	0.06	0.01	–0.08
	2.608		**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	1		0.04	–0.01	–0.04	0.02	0.00	–0.03	0.00	–0.01	0.00
	0.1		0.07	–0.02	–0.07	0.04	–0.01	–0.05	0.02	–0.03	–0.02
	Specific yield for baseflow (Sp_baseflow)										
	0.1	–	0.00	–0.01	0.00	0.00	–0.01	0.00	0.07	–0.01	–0.11
	0.2		0.00	0.00	0.00	0.00	–0.01	0.00	0.04	–0.01	–0.06
	0.4		0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	–0.02
	0.618		**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	0.8		0.00	0.00	–0.01	0.00	0.00	–0.01	–0.01	0.00	0.01
	Time constant for baseflow (*T*_baseflow)										
	20	Day	0.00	0.00	0.00	0.00	–0.01	0.00	0.05	–0.01	–0.07
	40		0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	–0.03
	60		0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	–0.01
	72.21		**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	80		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OL	Manning number (*M*)										
	10	$M^{1/3}s^{-1}$	0.00	0.01	0.00	0.02	–0.01	–0.02	0.01	0.00	–0.01
	25.5		**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	30		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	40		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	50		0.00	0.00	0.00	–0.01	0.00	0.01	0.00	0.00	0.00
	Detention storage (*D*)										
	2	mm	–0.02	–0.01	0.01	–0.02	0.00	0.03	0.01	0.01	–0.02
	4		–0.01	0.00	0.01	–0.01	0.00	0.01	0.00	0.00	0.00
	6		**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	8		0.01	0.00	–0.01	0.01	0.00	–0.02	0.00	–0.01	–0.01
	10		0.03	0.00	–0.02	0.03	0.00	–0.03	0.01	–0.02	–0.01

* The figures in bold and italic are the multi-site calibrated parameter values. The relative changes in performance measures is estimated according to $(S' - S)/S$, in which S' means the simulation results of the changed parameter values, and S is the results of the multi-site calibration protocol.

Table 3. Continued.

Module	Parameter*	Unit	Xiahui			Daiying			Dage		
			RMSE	*R*	EF	RMSE	*R*	EF	RMSE	*R*	EF
UZ	Saturated water conductivity (K_s)										
	0.000001	$m\,s^{-1}$	0.18	–0.05	–0.18	0.17	–0.10	–0.24	0.12	–0.07	–0.19
	6E–07		0.09	–0.03	–0.09	0.08	–0.04	–0.11	0.08	–0.05	–0.12
	4E–07		**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	6E–08		0.11	–0.03	–0.11	0.04	–0.03	–0.05	0.89	–0.04	–1.81
	1E–08		0.26	–0.06	–0.27	0.17	–0.06	–0.23	1.24	–0.05	–2.81
	Lower UZ boundary (Bnd_UZ)										
	–0.5	m	0.19	0.01	–0.19	0.26	–0.05	–0.37	2.22	–0.06	–6.54
	–1		–0.03	0.01	0.03	–0.02	0.00	0.02	0.03	0.00	–0.04
	–1.5		**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	–2		0.24	–0.10	–0.25	0.15	–0.05	–0.21	0.18	–0.14	–0.28
	–3		0.32	–0.14	–0.34	0.21	–0.07	–0.29	0.38	–0.29	–0.64
ET	Cint										
	0.5	mm	0.01	0.00	–0.01	0.01	0.00	–0.01	0.01	–0.01	–0.01
	0.1		0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	–0.01
	0.05		0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	–0.01
	0.01		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.005		**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	C1										
	0.1	–	–0.01	0.00	0.01	–0.01	0.00	0.01	0.05	–0.01	–0.07
	0.3		**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	0.5		0.00	0.00	0.00	0.00	0.00	0.00	–0.01	0.00	0.01
	0.8		0.00	0.00	0.00	0.00	0.00	0.00	–0.01	0.00	0.01
	1		0.00	0.00	0.00	0.00	0.00	0.00	–0.01	0.00	0.01
	C2										
	0.1	–	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.2		**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	0.5		0.00	0.00	0.00	–0.01	0.00	0.00	0.00	0.00	–0.01
	0.8		0.00	0.00	0.00	0.00	0.00	0.00	0.02	–0.01	–0.03
	1		0.00	–0.02	0.00	0.01	–0.04	–0.01	0.45	–0.04	–0.78
	C3										
	5	$mm\,day^{-1}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	–0.01
	10		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	20		**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	30		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	40		–0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Aroot										
	0.1	1/m	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.5		**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	1		0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	–0.01
	2		0.00	0.00	0.00	0.00	0.00	0.00	0.02	–0.01	–0.03
	3		–0.01	0.00	0.01	–0.01	0.00	0.01	0.07	–0.02	–0.10

* The figures in bold and italic are the multi-site calibrated parameter values. The relative changes in performance measures is estimated according to $(S' - S)/S$, in which S' means the simulation results of the changed parameter values, and S is the results of the multi-site calibration protocol.

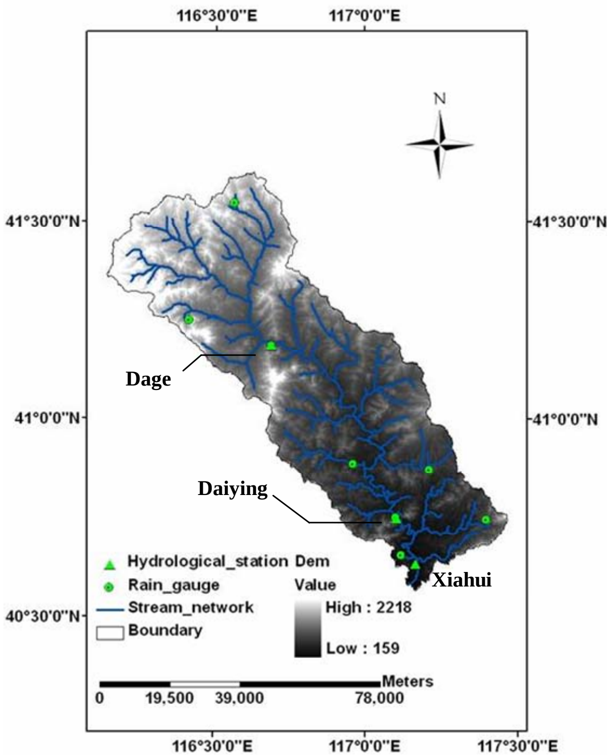

Fig. 1. Topography and the distribution of hydroclimatic stations of Chaohe watershed.

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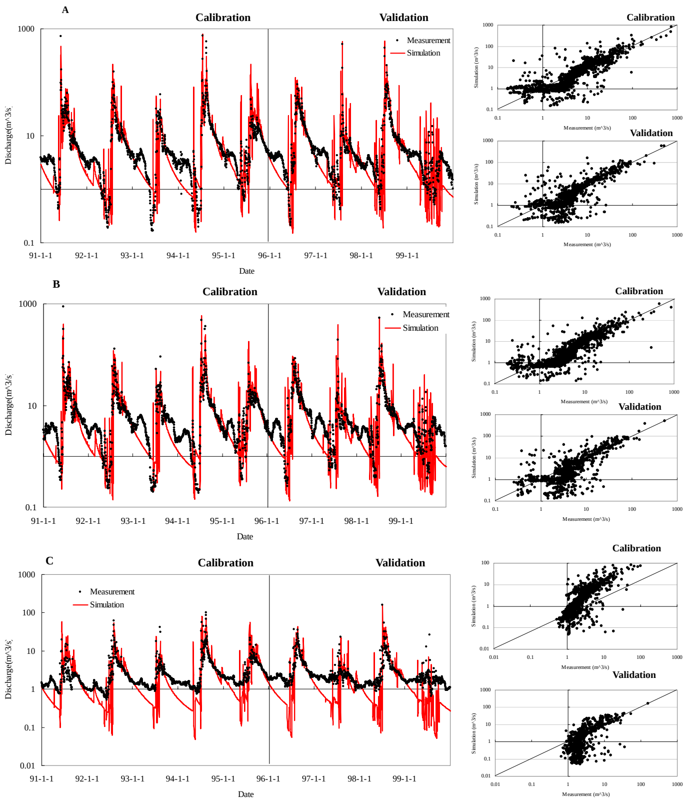

Fig. 2. Comparison of model simulation by single-site calibration procedure with measurement for the testing period. **(A)** Xiahui station; **(B)** Daiying station; **(C)** Dage station.

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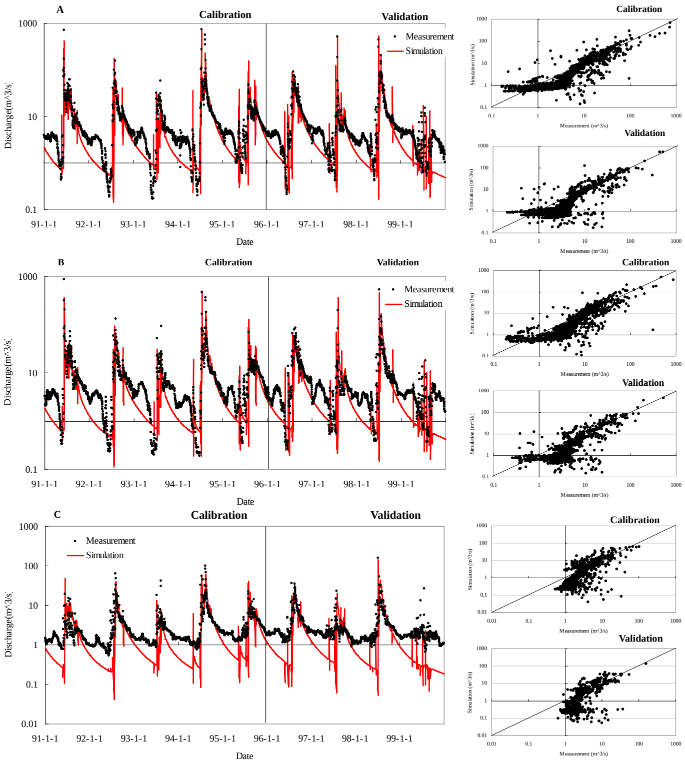

Fig. 3. Comparison of model simulation by multi-site calibration procedure with measurement for the testing period. **(A)** Xiahui station; **(B)** Daiying station; **(C)** Dage station.

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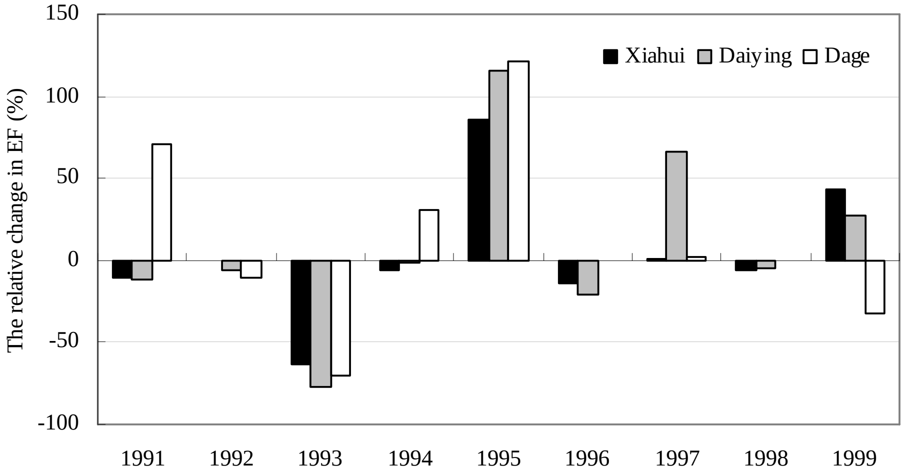

Fig. 4. The relative change in EF when compared the multi-site model calibration protocol with the single-site model calibration protocol. The relative change in EF was estimated according to to $(S' - S)/S$, in which S' denotes the multi-site model calibration results, and S means the single-site model calibration results.

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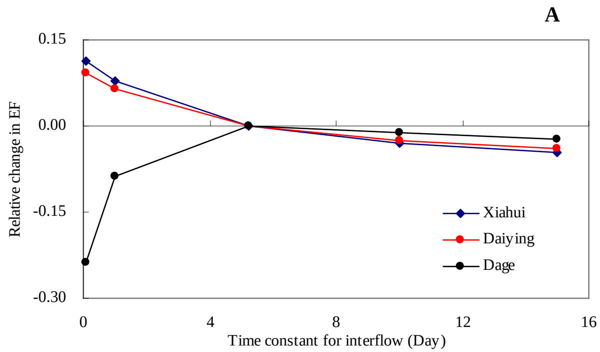

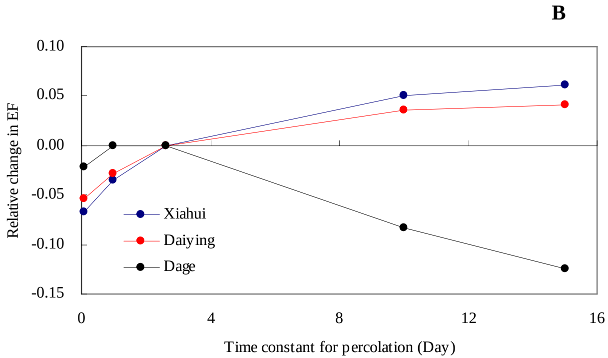

Fig. 5. Relative changes in EF in response to the variation of (A) time constant for interflow; and (B) time constant for percolation. The change was estimated according to $(S' - S)/S$, in which S' denotes the simulation with the changed parameter values, and S means the simulation with the calibrated values.

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