Transferability of a lumped hydrologic model, the Xin'anjiang model based on similarity in climate and geography

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ABSTRACT

Hydrological experiments are essential to understanding the hydrological cycles and promoting the development of hydrologic models. Model parameter transfers provide a new way of doing hydrological forecasts and simulations in ungauged catchments. To study the transferability of model parameters for hydrological modelling and the influence of parameter transfers on hydrological simulations, the Xin'anjiang model (XAJ model), which is a lumped hydrologic model based on a saturation excess mechanism that has been widely applied in different climate regions of the world, was applied to a low hilly catchment in eastern China, the Chengxi Experimental Watershed (CXEW). The suitability of the XAJ model was tested in the eastern branch catchment of CXEW and the calibrated model parameters of the eastern branch catchment were then transferred to the western branch catchment and the entire watershed of the CXEW. The results show that the XAJ model performs well for the calibrated eastern branch catchment at both daily and monthly scales on hydrological modelling with the NSEs over 0.6 and the REs less than 2.0%. Besides, the uncalibrated catchments of the western branch catchment and the entire watershed of the CSEW share similarities in climate (the precipitation) and geography (the soil texture and vegetation cover) with the calibrated catchment, the XAJ model and the transferred model parameters can capture the main features of the hydrological processes in both uncalibrated catchments (western catchments and the entire watershed). This transferability of the model is useful for a scarce data region to simulate the hydrological process and its forecasting.

Key words | hydrological modelling, parameter transfer, the Chengxi experimental watershed, Xin'anjiang model

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HIGHLIGHTS

- The suitability of the Xin'anjiang model for low hilly catchment in eastern China;
- Transferability of model parameters for hydrological modelling;
- Anthropic impact on hydrological process modelling.

INTRODUCTION

Hydrological experiments are important basic work in understanding regional hydrological laws, studying the impact of environmental changes and constructing watershed hydrologic models (Hopmans & Pasternack 2006; Yang *et al.* 2018). Different regions have different hydrological characteristics due to different climates and underlying surface conditions (Mahmoud & Gan 2018; Liu *et al.* 2020). In 1965, the International Hydrological Programme (IHP), proposed the experimental watershed study as one of its core contents to promote the development of hydrological experimental work in various countries (Jimenez-Cisneros 2015). In the 1950 and 1960s, China established a large number of hydrological experimental watersheds (Han *et al.* 2014), and accumulated valuable experimental data (Fu *et al.* 2011), which provided a scientific basis for more in-depth disclosure of hydrological phenomena and exploration of hydrological laws (Gu *et al.* 2003). Theoretical and practical hydrological experiments play an important role in water resources management and development as well as research on water circulation mechanisms (Meshesha & Khare 2019). Germer *et al.* (2008) established a pasture in a forest area in the southwestern Brazilian Amazon state and found that human activities had the potential to modify the hydrology of small watersheds and the fluxes of solutes. Montenegro *et al.* (2014) evaluated changes in vegetation cover of an experimental watershed in Pernambuco State, Brazil, based on the NDVI index, and revealed the fundamental importance of experimental catchments in river basin management. Hao *et al.* (2014) analyzed the variation trends of key variables of the hydrological cycle (e.g. temperature, precipitation, wind, sunshine, relative humidity, potential evaporation, actual evaporation) based on the observations of the Wudaogou experimental station and explored the impacts of different drivers on actual evaporation. Vaze *et al.* (2013), used the conceptual modelling experiment for the Australian continent, implementation of the results for AWRA-L (landscape) across 607 gauged catchments show that in both calibration and validation, the model typically provides streamflow predictions that are similar to those from other widely used conceptual hydrological models. The observations from worldwide hydrological experimental watersheds have helped improve knowledge of the hydrological cycles.

Hydrological knowledge based on experimental watersheds has promoted the development of the hydrologic models (Lavenne *et al.* 2019; Krysanova *et al.* 2020). Hundreds of watershed models have been developed for flood forecasting, flow simulation, and water resources assessment (Vaze et al. 2013; Nakayama 2014; Wang *et al.* 2018; Tian *et al.* 2019). According to the degree of dispersion of hydrological process in the basin, the watershed models can be categorized as lumped hydrologic models (e.g. Stanford Model (Crawford & Linsley 1966), the Xin'anjiang Model (Zhao 1992), the Tank Model (Sugawara 1979), etc.); semi-distributed hydrologic models (e.g. TOPKAPI Model (Ciarapica & Todini 2002), TOPMODEL (Beven *et al.* 1984) and HBV Model (Kobold & Brilly 2006), etc.); and distributed hydrologic models (e.g. SWAT Model (Ding & Pan 2007), SHE Model (Abbott *et al.* 1986) and IHDM (Rogers *et al.* 1985), etc.).

The Xin'anjiang Model is a lumped hydrologic model based on a saturation excess mechanism (Xu 2009), and has been widely applied in different climate regions of the world (Hao *et al.* 2015; Rahman & Lu 2015). Song *et al.* (2012) applied the Xin'anjiang model with artificial neural networks (ANNs) in the Yanduhe watershed and found that the hybrid rainfall-runoff model could achieve promising results with acceptable accuracy for flood events simulation and forecast. Lin *et al.* (2014) integrated the Xin'anjiang model and the Curve Number of SCS-CN (Soil Conservation Service) model to assess runoff changes in the Dong River basin and found the impact of land-use change on runoff was more evident in the flood season compared to the dry season. Yang *et al.* (2011) developed a EcoHAT model by coupling the Xin'anjiang model and SWAT model, simulating the hydrologic pollutant adequately in Hainan based on remote sensing data. The previous studies indicated that the Xin'anjiang model, whether by itself or by coupling with other models, achieved satisfying applications to worldwide catchments to simulate the hydrological processes (Alazzy *et al.* 2015; Meng *et al.* 2018).

Hydrologic models play an essential role in hydrological phenomena analysis in gauged catchments (Kittel *et al.* 2020). However, when it comes hydrological forecasting for ungauged catchments, the parameter calibration of the models has faced a great challenge (Elmahdi et al. 2007; Yao *et al.* 2014; Biondi & De Luca 2015; Antonetti *et al.* 2017). For this case, the commonly used approaches are regional parameter regression based on relationships between model parameters and physical catchments indexes, and parameter transferring based on catchment similarity (Singh *et al.* 2014; Zhou *et al.* 2016; Song *et al.* 2017).

The Chengxi experimental watershed was established in 1962 and operated from 1962 to 1966. There are 4–5 years of hydro-meteorological data available. Eastern China has a highly developed economy but due to its location in the East Asian monsoon climate zone, the area is frequently hit by flash floods, damaging and constraining the social economy to some extent (Xie *et al.* 2016; Bloemen *et al.* 2018). Effective flood forecasting is urgently needed to support the regional economy's sustainable development (Felder *et al.* 2017). This paper's main objectives are to test the Xin'anjiang model's performance in eastern China, where the experimental watershed is situated, and to study the transferability of the model parameters to ungauged regions based on similarity in climatic and geographical conditions.

DATA AND METHOD

Study catchment

The Chengxi hydrological experimental station (118°13'E, 32°18'N) is located in Chuzhou, Anhui province, China, and has a drainage area of 82.1 km². The watershed is surrounded by low hills, including Langya Mountain and Hua Mountain, and its river system consists of three branches – the eastern branch, the middle branch and the western branch (Figure 1). Most of the Chengxi experimental watershed is covered by forest and farm land, and the soil consists mainly of sandy loam and clay loam. Irrigation agriculture has developed in the watershed's western branch due to the flat morphology and easily accessible water resources, while the eastern branch catchment generally remains in a comparatively natural state.

Four hydrometric stations and nine rain gauges were set up in the Chengxi watershed. Hydro-meteorological data from 1962 to 1966 were collected from Hydrological Year Book Series issued by the Ministry of Water Resources. There are 4–5 years of data for the Honghuaqian station on the eastern branch, the Sanchahe station on the western branch, and the Chengxi station on the main steam of the Chengxi experimental watershed, while there are only 2 years of discharge observation data available for the Shenying station on the middle branch. Therefore, the authors consider more analysis and study focus on the eastern branch catchment, the western branch catchment and the entire Chengxi watershed. Table 1 shows the hydrological statistics for the three study catchments. Because the eastern monsoon climate highly influences it, the Chengxi watershed has an average annual temperature of about 15 °C and abundant rainfall. The watershed's average annual precipitation is approximately 850 mm with more rainfall occurring in the surrounding higher elevation areas. Although the three catchments are similar in climatic (precipitation) and geographical (soil texture and vegetation cover) features, their hydrological features are quite different. The average annual runoff in the eastern branch catchment is 445 mm, almost twice that of the western branch catchment (246 mm). The recorded runoff in the western branch catchment and the entire watershed is also much lower than that in the eastern branch catchment, probably due to water being pumped from the river stream for agriculture irrigation.

In this study, the authors calibrate the Xin'anjiang model for the eastern branch catchment to test suitability, and set the western branch catchment and the entire Chengxi watershed as target catchments to test the transferability of the Xin'anjiang model.

The Xin'anjiang model and objective functions

The Xin'anjiang model is a lumped hydrologic model based on a saturation excess mechanism. As shown in Figure 2, the model structure has four main components: evapotranspiration, runoff production, runoff components separation and flow routing. In all, 17 parameters need to be calibrated with discharge measurements, and the notations and physical meanings of the model parameters (italicized in
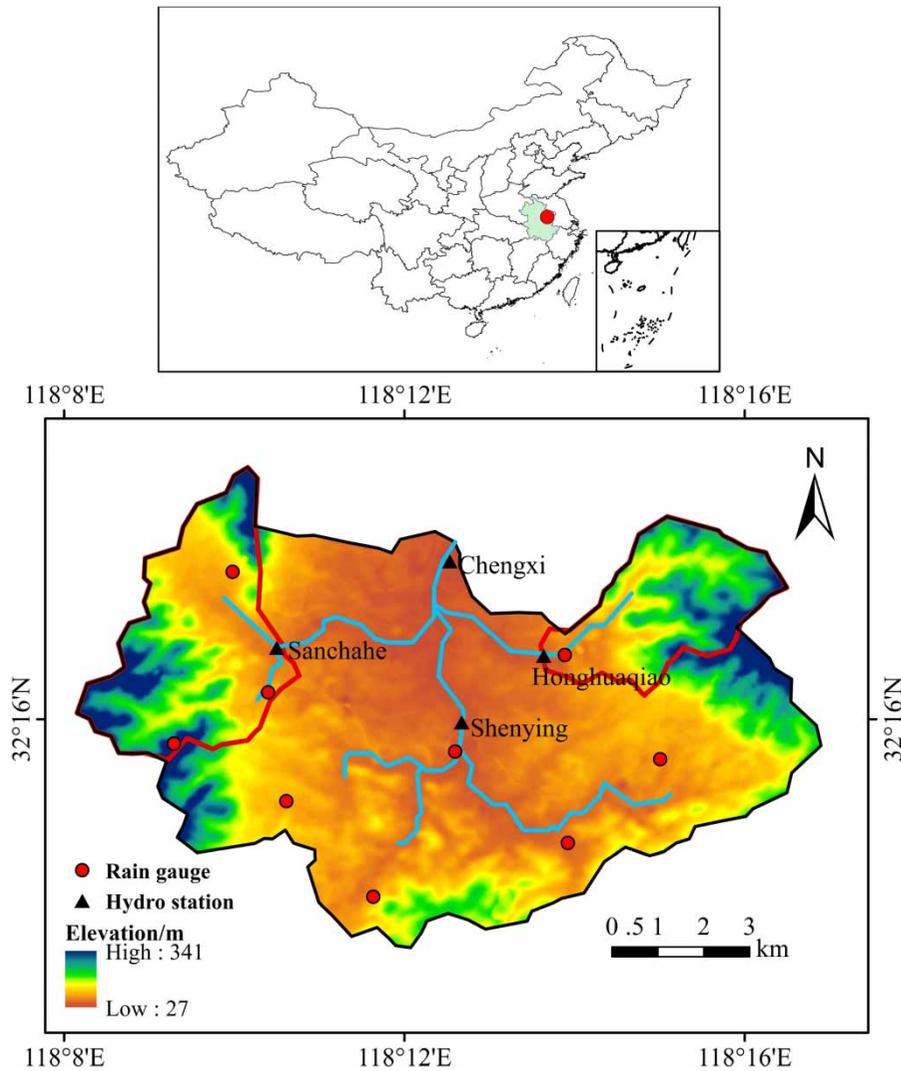
Figure 1 | River system and location of hydrometric stations and rain gauges in the Chengxi experimental watershed.

Table 1 | Hydrological information of the three study catchments

Catchments	Hydrometric stations	Area/km^2	Precipitation/mm	Pan evaporation/mm	Runoff/mm	Data series
Eastern branch	Honghuaqiao	8.6	994.25	1,039.99	445.26	1963–1966
Western branch	Sanchahe	17.5	960.96	1,037.05	245.86	1963–1966
Entire watershed	Chengxi	82.1	853.89	819.47	280.25	1962–1966

Figure 2) and state variables can be found in references (Zhao 1992). The Xin'anjiang model has been widely applied to many fields of hydrological forecasting, water resources assessment, as well as environmental change impact analysis because of its advantages of simple structure, clear parameter interpretation and relatively high simulation precision (Tian *et al.* 2013; Zhu *et al.* 2017; Li *et al.* 2019).

The Nash Efficiency Coefficient (NSE) and Relative Error (RE) reflect the agreement between simulated discharges and observed discharges (Nash & Sutcliffe 1970).
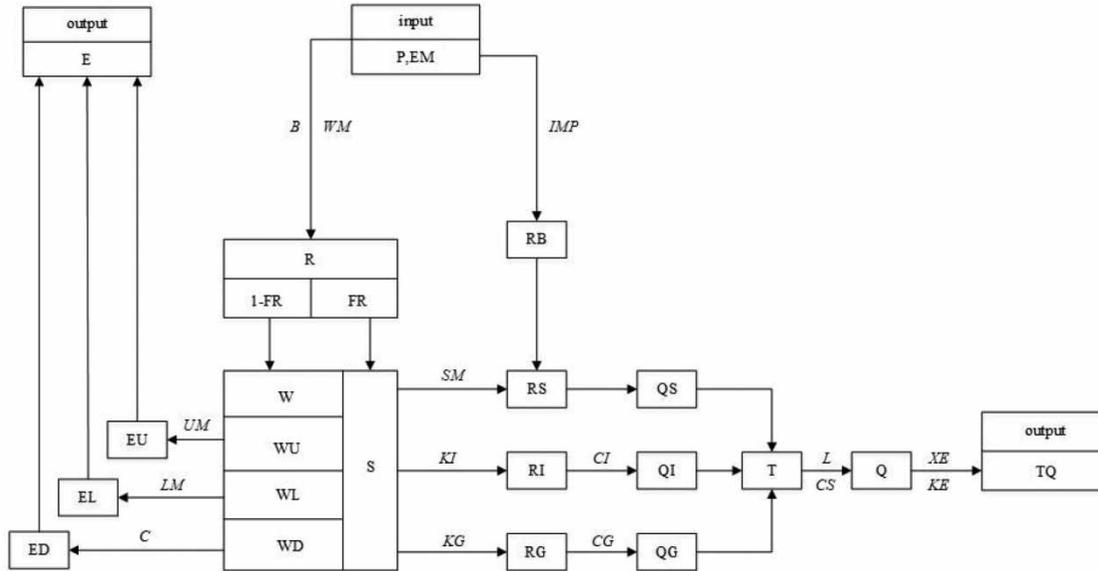
State variables:

P	Precipitation (mm)	E	Evapotranspiration (mm)
EM	potential evaporation (mm)	TQ	area total outflow (m3/s)
R	runoff produced in pervious area	FR	impervious area
RB	runoff produced in impervious area	S	surface free water
RS	surface runoff	W	tension water
RI	interflow runoff	T	total inflow of river network (m3/s)
RG	groundwater runoff	Q	outflow of unit area (m3/s)

EU, EL and ED are evapotranspiration of the upper, lower and deeper layer, respectively (mm)

WU, WL and WD are tension water of the upper, lower and layer, respectively (mm)

QS, QI and QG are total inflow of the surface, interflow and groundwater runoff (m3/s)

Figure 2 │ Framework of the Xin'anjiang model.

The NSE and RE are therefore employed as objective functions to calibrate model parameters. A good simulation will have an NSE close to 1 and RE close to 0. The objective functions are calculated using Equations (1) and (2) as follows:

$$NSE = 1 - \frac{\sum\limits_{i=1}^{N} (Q_i^{obs} - Q_i^{sim})^2}{\sum\limits_{i=1}^{N} (Q_i^{obs} - Q_{avg}^{obs})^2} \quad (1)$$

$$RE = \frac{\left| \sum\limits_{i=1}^{N} Q_i^{obs} - \sum\limits_{i=1}^{N} Q_i^{sim} \right|}{\sum\limits_{i=1}^{N} Q_i^{obs}} \times 100\% \quad (2)$$

where Q_i^{obs}, Q_i^{sim} and Q_{avg}^{obs} are the observed daily/monthly discharge, simulated daily/monthly discharge, and average observed daily/monthly discharge, respectively (m^3/s), N is the length of runoff sequence and i is the serial number.

RESULTS AND DISCUSSION

Model calibration and hydrological modelling for the eastern branch catchment

The eastern branch catchment has four years of data from 1963 to 1966. The first three years of data were used to

Table 2 | Results of the main parameter calibration in the eastern branch catchment

Parameters	KC	UM	LM	C	WM	B	IMP	SM
Values	0.568	35	60	0.213	0.128	0.371	0.01	45
Parameters	EX	KG	KI	CI	CG	CS	L	XE
Values	1.065	0.21	0.49	0.252	0.999	0.268	0	0.198

Note: KC: Reduction coefficient of evaporation; UM: Storage capacity of the upper layer; LM: Storage capacity of the lower layer; C: Evapotranspiration coefficient of deeper layer; WM: Average water storage capacity in the catchment; B: Exponent of storage capacity curve; IMP: Impervious area proportion; SM: Storage capacity of free water; EX: Exponent of free water storage capacity curve; KG: Outflow coefficient of free water storage to groundwater; KI: Outflow coefficient of free water storage to interflow; CI: Regression coefficient of interflow storage; CG: Regression coefficient of groundwater storage; CS: Regression coefficient of surface runoff; L: Coefficient of hysteresis; XE: Muskingum parameter.

calibrate the model parameters, and the data from the last year was used to validate model performance. In order to avoid the influence of initial model parameters, the authors used repeated 1963 as a warming period before model calibration. Using daily rainfall and pan evaporation to drive the Xin'anjiang model, the Rosenbrock method was employed to optimize model parameters (Wang *et al.* 2014). The main calibrated model parameters are shown in Table 2, and the simulation results are statistically given in Table 3 and Figure 3, respectively.

Table 2 shows the calibrated parameters and their physical interpretation of the Xin'anjiang model for the eastern branch catchment. According to the influence degree of model parameters on hydrological simulation, the parameters can be classified into two categories, sensitive parameters and insensitive ones. The sensitive parameters include KC, SM, KI, CI, CG, CS, L and XE which negatively influence on simulation results (NSEs and REs).

Table 3 shows that the Xin'anjiang model could simulate the hydrological processes well for the eastern branch catchment, with the NSEs of calibration and validation over 0.6 and the REs controlled in 2.0% at both daily and monthly scales. The model performed better at monthly scale than daily scale. Monthly discharge simulations in calibration and validation periods have NSEs of 0.9 and 0.8 respectively

while daily discharge simulations in both periods have NSEs of 0.67 and 0.6. Figure 3 indicates that the recorded discharges matched well with the simulated ones in general, although we also find the Xin'anjiang model always underestimated high flows in the flood season and overestimated low flows in the dry season both at daily and monthly scales. Both Table 3 and Figure 3 assured the Xin'anjiang model's suitability to the low hilly region in eastern China for daily or monthly discharge simulations.

Hydrological modelling for the western branch catchment and entire Chengxi watershed based on parameter transfer

The western branch catchment and the entire Chengxi watershed shared the same climatic and geographical conditions, precipitation, soil texture, as well as vegetation cover, etc with the eastern branch catchment. The calibrated model parameters were transferred from the eastern catchment to the western branch catchment (drainage area 17.5 km^2) and the entire Chengxi catchment (drainage area 82.1 km^2) for discharge simulations. The simulation results are shown in Table 4 and Figure 4.

Figure 4 shows that the Xin'anjiang model simulates well the daily and monthly discharges for the first period before 1965 by using the transferred parameters, and overestimated discharges in 1965–1966 for both catchments of the western branch catchment and the entire Chengxi watershed. Statistical results in Table 4 indicate the NSEs in the first period (before 1965) are >0.6 for daily simulations and >0.9 for monthly simulations both for the western branch catchment and the entire Chengxi watershed while the relative errors are a little bit larger (all <20%). However,
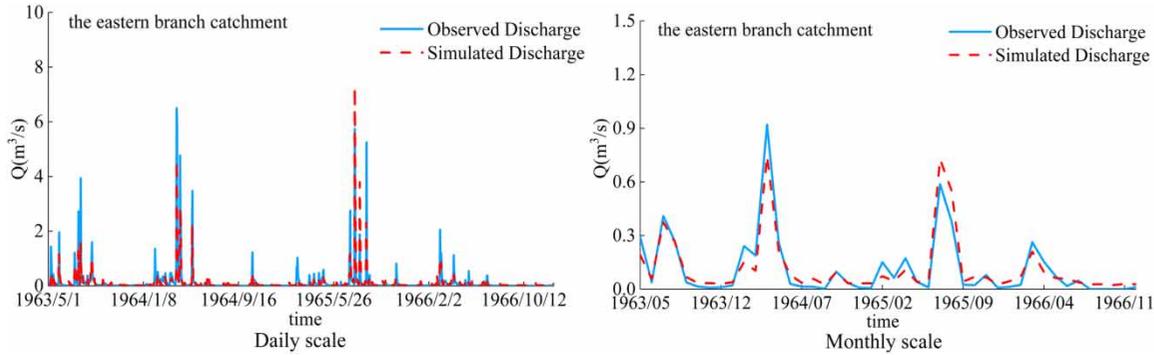
Table 3 | Simulation accuracy of hydrological modelling for the eastern branch catchment

Scale	Calibration period (1963–1965)		Validation period (1966)	
	NSE	RE/%	NSE	RE/%
Daily	0.67	0.02	0.60	0.17
Monthly	0.90	0.90	0.80	1.59

Figure 3 │ Discharge simulation processes in the eastern branch catchment at daily and monthly scales.

Table 4 │ Hydrological modelling for the western branch catchment and the entire Chengxi watershed based on parameter transfer

Catchment	Scale	Before 1965		1965–1966	
		NSE	RE/%	NSE	RE/%
Western branch	Daily	0.64	18.67	−1.96	192.22
	Monthly	0.94	19.86	−1.08	191.67
Entire Chengxi	Daily	0.63	8.40	−0.47	77.47
	Monthly	0.96	8.31	0.30	76.97

simulation results for the second period (1965–1966) are relatively poor with small or negative NSEs and large relative errors (REs >70%) for both transferred catchments.

Parameters transfer offers a better hydrological simulation for the entire Chengxi watershed with the NSE reaching 0.63 at daily scale and 0.96 at monthly scale, and both REs of the two scales are controlled within 9.0% than its sub-catchment (the western branch catchment), which is mainly covered by forests and fields. And the
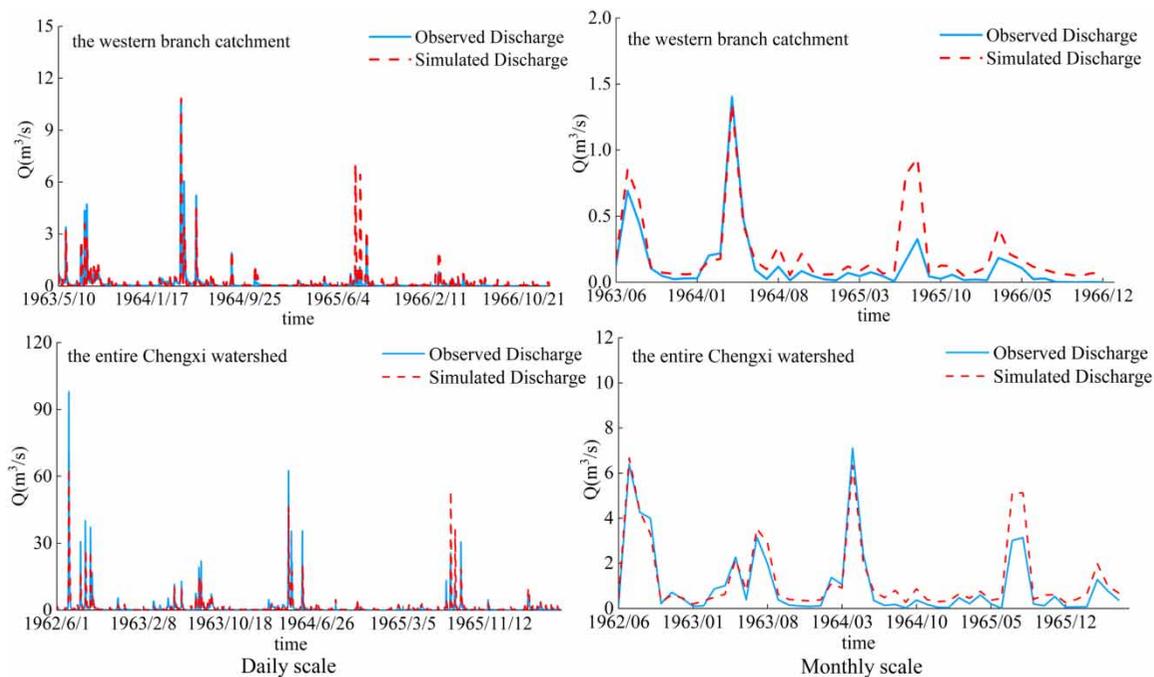

Figure 4 │ Simulated and recorded discharge processes at daily and monthly scales for the western branch catchment and the entire Chengxi watershed based on parameter transfer.

Xin'anjiang model performed better at monthly scale than daily scale.

At the end, the Xin'anjiang model and the transferred parameters could capture the main hydrological features of the catchments in the study area. The Xin'anjiang model could be applied to the ungauged catchments based on the similarity in climatic and geographical conditions. And the model could have better simulation results with transferred parameters if the ungauged catchments shared higher similarities with the gauged one. However, the transferred parameters usually led to a higher but acceptable simulation error within a tolerance level.

Discussion

The Year Books of Chuzhou county indicate that the county has developed agricultural water conservancy projects since the 1960s. A small reservoir in the western branch catchment has been used for irrigation since 1965, with stream flow stored and reduced discharges gauged at Sanchahe station. The relationship between runoff and precipitation was changed by human activities, such as reservoir contribution and pumping water from the river for irrigation use (Figure 5). It is worth noting that the transferred parameters reflected runoff generation under natural conditions. Human activities influence hydrologic models' transferability, although the model could capture the hydrological processes' main features based on parameter transfer.
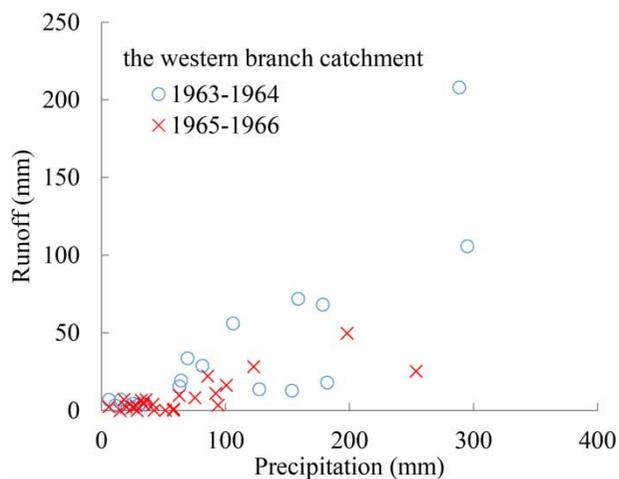

Figure 5 │ The relationship between monthly runoff and precipitation for the western branch catchment.

The authors calibrated the Xin'anjiang model with the recorded hydro-meteorological data of the two target catchments, and the simulation results are shown in Table 5. The results indicate that the calibrated Xin'anjiang model does not significantly improve NSEs but lowers relative errors of discharge simulation for the calibration period before 1965. However, relative errors are still quite large for the validation period of 1965–1966, particularly for the western branch catchment (RE > 150%).

The Chengxi experimental watershed operated for several years. The monitored hydro-meteorological data provides vital support to test model performance and transferability of model parameters. However, the short available data series may not fully reflect the variability of this region's hydrological features, thus leading to uncertainty in model parameters based on historical calibration. Availability of multiple data sources and hydrological modelling in a changing environment is essential and expected to enhance further study.

The Xin'anjiang model has a better simulation accuracy for the eastern branch catchment, which is in a natural state, but performs realitvely poorly in the western branch catchment and the entire Chengxi watershed with certain human activities. Human activities influence hydrological regimes and affect hydrological modelling because they complicate the regional water cycle by storing and pumping water for irrigation or other uses that all change natural flow conditions.

The eastern low hilly region in China is relatively wet and warm. Model application shows good transferability of the Xin'anjiang model based on similarities. However, hydrological features in different climatic zones are different

Table 5 │ Simulation accuracy of hydrological modelling for the western branch catchment and the entire Chengxi watershed

Catchments	Scale	Calibration period before 1965		Validation period 1965–1966	
		NSE	RE/%	NSE	RE/%
Western branch	Daily	0.74	6.19	0.13	154.05
	Monthly	0.87	5.23	−0.50	155.25
Entire Chengxi	Daily	0.64	6.71	0.32	66.15
	Monthly	0.85	5.26	0.87	60.11

as well. Tests of model transferability to different climatic zones should be enhanced in further studies.

CONCLUSIONS

This study investigates the suitability and transferability of a lumped hydrologic model (Xin'anjiang model) for low hilly catchment with a case study in eastern China. This study's results and analysis indicate the Xin'anjiang model can simulate the hydrological processes well for the catchments in the low hilly area of eastern China both at daily and monthly scales. And the model performs better for monthly discharge simulations. High flows in the flood season are underestimated while low flows in the dry season are over-simulated for most cases.

The Xin'anjiang model is also transferable to the ungauged catchments with the calibrated parameters of the gauged catchment based on similarity in climatic and geographical conditions. The model can capture the main features of hydrological processes. The entire Chengxi watershed shows better simulation results, with more similarities with the eastern branch catchment. Using transferred model parameters usually leads to a larger simulation error, but it is still within the tolerance level and acceptable when there is no data (scarce data region).

The highly developed economy and intensive human activities have complicated the hydrological situation of the watersheds, and further influence the streamflow and accuracy of hydrological modelling. Further study of the hydrological modelling should fully consider the anthropic impact on hydrological process modelling in different climatic zones.

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CONTRIBUTORS

Jian-yun ZHANG, Guo-qing WANG and Amgad Elmahdi designed the study and analyzed results, improved the manuscript, and ensured it captured the right literature and fit in the global agenda and contribute to the science gap. Yue LIU and Xiao-xiang GUAN performed calculations and drafted the paper. Cui-shan LIU and Rui-min HE collected hydro-meteorological data. and Qin-li YANG reviewed the document and edited the final version.

CONFLICT OF INTEREST

Yue LIU, Jian-yun ZHANG, Amgad Elmahdi, Qin-li YANG, Xiao-xiang GUAN, Cui-shan LIU, Rui-min HE and Guo-qing WANG declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

All relevant data are available on request to the corresponding author (E-mail: gqwang@nhri.cn).

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