Water balance assessment of an ungauged area in Poyang Lake watershed using a spatially distributed runoff coefficient model

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ABSTRACT

The Poyang Lake ungauged area (PLUA) is an essential hydrology buffer surrounding Poyang Lake. For such a data-scarce area, a novel spatially distributed runoff coefficient model (SDRCM) was developed based on the underlying surface properties using remotely sensed precipitation and reanalysis data after their validation. The runoff simulated by the SDRCM based on both sets of gridded precipitation data were validated in a subbasin where R^2 and E_{NS} are larger than 0.87. In addition, a hydrodynamic model was applied to validate the proposed model further by considering the estimated water yield for PLUA that involves boundary inputs, in which the result more closely aligns to the monthly observed discharge. On an annual basis, the PLUA water flow accounted for 12%–19% of the total annual water flow within the watershed, which was approximately equal to the proportion of the area of PLUA in relation to the entire watershed. Finally, the water balance between inflow and outflow of Poyang Lake was investigated, with relative errors observed at the Hukou gauging station all being less than 10% from 1998 to 2009. The proposed model will be helpful in understanding the significance of water yields of such ungauged plain area when evaluating the water balance.

Key words | hydrodynamic model, hydrology prediction, Poyang Lake, spatially distributed runoff coefficient model (SDRCM), ungauged area

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INTRODUCTION

It is likely that runoff estimation for ungauged basins is one of the most challenging tasks for hydrologists. This long-standing issue has received increased attention recently due to the PUB (Prediction in Ungauged Basins) initiative launched in 2003 (Hrachowitz *et al.* 2013). Because the water cycle on the Earth's surface is influenced by ongoing human activities and climate change, more research is warranted to understand, simulate and predict the hydrological regimes of the system (Wagener *et al.* 2010). The Poyang Lake plain, at the heart of the Yangtze River watershed, is an indicator of climate change and is connected to the Yangtze River through the Hukou waterway (Zhang *et al.* 2015a). It suffers a high likelihood of an increase in frequency and severity of flooding and droughts. Ungauged area, an area of interest in ungauged basins (Sivapalan *et al.* 2003), which stretches from the downstream boundary of a gauged basin to the upper boundary of an adjacent water body, universally exists in river, lake, and ocean catchments (Zhang *et al.* 2017). The Poyang Lake ungauged area (PLUA), located in the Poyang Lake plain, has not been gauged to develop stream flow records, which prevents hydrological engineers and scientists from accurately

predicting the volume of water resources and analyzing water balances. Due to the complexity of drainage networks and lakes in a flat area, such as the PLUA, it is difficult to develop a distributed hydrological model for water flow prediction. In addition, little observation data are available to calibrate and validate a sophisticated hydrological model. Therefore, it is necessary to develop a new method to assess the water balance in this ungauged area.

Hydrological prediction is limited by absent hydrological observations and insufficient data quality and reliability, which is especially true for developing countries where watersheds are often ungauged (Piman & Babel 2013). Because traditional data gathering is usually constrained by financial and time limitations, innovations and advances in sensing technologies have the potential to be highly valuable for the field of hydrology (Schmugge *et al.* 2002; Krajewski *et al.* 2006). During the PUB decade, major strides have been made in the availability, quality, and variety of environmental data that can be obtained from different observation technologies and strategies. The hydro-climate data commonly collected by ground stations were utilized for this hydrological model. In addition, the availability of other sources of data (i.e., satellite rainfall and reanalysis data) where there is no conventional ground station has recently attracted the interest of hydrologists. Indeed, a hydrological model can benefit from satellite observation data as well as global reanalysis data, such as TRMM (Tropical Rainfall Measuring Mission), ECMWF (European Centre for Medium-Range Weather Forecasting) ERA-40 (40-year reanalysis), TMPA (TRMM Multi-satellite Precipitation Analysis) and CMORPH (Climate Prediction Center morphing technique), and CFSR (Climate Forecast System Reanalysis) to overcome data limitations (Behrangi *et al.* 2011; Ward *et al.* 2011; Sun *et al.* 2013; Worqlul *et al.* 2014; Li *et al.* 2015). Consequently, such gridded data (satellite imagery and reanalysis data) provide an unprecedented opportunity for hydro-meteorological applications and climate studies. Although expanding, currently the application of remote sensing and global reanalysis data for hydrological application remains highly limited (Behrangi *et al.* 2011), especially application in ungauged areas, such as PLUA.

During the PUB decade, hydrological scientists made significant efforts to better understand spatiotemporal heterogeneity and hydrological processes (Hrachowitz *et al.* 2013). As a result, hydrological models have been developed that include advancements in model structure design and modeling strategies for ungauged areas. Several process-based modeling frameworks have been developed for testing and comparison (McDonnell 2003; Fenicia *et al.* 2011) in addition to evaluation indexes (Criss & Winston 2008; Gupta *et al.* 2009), tools for model calibration and validation (Blöschl *et al.* 2013), and approaches for comprehensive uncertainty assessment (Wagener *et al.* 2003; Nester *et al.* 2012). However, parameters for hydrological processes vary across different climatic zones and underlying surface properties and, as a result, these hydrological models are not universally applicable.

As to the ungauged basin, models are often parameterized to predict a hydrologic response by relating model parameters and catchment (Wagener & Wheater 2006; Buytaert & Beven 2009) or in a statistical manner with geomorphologic and climatic information (Castiglioni *et al.* 2010). In these studies, parameters are often calibrated in gauged basins and then applied to hydrologically similar ungauged basins with suitable modifications, but model parameters need to be adapted for differences between a calibration and a prediction basin due to the uniqueness of every basin (Andréassian *et al.* 2001). Consequently, in extrapolating model parameters from a calibrated basin, the prediction basin may lead to a weak relationship between the model parameters (Cibin *et al.* 2014). Thus, as in many cases no local data are available, alternative methods should be applied (van Emmerik *et al.* 2015). In this study, we try to introduce a hydrodynamic model for water in stream outlet to validate the upstream watershed hydrologic model.

Because of the effects of frequent water exchange and turbulence, the Yangtze River affects the water level and runoff hydrograph at the Hukou outlet (Ye *et al.* 2011), preventing accurate measurements. As a result, the rainfall–runoff relationship and water budget analysis in PLUA is a problem that has yet to be solved. Several different methods have been tried to estimate the runoff for this ungauged area. For example, Guo *et al.* (2011) applied a variable infiltration capacity (VIC) model based on remotely sensed land to simulate daily runoff in this area, but it was not able to delineate the subbasin in detail in such a small plain ungauged area because VIC is a large-scale hydrologic model. In addition, Huang *et al.* (2011) developed a semi-distributed

hydrological model based on different runoff productions for four classes of land use, but it was difficult to validate the entire model results for the ungauged area. Li *et al.* (2014) reported surface runoff estimation for lake plain area using a coarsely constant runoff coefficient of 0.6 for the whole area; the estimated result was implicitly given but not yet validated for the lake plain area in this study. Zhang *et al.* (2017) set up a subbasin validated Soil and Water Assessment Tool (SWAT) model and transferred it to simulate the streamflow in the ungauged area. However, in such a flat plain with complex river networks, it is difficult to calibrate parameters for a processes-based hydrological model due to the scarcity of data in this ungauged area. There is also not adequate observed data to validate and evaluate the modeling results. In order to solve these issues, we developed a spatially distributed runoff coefficient method (SDRCM) after investigating the slope and land use to predict the water flow in the data-scarce area of PLUA. This process was based on remote sensing precipitation products and weather data from CFSR. A lake hydrodynamic model was also applied to validate runoff in the PLUA estimated by the SDRCM. Combined with observation data from the upstream hydrological gauging station for the entire Poyang Lake watershed, the water balance is investigated by comparing these results to observations made at the Hukou gauging station.

STUDY AREA AND DATA PREPARATION

Study area

The Poyang Lake watershed drains an area of $16 \times 10^4 \, \text{km}^2$ and five main tributaries including the Xuishui River, Ganjiang River, Fuhe River, Xinjiang River, and Raohe River, with seven inlets discharging into the lake (Figure 1). Water storage contributions to the lake are mainly derived from catchment discharges and the interaction with the Yangtze River at the northern end of the lake. There is abundant rainfall in the Poyang Lake region with an annual mean of approximately 1,500–2,000 mm and an annual mean temperature of 17 °C–19 °C. The PLUA, an important hydrology buffer surrounding the lake, is separated by seven upstream hydrological gauging stations (Qiujin, Wanjiabu, Waizhou, Lijiadu, Meigang, Hushan, and Dufengkeng at seven inlets)

for the five main tributaries that discharge into Poyang Lake. The PLUA is located downstream of hydrological gauging stations to the river outlet which is not gauged by any hydrological station. With an area of approximately $2.9 \times 10^4 \, \text{km}^2$, it is larger than the Xiushui River, Fuhe River, Xinjiang River, and Raohe River basins and slightly smaller than the Ganjiang River basin. Further, it is a major component of the total water resources in the watershed. In this study, we attempted to estimate water yields of the PLUA based on reanalysis and remote sensing data.

Hydro-meteorological data

In order to sufficiently estimate the water flow in the PLUA, three types of meteorological data were used to compare estimated results in this study, including the TRMM, CFSR precipitation and Ground-based Meteorological Station (GMS) weather data. TRMM is a joint mission between the United States National Aeronautics and Space Administration and the Japan Aerospace Exploration Agency designed to determine rainfall in tropical and subtropical regions of the Earth for weather and climate research. The TRMM satellite, with a design lifetime of three years, was launched in November 1997 to produce valuable scientific data. Among the five instruments carried on the TRMM satellite, the instrument PR (precipitation radar) was the first space-borne instrument designed to provide three-dimensional maps of storm structure and rain information including the rain intensity and distribution, rain type, storm depth, and height at which the snow melts into rain. Datasets of the TRMM 3B43 V7 monthly precipitation products of 0.25×0.25 degrees from the period of January 1998 to December 2013 were used in this study.

The CFSR weather data, simulated from the reanalysis model from 1979 to the present, have a horizontal resolution of 38 km and are produced by a forecast model using data assimilation techniques to integrate GMS observations from the global weather station network along with remotely sensed products from satellites (Saha *et al.* 2010). The CFSR weather dataset can provide real-time weather estimates every hour for the entire globe, allowing for real-time estimates of precipitation for hydrologic forecasting. The CFSR weather data for January 1998 to December 2013 were downloaded for this study.
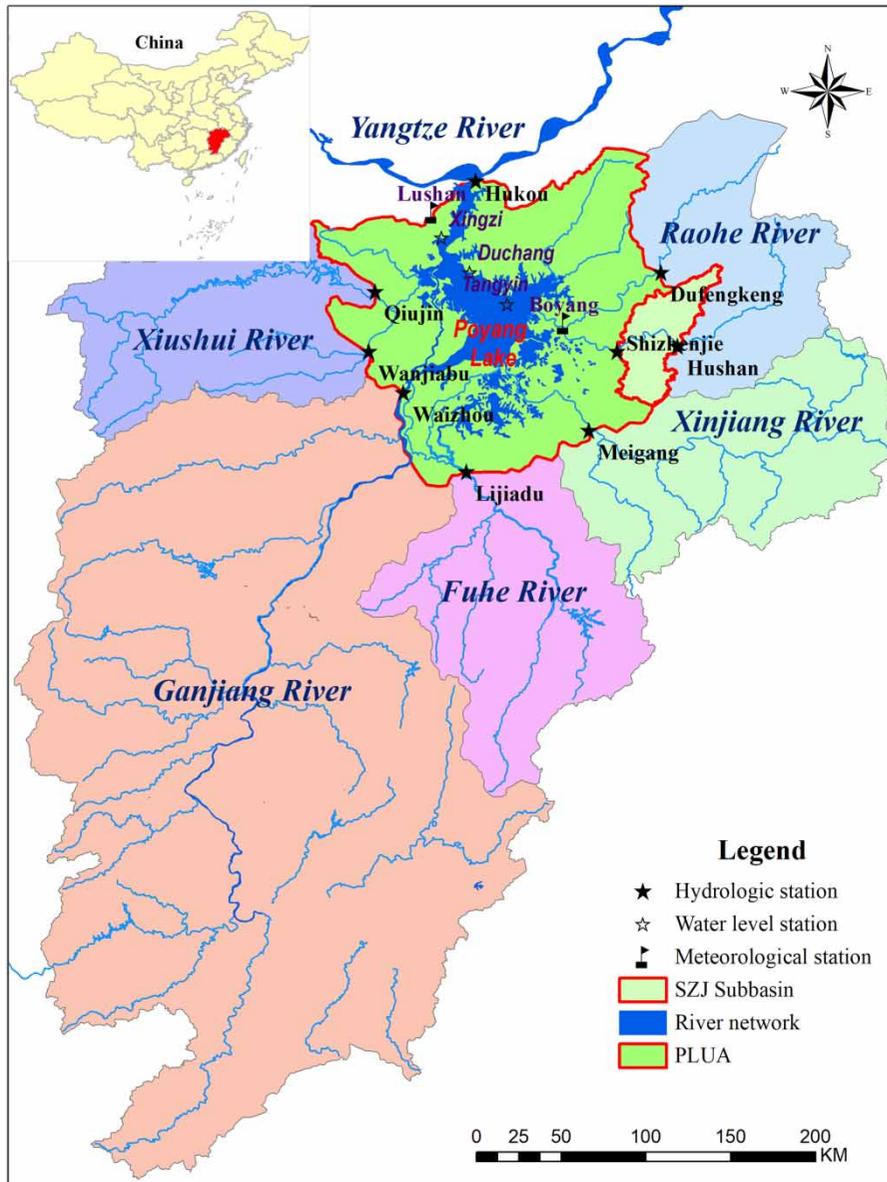
Figure 1 | Study area.

Daily observed weather data at the Lushan and Boyang stations for the period of 1998 to 2013 were downloaded from the China Meteorological Data Sharing Service System (http://cdc.nmic.cn). Both the Lushan and Boyang meteorological stations have an elevation of 1,164 m and 40 m, respectively. The weather data were used to validate both the TRMM and CFSR precipitation. Precipitation at the Lushan station represents weather occurring in a mountainous area while rainfall at the Boyang station represents weather occurring in a flat region around the lake. Daily

water discharge data were collected from hydrological stations for the five rivers. These gauging stations measure discharges for the following rivers: Wanjiabu and Qiujin stations for the Xiushui River; Waizhou station for the Ganjiang River; Lijiadu station for the Fuhe River; Meigang station for the Xinjiang River; and Hushan and Dufengkeng stations for the Raohe River. The monthly discharges at Shizhenjie station, which recorded partially incomplete data, were also collected to validate the model in its subbasin in 2007. Daily water level records were collected at

Xingzi, Duchang, and Tangyin stations in Poyang Lake, which is used to validate the lake hydrodynamic model. Daily water discharge and daily water level records were collected at Hukou gauging station, which is located at the junction of Poyang Lake and the Yangtze River (Figure 1). The water discharges at Hukou station were used to investigate the differences between inflow and outflow of Poyang Lake in magnitude and in time synchrony, while the water levels at Hukou station were applied as open boundary condition of Poyang Lake hydrodynamic model.

Spatial data

Digital elevation model (DEM) data were obtained through the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global DEM (GDEM) with a 30 m resolution from which the percentage of slope was calculated. Land use affects the runoff process on the surface of the land and thus has an important influence on hydrological responses. Hence, a land use map was obtained by unsupervised classification method with maximum likelihood clustering while DEM data using the Landsat TM/ETM+ images with 30 m resolution was acquired for the 2000s. During this period the images acquired, the primary land use types were forest land, paddy field, and farmland (Chen *et al.* 2007) (Figure 2).

METHODS

Water balance equation for Poyang Lake

For a certain period of time, water balance for the PLUA can be described by the following equation:

$$Q_{\text{in}} + \Delta V = Q_{\text{out}} \tag{1}$$

where Q_{in} is the water volume discharging into Poyang Lake from the tributaries around the lake; Q_{out} is the water volume flowing out of Poyang Lake and ΔV represents water volume changes, including ground water exchange, precipitation, and evaporation in the lake, which affect water storage in the lake.

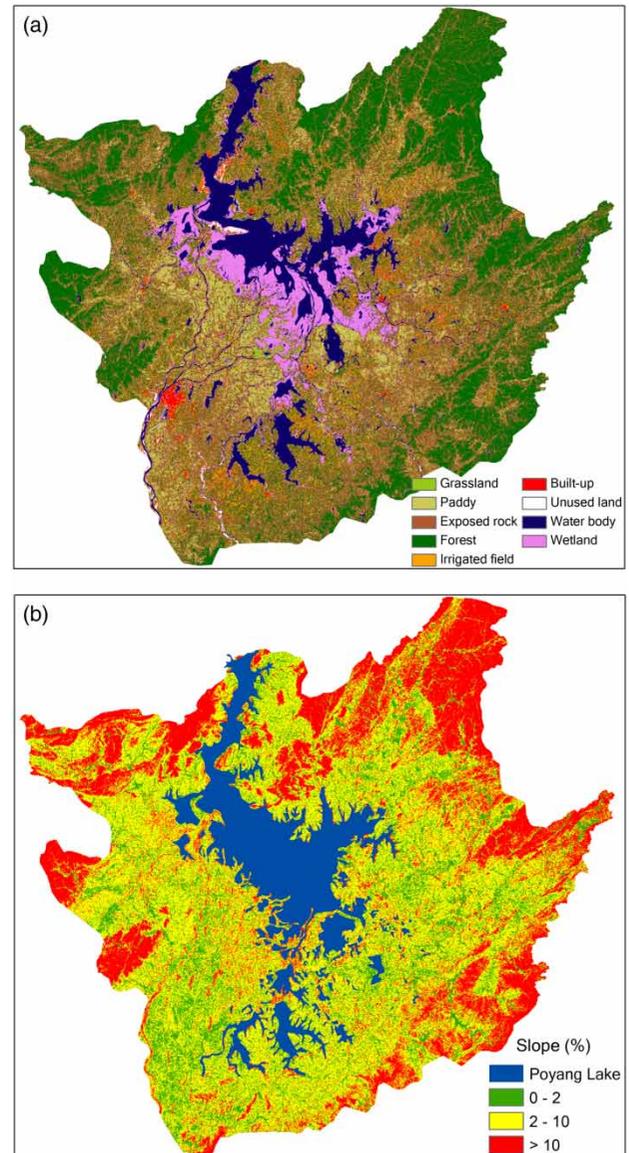The water volume out of Poyang Lake can be expressed by the observed discharge at Hukou gauging station outlet,

Figure 2 | Land use (a) and slope ratio with percentage (b) in PLUA.

while the water volume discharging into Poyang Lake can be described by the total water flow discharging from all five main tributaries (seven gauging stations) and the water yields in the PLUA ungauged area and can be represented as:

$$Q_{\text{out}} = Q_{\text{Hukou}} \tag{2}$$

$$Q_{\text{in}} = Q_{\text{PLUA}} + Q_{\text{Qiujin}} + Q_{\text{Wanjiabu}} + Q_{\text{Waizhou}} + Q_{\text{Lijiadu}} \\ + Q_{\text{Meigang}} + Q_{\text{Hushan}} + Q_{\text{Dufengkeng}} \tag{3}$$

where Q_{Hukou} is observed water discharge out of Poyang Lake at the Hukou gauging station; Q_{Qiujin}, $Q_{Wanjiabu}$, $Q_{Waizhou}$, $Q_{Lijiadu}$, $Q_{Meigang}$, Q_{Hushan}, and $Q_{Dufengkeng}$ are the observed water discharged into the PLUA at Qiujin, Wanjiabu, Waizhou, Lijiadu, Meigang, Hushan, and Dufengkeng gauging stations, respectively, and Q_{PLUA} is the water flow calculated for the PLUA, which is unknown and had to be calculated for this study.

Distributed runoff coefficient model setup

Due to difficulties with delineating river network and subbasins in a plain flooding area, and modeling spatial variability of water production and convergence, as well as groundwater exchange, infiltration, and evapotranspiration, the empirical approaches using runoff coefficient have been often applied in estimating hydrology. The rational method is usually the method most often applied by hydraulic and drainage engineers to estimate discharges for small watersheds. Thus, the rational method (Kuichling 1889) computes the water discharge using the following equation:

$$Q = m \, P \, C \, A \tag{4}$$

where Q is water discharge (m³/s); P is rainfall intensity (mm/h); C is the runoff coefficient (dimensionless) to reflect the ratio of rainfall to surface runoff; A is the drainage area (km²) and m is the dimensional correction factor for unit conversion ($m = 3.6$).

In the equation, the runoff coefficient is the most important factor to estimate water production and convergence for a basin. It is also essential for flood control and the delineation of possible flood zone hazards. A high runoff coefficient value may indicate areas prone to flash flooding during storms as water moves quickly over land towards a river channel. The runoff coefficient can be defined either as the ratio of total depth of runoff to total depth of rainfall or as the ratio of peak rate of runoff to rainfall intensity for the time of concentration. Typical runoff coefficient values represent the integrated effects of many watershed conditions (Dhakal *et al.* 2012). The runoff coefficient is a dimensionless coefficient that represents the amount of runoff to the amount of precipitation received in a basin

(SWRCB 2011). In fact, it represents the interaction of many complex factors, including the storage of water in surface depressions, infiltration, antecedent moisture, ground cover, ground slopes, and soil types. As a result, and in reality, the runoff coefficient may vary with respect to prior wetting and seasonal conditions. The use of average values has been adopted to simplify the determination of this coefficient. The runoff coefficient is often measured by determining the soil type, gradient, permeability, and land use (ODOT 2014). The coefficient has a larger value for areas with low infiltration and high runoff (e.g., pavement and steep gradients) and lower for permeable, well-vegetated areas (e.g., forest and flat land). Therefore, land use, land cover, and slope ratio are the most important factors in determining the runoff coefficient. Considering previous studies (Guo *et al.* 2006; Li *et al.* 2014) of runoff coefficient in Poyang Lake watershed, the runoff coefficient in this study was determined for the heterogeneous underlying surface for the PLUA. The runoff coefficient, shown in Table 1, refers to these properties of runoff convergence under different land uses and slope ratio impacts. The larger values correspond to higher runoff and lower infiltration.

To predict the water flow in the PLUA, we developed a SDRCM based on the slope ratio and land use classifications to compute the water convergence in the area using CFSR and TRMM precipitation data. By overlaying the land use and slope ratio, and setting runoff coefficient values for each pixel, a spatially distributed runoff coefficient map was generated (Figure 3) according to the values listed in Table 1. The runoff coefficients were defined as the ratio

Table 1 | Runoff coefficients selected according to different land uses and slope ratios in the PLUA

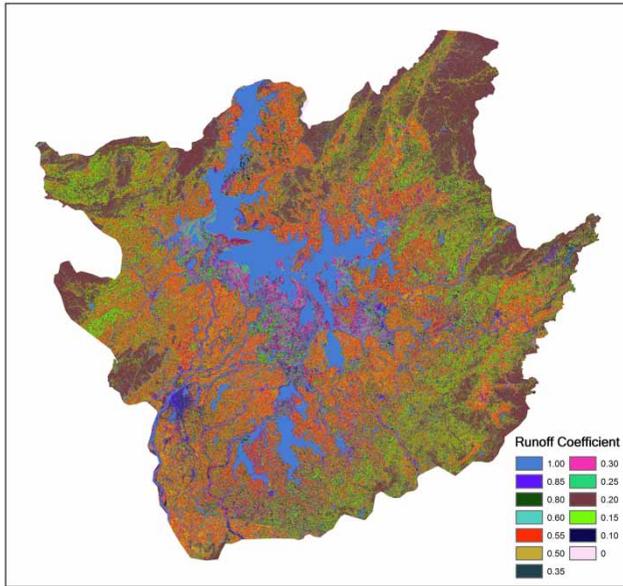| Land use	Flat (slope ≤ 2%)	Rolling (2%–10%)	Hilly (slope >10%)
Grassland	0.1	0.15	0.2
Paddy	0.5	0.55	0.6
Exposed rock	0.85	0.85	0.85
Forest	0.1	0.15	0.2
Irrigated field	0.5	0.55	0.6
Built-up	0.8	0.85	0.85
Unused land	0.1	0.2	0.3
Water body	1	1	1
Wetland	0.25	0.3	0.35

Figure 3 | Spatial distribution pattern of runoff coefficient for the PLUA.

of total depth of runoff to total depth of rainfall in the study. The spatial pattern of runoff coefficient represents the properties of water production and convergence in this alluvial area. As such, the distributed runoff depth can be calculated with the aid of rainfall data based on the distributed runoff coefficient map following Equation (4). In this study, a Kriging interpolation method was applied to obtain the spatially distributed rainfall with spatial resolution of approximately 1 km based on CFSR grids and TRMM points for each month. Meanwhile, the CFSR and TRMM precipitations were clipped by the PLUA boundary. With the spatially distributed runoff coefficient map, the runoff can then be computed based on the distributed precipitation within the PLUA. According to the precipitation data, the distributed runoff depth can be simulated with the same temporal and spatial scale of precipitation, so that we were able to obtain the distributed monthly runoff with 1 km resolution.

Hydrodynamic model setup

In this study, the Delft3D-FLOW numerical modeling system, which has been widely applied in hydrodynamic simulations of lakes, is used to set up the two-dimensional hydrodynamic model of Poyang Lake. This system has

been developed for the modeling of unsteady water flow, temperature, salinity, and cohesive/non-cohesive sediment transport in shallows seas, estuarine and coastal areas, rivers and lakes (WL Delft Hydraulics 2006). Delft3D-FLOW solves the shallow water equations for a given set of initial and boundary conditions in two or three dimensions.

Orthogonal curvilinear model grids were generated under the Cartesian coordinate system based on the water boundary. Model run time extended from January 1, 2001 to December 31, 2011, and the model time step was set as 30 s. The lower open boundary condition was set at the junction between the lake and the Yangtze River at Hukou. In this lake model based on Delft3D, the open boundary type was time-series water levels and the daily water levels measured at Hukou station were prescribed at the grid points along the open boundary. The river flow rates measured at the hydrological stations along the five main rivers were prescribed as the upper inflow boundary condition of the river inlets (Figure 1). Discharges at Qiujin, Wanjiabu, Waizhou, Lijiadu, Meigang, Hushan, and Dufengkeng gauging stations were directly used to drive the hydrodynamic model where the runoff of the ungauged PLUA was not considered first. The current velocities were initialized with zero values. Consequently, the current velocities in the lake from the upper river mouth to the open boundary were calculated in this hydrodynamic model (Zhang *et al.* 2015b). The daily observed series of water levels at Xingzi, Duchang, and Tangyin gauging stations in the lake were used to calibrate and validate the hydrodynamic model.

In order to evaluate the model performance, the following three indices, the root mean square error (RMSE), the correlation coefficient (R^2) and Nash–Sutcliffe efficiency coefficient NSE (E_{NS}), were applied in this study. The RMSE, E_{NS} and R^2 are defined by following equation:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(O_i - S_i)^2}{n}} \tag{5}$$

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{6}$$

$$R^2 = \frac{\left(\sum_{i=1}^{n}(S_i - \bar{S})(O_i - \bar{O})\right)^2}{\sum_{i=1}^{n}(S_i - \bar{S})^2 \sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{7}$$

where Q_i and S_i is observed and simulated data, respectively. $\bar{O}$ and $\bar{S}$ are the mean observed and simulated data and n is the total number of data records. The RMSE indicates a perfect match between observed and predicted values when it equals 0, with increasing RMSE values indicating an increasingly poor match. The RMSE is used to assess the modeling accuracy of hydrodynamic model for the lake in this study. E_{NS} ranges from negative infinity to 1. The optimal value of E_{NS} is 1.0, indicating perfect agreement between observed data and simulated results, while negative values indicate that the average observed value is a better predictor than the simulated value, which is unacceptable performance. R^2 ranges from 0 to 1, with $R^2 = 1$ representing a perfect agreement between observed and simulated stream flow. It can be used to assess how well simulated data fits the measured data.

RESULTS AND DISCUSSION

CFSR and TRMM precipitation validation by data from ground meteorological stations

In order to understand the performance of CFSR and TRMM monthly rainfall, we must assess the accuracy of the CFSR and TRMM precipitation data before applying the model. The CFSR and TRMM rainfall were first extracted according to the locations of the Lushan and Boyang stations (GMS) (Figure 1), then compared to the observed rainfall and extracted precipitation from both sources of data. Figure 4 shows the monthly CFSR and TRMM precipitation validation according to precipitation data for the Lushan and Boyang stations during the period of January 1998 to December 2013. With respect to Figure 4(a) and 4(b), both the CFSR and TRMM precipitation results had a high coefficient of determination, which were larger than 0.68. TRMM- and CFSR-derived rainfall data at Boyang station were more accurate than that of the Lushan station because linear fittings for both CFSR and TRMM precipitation have a much higher correlation coefficient than the Lushan station. This implicitly demonstrated that the CFSR and TRMM precipitation data might have a higher accuracy in areas of plains (e.g., Boyang station) than in mountainous regions (e.g., Lushan station).
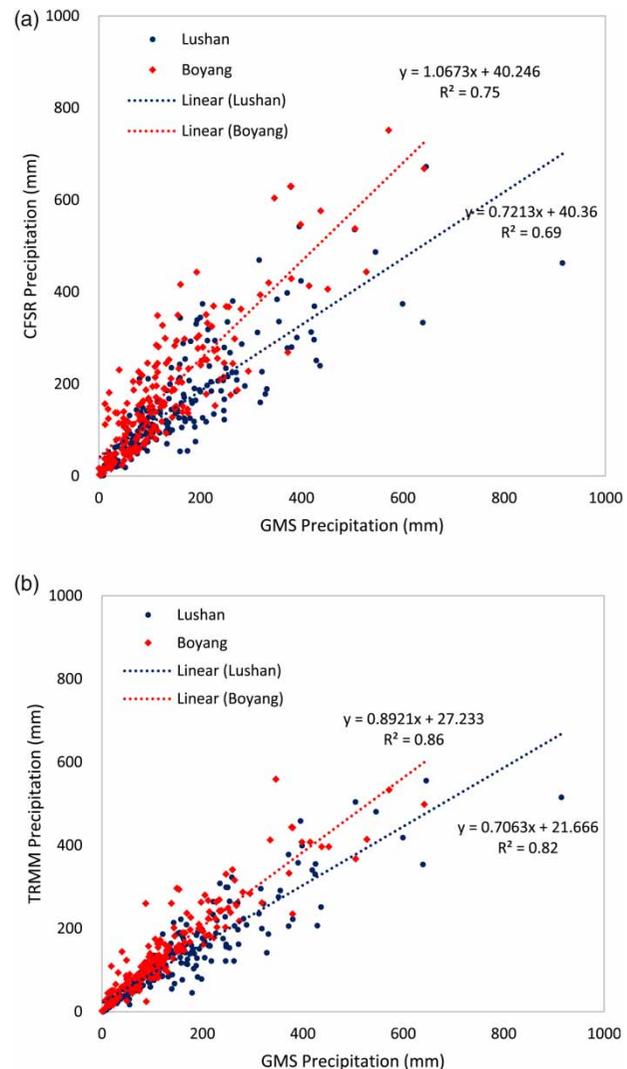

Figure 4 | Monthly CFSR (a) and TRMM (b) precipitation validation using precipitation data from the Lushan and Boyang ground meteorological stations during the period of January 1998 to December 2013 (N = 192).

Additionally, from the coefficient of determination, it illustrated that the TRMM precipitation correlated better than the CFSR precipitation from the linear fittings at both the Lushan and Boyang stations.

The CFSR and TRMM precipitation data are reasonably accurate in representing weather conditions in the study area during the period of January 1998 to December 2013 in the PLUA. This is according to the validation of CFSR and TRMM precipitation with GMS data from two representative meteorological stations. Therefore, both precipitation datasets from CFSR and TRMM are general indicators representing weather conditions occurring in the watershed.

Consequently, it is possible to predict runoff using the CFSR and TRMM precipitation datasets with a hydrological model in the PLUA with the goal of assessing the feasibility of applying CFSR and TRMM data in hydrology prediction within the ungauged area.

Water yield in the PLUA and its validation

Distributed runoff map for PLUA and its validation

With the aid of a spatially distributed runoff coefficient map, we can derive the spatial distributed results of the monthly runoff depth for the PLUA based on CFSR and TRMM precipitation maps during the period of January 1998 to December 2013. Figure 5 shows the distributed spatial pattern of the simulated runoff in the PLUA for April 1999 based on CFSR and TRMM precipitation data.

Based on the distribution pattern of monthly runoff depths shown in Figure 5, a general alignment can be identified with the simulation results based on the CFSR and TRMM precipitation data for April 1999 in the PLUA. The most intensive runoff occurred in the lake and around the lake plain area. At the same time, areas of less runoff were located at the boundary of the PLUA which are well-vegetated, permeable, and feature steep slopes. This clearly illustrates that larger runoff depths are present in areas prone to flooding at the lower reaches of the rivers. Additionally, the spatial pattern of runoff depths reflects the properties of both the quantity of water production and convergence in this ungauged alluvial area. As a result, the PLUA water discharge to the lake can be calculated based on this series of maps showing distributed runoff depths.

In order to assess the accuracy of the simulated results, a small subbasin known as Shizhenjie, lying east of the PLUA, was selected to validate the distributed runoff coefficient model. The Shizhenjie (SZJ) subbasin, shown in Figure 1, is a region located between the Hushan and Shizhenjie gauging stations and is part of the PLUA. Not only is the SJZ subbasin a representative area for the hydrological regime in the PLUA, it is valuable because observed discharge data are available that can be used for validating our model in this ungauged area. In doing so, the differences in observed discharges at the Hushan and Shizhenjie
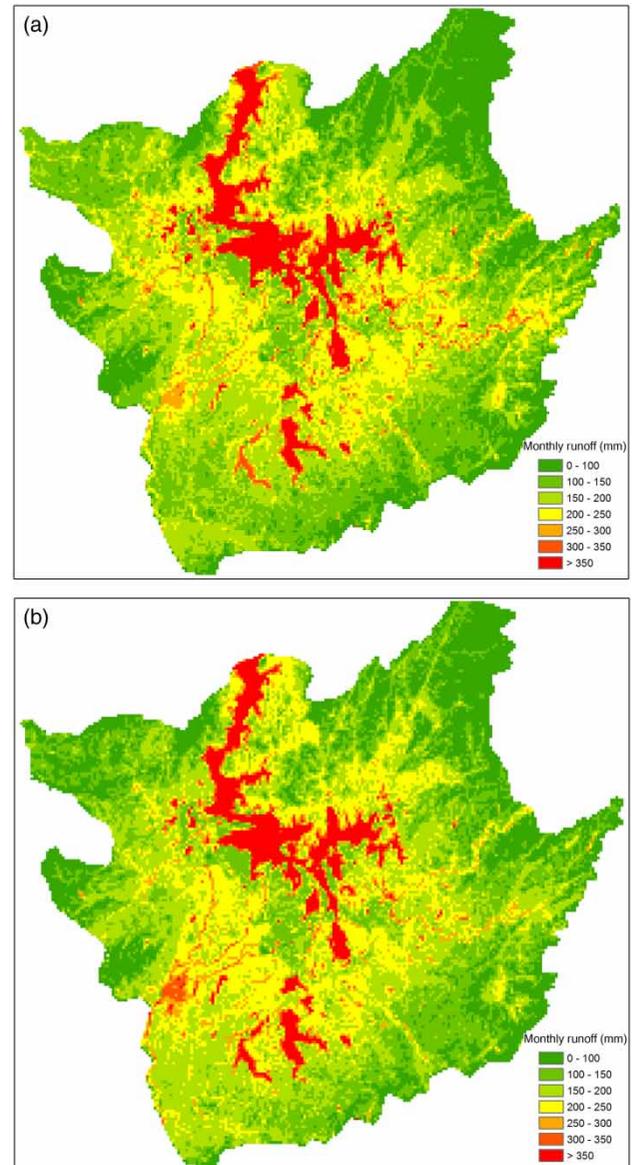

Figure 5 | Spatial distribution pattern of the estimated monthly runoff depth based on CFSR (a) and TRMM (b) precipitation data for April 1999 in the PLUA.

gauging stations were compared with the simulated monthly runoff in the Shizhenjie subbasin. Figure 6 shows the comparison between monthly streamflow simulated with CFSR and TRMM precipitation data and the observed monthly streamflow during 2007 for the SJZ subbasin.

According to the comparison between monthly simulated water yields based on CFSR and TRMM rainfall data and observed streamflow in the SJZ subbasin, both the simulated water yields agreed with the observed data,
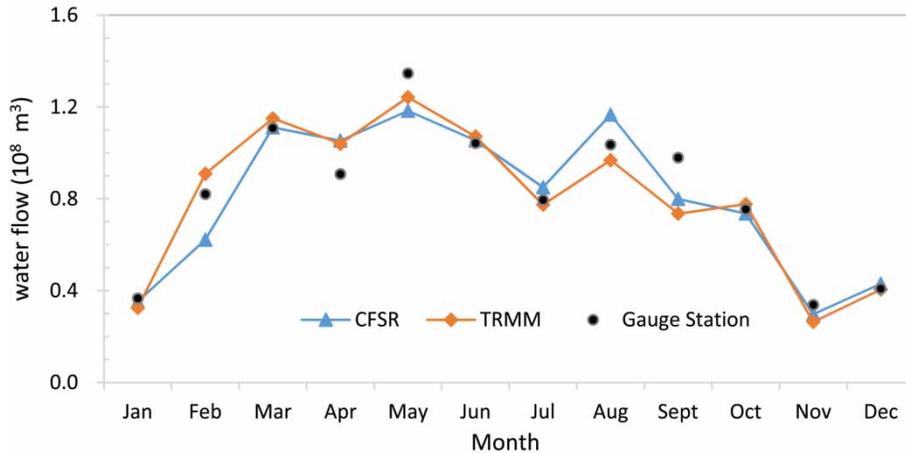
Figure 6 | Monthly streamflow validation simulated with CFSR and TRMM rainfall data using observed discharge differences between the Shizhenjie and Hushan gauging stations in 2007.

because the R^2 and E_{NS} were 0.88 and 0.87 for CFSR results and 0.91 and 0.91 for TRMM results, respectively. Also, the TRMM-driven model results of water yields were better than that of the CFSR-driven model. Compared with the model accuracy in some studies (Huang *et al.* 2011; Guo *et al.* 2011), the SDRCM proposed in our study generated rather comparable or more superior results than previous studies. For the simulated monthly streamflow in the SZJ subbasin, the results were more accurate for January, March, June, October, and December than for February, April, May, August, and September. The higher accuracy happened in the months of dry seasons, and the model tended to predict streamflow more accurately during dry seasons in such areas. The same pattern was found with simulated results using CFSR rainfall data. At any rate, results can be reasonably accepted for the purpose of hydrology prediction in the PLUA.

Water yield for the PLUA based on CFSR and TRMM precipitation for the period 1998 to 2012

After validating results for the SZJ subbasin, the model was applied to the entire PLUA for streamflow prediction. Both sets of CFSR and TRMM precipitation data were used to model water yields in the study area. Accordingly, the monthly streamflow was simulated based on the SDRCM using CFSR and TRMM rainfall data during the period of January 1998 to December 2013 in the PLUA, shown in Figure 7. The results from both sources of data used in the model varied in keeping the same fluctuant pace, and the coefficient of determination R^2 amounted to 0.85 between both results.

According to Figure 7, over 15 years from 1998 to 2013, the most peaks in water yield occurred in June in the PLUA. The highest monthly water yield happened in June
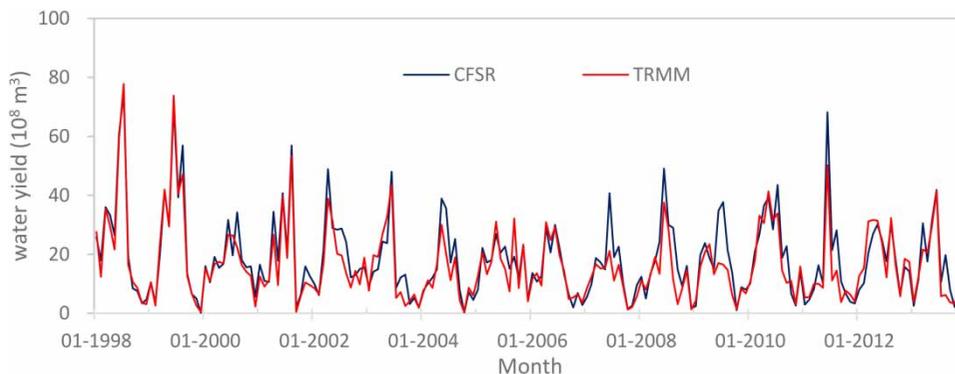

Figure 7 | Monthly runoff hydrographs simulated with CFSR and TRMM precipitation-driven models during the period of January 1998 to December 2013 for the PLUA.

1998 with an amount larger than 70×10^8 m^3, in which abundant rainfall occurred with approximately 550 mm. Hydrometeorology concurs with the fact that one of the greatest flooding records was in the year of 1998. However, the inter-seasonal distribution pattern of precipitation varied significantly, which led to considerable streamflow variance across different seasons. Figure 7 shows that 51% of the total annual rainfall occurred from May to July, while little rain fell during the winter and spring (October to March), which is why the water yields fluctuated significantly across seasons from 1998 to 2013. According to the overall trend, the figure shows that the peak water yield declined from 1998 to 2005 and then increased from 2006 to 2011, after which it reached a much higher peak in June 2011. Afterwards, water yield peaks fluctuated on a stable basis from 2012 to 2013.

Discharge validation by the hydrodynamic model for the PLUA water flow

The study area PLUA is located in the down reaches of the catchment gauging stations, so the observed data at catchment stations cannot validate the model. Only one gauging station with incompletely observed data was included in the PLUA to validate the model in a subbasin. In addition, the lake in the PLUA is able to store and regulate the water volume, and will impact the time of flow to the outlet. Therefore, the observed discharges at Hukou gauging station are not suitable to validate the hydrological model. We took advantage of the hydrodynamic model by combining discharge observed at gauging stations and simulated in the PLUA to indirectly validate PLUA water flow. With the built hydrodynamic model driven by discharges observed at gauging stations (Qiujin, Wanjiabu, Waizhou, Lijiadu, Meigang, Hushan, and Dufengkeng), Figure 8 shows the hydrodynamic model was calibrated and validated during January 1, 2001 to December 31, 2005 and January 1, 2006 to December 31, 2010, respectively. Generally, the hydrodynamic model is capable of satisfactorily simulating the water level dynamic of Poyang Lake following calibration and validation, in which the accuracies were comparable to results from the hydrodynamic model in a previous study (Li *et al.* 2014).

In order to further validate the SDRCM for the PLUA, the hydrodynamic model for Poyang Lake can also be applied indirectly to verify the SDRCM. The results simulated by SCRCM were added or removed as the boundary input component to drive the hydrodynamic model. The SDRCM in PLUA can be implicitly validated by assessing the accuracy of simulated water discharge from the hydrodynamic model. According to the previous results, the TRMM-driven model results of water yields were better than those of the CFSR-driven model. In order to simplify the discussion in this section, we selected the better one (runoff from TRMM-driven model) to be or not be involved as the boundary condition of the hydrodynamic model for Poyang Lake. For this study, the PLUA water runoff that was simulated based on TRMM data was used as part of the boundary conditions used in the hydrodynamic model. The purpose of this was to compare simulated outlet results with and without the PLUA runoff. Figure 9 shows the monthly average discharge measured at Hukou gauging station. The figure compares the simulated results with and without consideration of the PLUA runoff according to the hydrodynamic model.

Compared to the observed monthly discharge at the Hukou gauging station, the simulated water discharge by the hydrodynamic model involving the runoff from TRMM-driven SDRCM in PLUA as boundary input condition was better than the results simulated without involving the PLUA runoff. The figure illustrates this point by showing that the simulated results considering the PLUA runoff are more consistent with the Hukou observed discharge than the results simulated without PLUA runoff consideration. In addition, the R^2 and E_{NS} of the simulation with the PLUA runoff were 0.96 and 0.95, while they were 0.95 and 0.81 for results simulated without the PLUA runoff. The R^2 and E_{NS} of both simulated results further showed that the accuracy of the results simulated with the PLUA runoff was more precise than the simulated results without the PLUA runoff. According to Figure 9, the results simulated with the PLUA runoff are more closely aligned to the monthly peak discharge observed at the Hukou gauging station. As part of driving the boundary condition of the hydrodynamic model, including runoff for the PLUA in the model, makes it more accurate for predicting the rate of discharge. It implicitly reveals that the monthly runoff of PLUA simulated by the SDRCM is reasonably accurate. With validation of the SDRCM by an established hydrodynamic model for Poyang Lake, the importance of monitoring and predicting water yields in the PLUA is demonstrated.
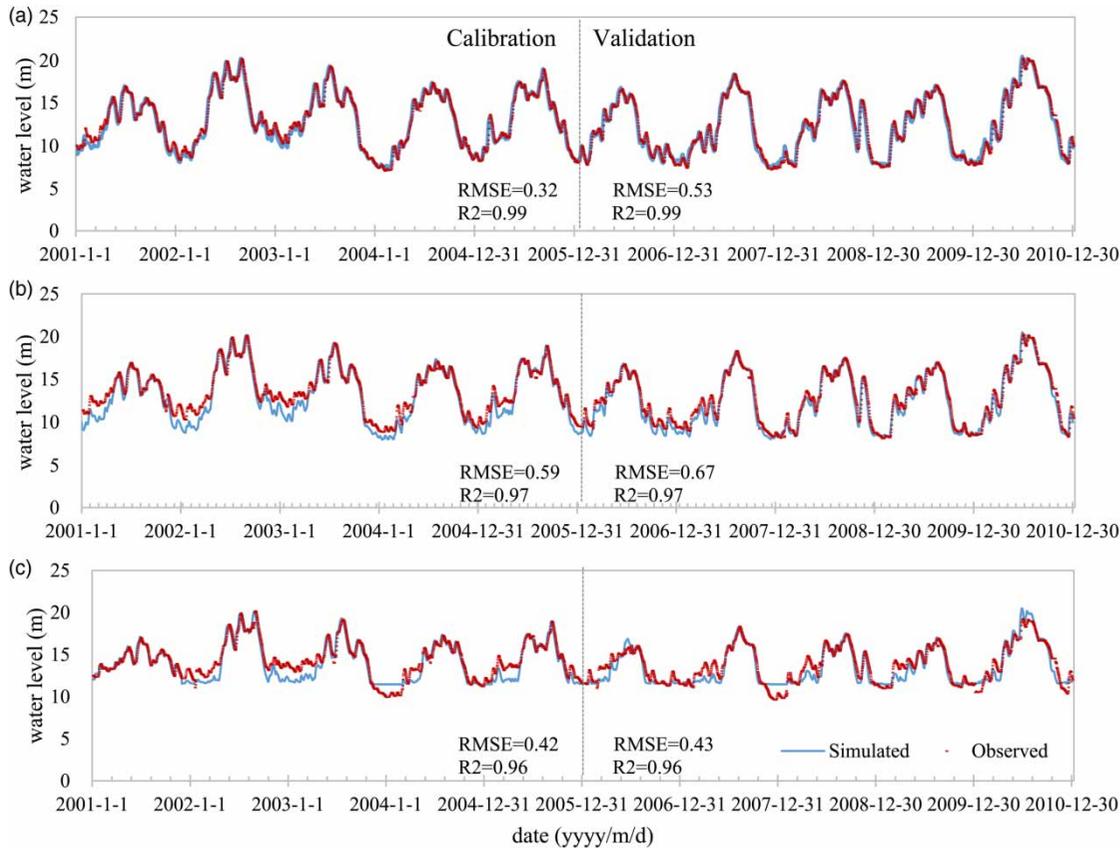
Figure 8 │ Hydrodynamic model calibration and validation for daily water level at (a) Xingzi, (b) Duchang, and (c) Tangyin gauging stations of Poyang Lake.

Water balance of the inflow and outflow of Poyang Lake

Based on the water flow simulation for the PLUA, we can now evaluate the water balance of the inflow and outflow of Poyang Lake. The monthly water yields in the PLUA were simulated by the proposed SDRCM in the previous section. Consequently, the total monthly inflow to Poyang Lake can be calculated from the five tributary basins and the PLUA, which was compared to the observed discharge rate at the Hukou gauging station outlet of the lake.
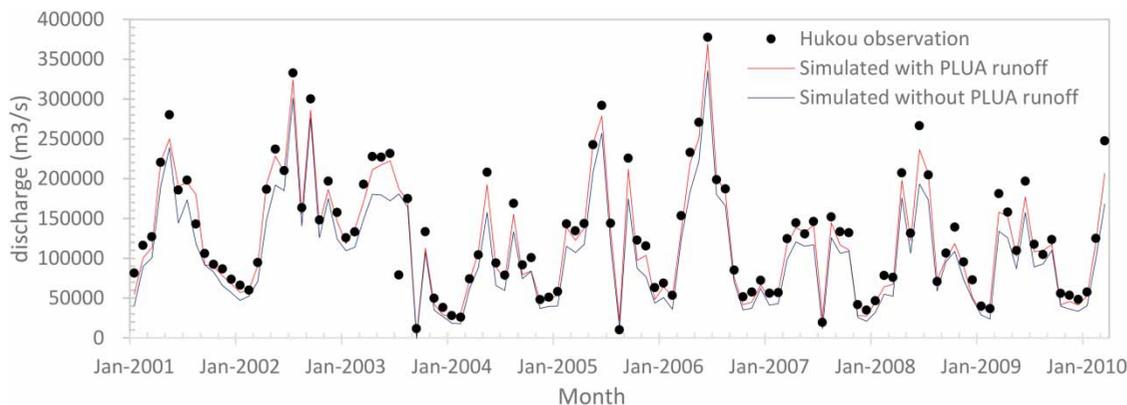

Figure 9 │ Monthly average discharge measured at the Hukou gauging station compared to the simulated results with and without consideration of runoff in the PLUA according to the hydrodynamic model.

Figure 10 shows the monthly inflow and outflow of Poyang Lake from January 1998 to December 2009. The total inflows estimated from both the CFSR and TRMM rainfall data have rather high correlations with the monthly outflow observed at Hukou station. Specfically, the estimates were $R^2 = 0.74$ and 0.75, and $E_{NS} = 0.73$ and 0.73 for CFSR and TRMM rainfall data, respectively. The total water flow simulated with TRMM rainfall data was slightly more accurate than that of the CFSR data. When comparing the evaluation indexes R^2 and E_{NS} between Figure 9 and Figure 10, it shows that the accuracy of the estimated monthly water flow provided in Figure 10 was much lower than that of the hydrodynamic model simulation. This may be due to a water flow time-lag effect from the upstream river to the lake. Indeed, from the gauging station to the lake inlet, a time delay was observed for water flowing into the PLUA, which is a flat plain where water flows slowly. In this case, it is likely that the outlet discharge simulated by the hydrodynamic model was more precise than the monthly total water flow that was simply added together for the five tributaries and the PLUA.

In order to assess the difference between the observed annual net outflow of the lake at Hukou gauging station and the simulated annual water flow into the lake, an experiment was conducted. According to Equation (1), ΔV, the water volume difference between discharging into and flowing out of the lake, represents water volume changes, including ground water exchange, precipitation, and evaporation in the lake, which affect water storage in the lake. Therefore, we investigated whether the observed outflow at Hukou gauging station was equal to the total water flow

from the PLUA and all subbasins including the Xiushui River basin, Ganjiang River basin, Fuhe River basin, and Raohe River basin, so as to assess the annual change of water storage (the ΔV in Equation (1)) for the Poyang Lake. The purpose of the experiment was to discern whether there was a balance between the simulated discharge observed at Hukou gauging station and the simulated water flow according to the proposed model and water balance equation over the period of a year. Table 2 shows the annual inflow and outflow of Poyang Lake and the relative errors of simulated inflow compared to the net outflow of the lake from 1998 to 2009. The water flow in the PLUA accounted for approximately 12% to 19% of the total annual water flow of the Poyang Lake watershed. This was in close alignment with the proportion of the area occupied by the PLUA in relation to the entire Poyang Lake watershed.

As shown in Table 2, all the relative errors of annual inflow and outflow were less than 10% during the period of 1998 to 2009. In addition, the absolute error in most years was less than $200 \times 10^8 \, \text{m}^3$ for the Poyang Lake watershed, except in 1998, when a major flood occurred within the Yangtze River watershed. From the results calculated in the table, it seems that an imbalance exists between estimated and observed annual water flow on an annual scale, which occurred for several reasons. Except for the water flow time lag mentioned previously, another explanation should be considered having to do with the unique characteristics of Hukou gauging station. Due to the frequent water exchange and turbulence between Poyang Lake and Yangtze River as well as many other uncertain reasons, the runoff hydrograph
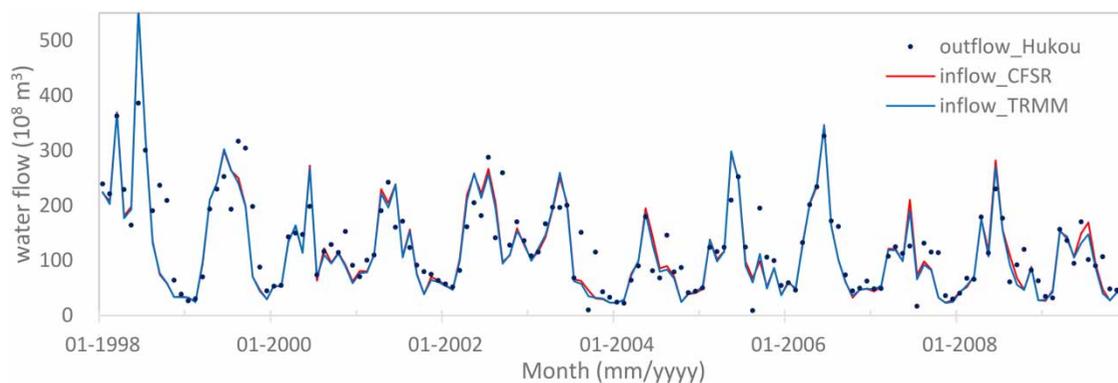

Figure 10 │ Monthly net outflow observed at the Hukou gauging station compared to the estimated total inflow from five tributary subbasins and the ungauged area of Poyang Lake from January 1998 to December 2009.

Table 2 | Annual inflow and outflow of Poyang Lake from 1998 to 2009

Year	F_CFSR/10^8 m^3	F_TRMM/10^8 m^3	FlowGS/10^8 m^3	FIn_CFSR/10^8 m^3	FIn_TRMM/10^8 m^3	FOut_Net/10^8 m^3	RE_CFSR/%	RE_TRMM/%
1998	318.46	306.51	2,076.11	2,394.58	2,382.62	2,640.89	−9.33	−9.78
1999	297.69	292.85	1,462.55	1,760.24	1,755.41	1,947.20	−9.60	−9.85
2000	218.68	198.26	1,122.70	1,341.38	1,320.96	1,423.78	−5.79	−7.22
2001	245.59	207.28	1,210.71	1,456.30	1,417.99	1,478.22	−1.48	−4.07
2002	252.83	207.77	1,615.45	1,868.27	1,823.22	1,860.60	0.41	−2.01
2003	178.72	176.95	1,087.98	1,266.70	1,264.93	1,404.30	−9.80	−9.92
2004	181.78	143.64	732.70	914.48	876.35	927.94	−1.45	−5.56
2005	209.44	204.26	1,178.54	1,387.98	1,382.80	1,464.55	−5.23	−5.58
2006	170.23	174.08	1,306.87	1,477.10	1,480.94	1,563.55	−5.53	−5.28
2007	172.51	134.90	814.55	987.06	949.46	1,012.93	−2.55	−6.27
2008	222.67	169.28	1,015.67	1,238.34	1,184.95	1,292.50	−4.19	−8.32
2009	205.72	148.88	833.33	1,039.05	982.21	1,059.22	−1.90	−7.27

(1) F_CFSR: CFSR-based simulated water flow for the PLUA; (2) F_TRMM: TRMM-based estimated water flow for the PLUA; (3) FlowGS: total water flow observed for five tributaries at seven inlet gauging stations; (4) FIn_CFSR: total annual inflow of Poyang Lake based on CFSR precipitation, FIn_CFSR = F_CFSR + FlowGS; (5) FIn_TRMM: total annual inflow of Poyang Lake watershed based on TRMM precipitation, FIn_TRMM = F_TRMM + FlowGS; (6) FOut_Net: net annual outflow of Poyang Lake observed at Hukou gauging station; (7) RE_CFSR: relative error of CFSR-based total annual inflow compared to the outflow observation at Hukou gauging station, RE_CFSR = (FIn_CFSR- FOut_Net) × 100/FOut_Net; (8) RE_TRMM: relative error of TRMM-based total annual inflow compared to the outflow observation at Hukou gauging station, RE_TRMM = (FIn_TRMM − FOut_Net) × 100/FOut_Net.

at the Hukou outlet control station is unable to be directly used in hydrological model calibration. In particular, the bottomlands around control stations are often submerged when flood occurs; in such cases, water moves through other paths instead of the control sections, leading to a considerable amount of water that cannot be measured (Guo *et al.* 2011). The runoff hydrograph at the Hukou outlet is not measured precisely by the Hukou gauging station. Specifically, areas located near the Hukou gauging station are often inundated with water during floods. During these events, water flows along other paths instead of through the gauging sections, resulting in a large amount of water that is not measured (Guo *et al.* 2011). What is more, at times, water will flow in reverse to Poyang Lake at its outlet to the Yangtze River. Therefore, the hydrological records at Hukou gauging station might only be a general representation of the real hydrological regime that exists between Poyang Lake and the Yangtze River. Consequently, hydrologists will only be able to discern a regular pattern for the hydrology regime between Poyang Lake and Yangtze River if the differences in the net water flows out of the watershed were evaluated according to both the model estimation and direct observation at Hukou gauging station.

CONCLUSIONS

While Poyang Lake is an essential regulator of hydrology and climate for the Yangtze River watershed, little has been determined previously regarding the hydrological regime of the ungauged area around the lake. Using the PLUA as a representation, a spatially distributed runoff coefficient model (SDRCM) was developed based on the land use and slope ratio in this area. The results, derived from both sets of gridded precipitation data during 1998 to 2013, showed the proposed model had rather high efficiency and accuracy to predict runoff in ungauged areas. This study presented an established hydrodynamic model for river outlets water Poyang Lake that was applied by using the simulated water yields and observed discharges at gauging stations as boundary conditions, so as to validate the simulated results from the proposed SDRCM in the PLUA. This method, integrating a hydrodynamic model of river outlet water to validate hydrologic results can be widely used for the ungauged area that is located downstream of gauging stations to the river outlets. The water flow in the PLUA based on both gridded CFSR and TRMM precipitation data, accounted for 12%–19% of the total annual water flow

of the Poyang Lake watershed, which was approximately equal to the proportion of the area for the PLUA in relation to the entire Poyang Lake watershed. At an annual scale, all the relative errors between inflow and outflow were less than 10% during the period of 1998 to 2009.

However, although inconsistencies were found between the simulated and observed water flow, the results were considered reasonable for studying the hydrology of the ungauged area. As reasons for these anomalies, the impoundment of the Poyang Lake leads to a time lag for the water retention in the lake and that unique characteristics of the Hukou gauging station also play an important role, which make it necessary to develop a hydrodynamic method for validation of hydrological prediction in this little-understood area. Therefore, with the aid of reanalysis and remotely sensed gridded data, the proposed SDRCM in this study is able to quickly predict and simulate hydrology to a reasonable extent for this data-scarce area. It is a robust tool for studying water balance of inflow and outflow of the lake as it relates to flooding in the Poyang Lake watershed.

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