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Stream flow simulation and verification in ungauged zones by coupling hydrological and hydrodynamic models: a case study of the Poyang Lake ungauged zone

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Abstract. To solve the problem of estimating and verifying stream flows without direct observation data; we extend existing techniques for estimating stream flows in ungauged zones, coupling a hydrological model with a hydrodynamic model, using the Poyang Lake basin as a test case. We simulated stream flows in the land covered area of the ungauged zone by building a SWAT model for the entire catchment area covering gauged stations and the land covered area; then estimated stream flows in the water covered area of the ungauged zone using the simplified water balance equation. To verify the results, we built two scenarios (original and adjusted scenarios) using the Delft3D model. In this study, the original scenario did not take stream flows in the ungauged zone into consideration, unlike the adjusted scenario that accounts for the ungauged zones. Experimental results show there was a narrower discrepancy between the stream flows observed at the outlet of the lake and the simulated stream flows in adjusted scenario. Using our technique, we estimated that the ungauged zone of Poyang Lake produces stream flows of approximately 180 billion m^3; representing about 11.4% of the total inflow from the entire watershed. We also analysed the impact of the stream flows in ungauged zone on the water balance between inflow and outflow of the lake. These results, incorporating the estimated stream flow in ungauged zone, significantly improved the water balance as indicated by R^2 with higher value and percent bias with lower value, as compared to the results when the stream flows in the ungauged zone were not taken into account, R^2 with lower value and percent bias with higher value. The method can be extended to other lake, river, or ocean basins where observation data is unavailable.

1 Introduction

In recent years, floods and droughts have occurred frequently (Cai et al., 2015;Tanoue et al., 2016), threatening lives and health, reducing crop yield and hindering economic development (Lesk et al., 2016;Smith et al., 2014). If we know the water yield of watersheds, we can predict and prevent droughts and floods. Therefore, it is necessary to fully understand the water yield of watersheds, in order to reduce the damage of floods and droughts to the population, agriculture and economy. However, in watersheds there is an ungauged zone lacking stream flow observations. Hydrological model is used to estimate water yields; and stream flow observations are used to calibrate the model and verify the estimation results. Therefore, lacking stream flow observations usually makes ungauged zones neglected in water yield estimation.

These ungauged zones is an area of interest in Ungauged Basins (Sivapalan et al., 2003). Ungauged zones, stretch from the most downstream boundary of a gauged basin to the lower boundary of an adjacent water body, existing in river, lake and ocean catchments. An ungauged zone usually occupies a large proportion of an entire watershed (Dessie et al., 2015;Li et al., 2014); thus, the neglect of ungauged zones adds uncertainty in models for water yield estimation. Therefore, stream flow simulations in ungauged zones are necessary to reduce uncertainty in accurate and reliable predictions of water yields and droughts-floods.

The simulation of stream flows in stream flow ungauged zones is one area of interest in the Prediction in Ungauged Basins (PUB) research program (Hrachowitz et al., 2013;Sivapalan et al., 2003). In the PUB research program, data acquisition techniques (Hilgersom and Luxemburg, 2012), and experimental studies (McMillan et al., 2012;Ali et al., 2012), advanced models and strategies (Harman, 2008), and new hydrological theory (Kleidon et al., 2013) have been developed to improve hydrological prediction results in prediction in the ungauged area. These advanced methods aid in stream flow simulations of ungauged zones.

In the PUB research, methods for stream flow prediction in stream flow ungauged zones focus on simple water balance equations and hydrological information transformation (Dessie et al., 2015;Song et al., 2015). For the simple water balance equations, there are no parameters to be calibrated. Feng et al. (2013) defined stream flow as the difference between precipitation and evapotranspiration. SMEC (2008) determined the stream flow of the ungauged zone based on a lake water balance equation, using measured lake water levels and inflow discharges from the upstream gauged catchment. This method is too rough for stream flow simulation. For some hydrological models, we need to calibrate the hydrological parameters. The researchers calibrated the parameters in the gauged areas similar to the ungauged areas. Then transform the parameters from gauged to ungauged areas. Wale et al. (2009) constructed a reginal model of the relationship between the hydrological model parameters and the catchment characteristics. Based on this reginal model, the hydrological parameters in the gauged area were transformed to the ungauged zone for stream flow simulations. However, these researches rarely take verification into consideration.

Verification of stream flow simulations in ungauged zones is however, the focus in some studies. Wang et al. (2007) computed stream flow in an ungauged zone by classifying the underlying surface. The stream flow of each type of surface was calculated based on the corresponding surface characteristics. Wang verified the prediction results by comparing the simulated and observed lake water level. The verification in Ma's study was based on the water balance of yearly inflow and outflow of the lake. These verification methods were coarse. Dessie et al. (2015) simulated stream flows in ungauged zones using a rainfall-runoff model and runoff coefficient. Dessie analyse the effect of the ungauged zone on water balance of the lake, which was indirectly verified for the hydrological prediction of the ungauged zones. However, the water balance of inflow and outflow is too rough to represent the hydrodynamic characteristics of the lake. Verification in these studies was indirect or too coarse for accurate and precise prediction results.

An approach coupling hydrology and hydrodynamics could be used to solve the verification problem. Usually, there are stream flow observation at the lower boundary of the ungauged zone. The observation can be used to verify the stream flow simulation of the whole watershed and furtherly verify stream flow simulation of the ungauged zone, by building hydrodynamic model for water covered area of the ungauged zone. The coupling of hydrology and hydrodynamic models is widely used to represent the catchment-water system and the interaction between catchments and water bodies. Inoue et al. (2008) combined hydrology and hydrodynamic models to simulate the hydrological cycle and hydrodynamic characteristics in a coastal wetland of the Mississippi River delta, and with effective model performance when predicting stream flows. Dargahi and Setegn (2011) combined a watershed hydrological (SWAT) model with a 3D hydrodynamic model (GEMSS) to simulate the Tana Lake

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Basin that addressed the impact of climate change. Bellos and Tsakiris (2016) combined a hydrological and hydrodynamic techniques for flood simulation in Halandri catchment. However, in the researches there is no clear and specific method of coupling hydrological and hydrodynamic models in space and time. Extending the existing research, the method of coupling hydrology and hydrodynamic models in space and time are presented in detail in the study.

The Poyang Lake Ungauged Zone (PLUZ), is a typical example of ungauged zones. There are stream flows observations at the outlet of the entire watershed. The stream flow from the PLUZ is usually estimated as the difference of the observed stream flow from upstream stations and that at the outlet of the lake. However, the observation at the outlet of the lake can not respond to the variation of the watershed hydrology in time and accurately, due to the function of water storage and flood regulation in the lake, which makes the stream flow peak clipped and time-lagged. This method is coarse for stream flow simulation in the PLUZ.

Attempts has been made for accurate and precise stream flow simulation results in the PLUZ. Huang et al. (2011) developed a runoff-fluex model especially for the plain area of the PLUZ. The simulation results were verified by comparing the outflow observation at Hukou with the summation of simulated streamflow in the PLUZ and the measured streamflow of the gauged upstream, on the yearly scale. The time scale of the verification was coarse; water storage and flood regulation function of the lake were not taken into consideration. Guo et al. (2011) simulated the daily runoff of the PLUZ by Variable Infiltration Capacity (VIC) and multiple-input single-out put system (MSIO) models. The verification was performed by comparing the simulated with the estimated results. However, the estimated result was derived from the time-lag equation, so it could not replace the observed value exactly, for the two reasons. The time-lag equation was a simple hydrodynamic model for the lake, which is not very accurate. In the equation, the streamflow at Hukou was adjusted by a modified coefficient at the annual scale, which is not reasonable to be applied in daily scale. Most recently, Li et al. (2014) combined the hydrological model (WATLAC) and hydrodynamic model (MIKE), where the streamflow in the ungauged area, was roughly calculated by the runoff coefficient method. However, the ungauged area did not take the water covered area into consideration. Further, there was no verification. In summary, there have has been no study including effective verification of stream flow simulation results for the PLUZ.

The object of this study was to solve the verification problem in stream flow simulation in the PLUZ by combining hydrological and hydrodynamic models. The stream flow simulation of the land covered area in the ungauged zone was conducted by building a SWAT model for the whole catchment covering the gauging stations and the land covered area; while the stream flow in the water covered area of the PLUZ was calculated by a simplified water balance equation. We established two lake hydrodynamic model (Delft3D) was established to further verify the streamflow simulation results. The hydrological and hydrodynamic models were coupled in both space and time. We estimated that the ungauged zone of Poyang Lake produces stream flows of approximately 180 billion m^3; representing about 11.4% of the total inflow from the entire watershed. The impacts of stream flows in the PLUZ on the water balance of the catchment-lake system were analysed; and the importance of ungauged zones in hydrological prediction for the whole watershed were verified.

2 Study area and data

2.1 Study area

Poyang Lake is the largest freshwater lake in China, connected with the Yangtze River in the north of Jiangxi province. The catchment is covered by the five major river sub-catchments and the ungauged zone shown in Fig. 1.

As shown in Fig. 1a, stream flow produced by the five major river catchments are measured by the seven stream flow stations. The PLUZ is a plain area and stretches from the stream flow gauging stations to the outlet of the lake. The PLUZ covers an area of 19,867 km^2, and amounts to 12% area of the lake catchment. The stream flow from the sub-catchments and the PLUZ discharges into the lake; then this water flows into Yangtze River at Hukou.

As shown in Fig. 1b, the lake received water from the gauged area (the five major river catchments) and the PLUZ. The lake topography varies from upstream hills at an elevation of approximately 2,100 m to downstream plain areas at an elevation of almost 35 m above sea level. The topography of the land covered area in the PLUZ is flat, with slope at less than five degrees. The Poyang Lake basin with an area of 162,000 km^2 has a subtropical wet climate characterized by a mean annual precipitation of 1680 mm and annual average temperature of 17.5℃.

2.2 Data

We provide data for SWAT and Delft3D models. Data required by the SWAT model include the forcing elements of daily rainfall and potential evapotranspiration for 1980 to 2014 collected at 16 national meteorological stations, distributed uniformly across the area (Fig. 1a), this data were downloaded from the hydrological information website of Jiangxi (http://www.jxsw.cn/). The digital elevation model (DEM) of the catchment origins from SRTM (Shuttle Radar Topography Mission) in 2000. The land-use data was obtained from Landsat TM and ETM+ images in 2000 (Chen el at. 2007). Land-use was categorized into forest (54%), farmland (25%), pasture (10%), water bodies (5%), bare land (3%), urbanization (2%), and wetland (1%). The soil data is generated from HWSD (FAO, 1995). The soil have the following catchment-aggregated proportions: Haplic Acrisols (55%), Cumulic Anthrosols (22%), Humic Acrisols (11%), Haplic Alisols (3%), Haplic Luvisols (2%), others (7%). The long time series daily/monthly discharges at seven gauging stations (Qiujin, Wanjiabu, Waizhou, Lijiadu, Meigang, Dufengkeng, Hushan) from 2000 to 2011 were get from the web of hydrological information in Jiangxi. Data required by Delft3D Model included shoreline of lake, topographic data and hydrological observation. The shoreline were delineated based on the remote sensing image of Poyang Lake during the flood period in 1998, which is the maximum area of the lake surface. The topographic data is measured by the Changjiang Water Resources Commission of China (http://www.cjw.gov.cn). The long time series observation for water level at stations of Xingzi, Duchang and Kangshan, and outflow discharges at Hukou from 2000 to 2011 were got from Web of hydrological information in Jiangxi.

3 Methodology

To solve the problem of estimating and verifying stream flows without direct observation data; we extend existing techniques for estimating stream flows in catchment-water systems, coupling a hydrological model with a hydrodynamic model using the Poyang Lake basin as a test case. We simulated stream flows in the land covered area of the ungagged zone by building a SWAT model for the entire catchment area covering the seven gauged stations and the land covered area; then estimated stream flows in the water covered area of the ungauged zone using the simplified water balance equation. To verify the results, we built two scenarios representing the original and adjusted stream flows sing the Delft3D model. In this study, the original scenario did not take stream flows in the ungauged zone into consideration, unlike the adjusted scenario that includes a hydrodynamic model that accounts for the ungauged zones.

3.1 Hydrology modelling

We used SWAT model to simulated stream flows in the land covered area of the PLUZ and a simple water balance equation to simulated stream flows in the water covered area of the PLUZ.

The stream flow simulation in the land covered area of the PLUZ was performed by building a SWAT model for the entire catchment area including gauged stations and the land covered area. SWAT (Soil and Water Assessment Tool) (Arnold et al., 1993) was physically-based and semi-distributed hydrological model. It has already been applied to watersheds widely in the world for stream flow simulation (Douglas-Mankin et al., 2010;Arnold et al., 2012;Luo et al., 2016).

A SWAT model used for prediction must be calibrated and validated by the measured data. The land covered area of the PLUZ is ungauged for stream flow while there are streamflow gauging station at the upstream boundary of the PLUZ. So we can establish a SWAT model for a larger catchment. The large catchment excludes the land covered area of the PLUZ, the gauging station and the gauged area to calculate streamflow in the PLUZ indirectly. We use the long time series monthly discharges at six gauging stations (Wanjiabu, Waizhou, Lijiadu, Meigang, Dufengkeng, Hushan) to perform the calibration from 2000 to 2005 and validation from 2006 to 2011. The performance indexes is determination coefficient (R^2), efficiency coefficient (Ens), and percent bias (PBIAS).

Since runoff produced by the water covered area was not taken into consideration by the hydrodynamic model (Delft3D), we calculated the stream flow by a simple water balance equation. The stream flow produced by water covered area of the PLUZ (Q'_{uw}) was assumed as the difference of the precipitation and the evapotranspiration in the lake area. The methodology is based on the assumptions that the ground water were ignored. Q'_{uw} was calculated by the following formula:

$$Q'_{uw} = P - E \qquad (1)$$

Where P is the precipitation and E represents the evapotranspiration in the water area. Long time series precipitation and evapotranspiration data was derived from the nearby meteorological station to the lake—Boyang station.

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3.2 Hydrodynamics modelling

To verify the streamflow simulation results in the PLUZ, we use Delft3D to build the hydrodynamic model for the lake. Delft3D-FLOW (Roelvink and van Banning, 1994) was used to simulate the hydrodynamic pattern of the lake. It has ability to simulate water–level variations and flows on surface water bodies in response to forcing elements of inflow discharges and climate factors, which has been proven by application on many surface water bodies around the world. Delft3D is considered appropriate for the wide and shallow characteristics of Poyang Lake. In the model, the shoreline of lake were delineated as the maximum area of the lake surface to make sure that the dynamic changes in the lake's water surface area did not surpass the inundation area. To better capture the rapid dynamic of inundation area and minimize the computing effort, the size of the model grids ranged from 200m to 300 m. The topographic data was interpolated into each computational node of the model grids. The water level was initialized as the mean of the three hydrological stations in Poyang Lake on 1 January, 2001, which are Xingzi, Duchang and Kangshan. The corresponding velocities were initialized as zero. The lower open boundary was the observed long time series daily water level at Hukou station. The model run from January 1, 2001 to December 31, 2010 and the time steps was set as five minutes in order to meet the Courant-Friedrich-Levy criteria for a stable condition. The long time series observed data for water level at Xingzi, Duchang, Tangying, Kangshan and Longkou gauging stations, and outflow discharges at Hukou gauging station, were used for calibration from 2001 to 2005 and validation from 2006 to 2010.

Two Scenarios was established, the adjusted scenario (Adjusted Scenario) and the original scenario (Original Scenario). In this study, Original Scenario did not take stream flows in the ungauged zone into consideration, unlike Adjusted Scenario that accounts for the ungauged zones. In Original Scenario, the upper boundary was the long time series observed daily discharges at the seven gauging stations, in which the streamflow produced by the PLUZ is ignored. There are 9 inflow points—d_1, d_2, d_3, d_4, d_5, d_6, d_7, d_8, d_9 located at the upper boundary of the lake, representing the upper boundary condition for the lake model (Fig. 1b). The inflow into d_1, d_6, d_8 and d_9 points comes from Xiushui River, Fuhe River, one of Raohe River tributaries, the other one of Raohe River tributaries, respectively. The inflow into d_6, d_8, d_9 and d_1 were set as the observed streamflow at Lijiadu station, Meigang station, Hushan station, Dufengkeng station, the sum from Wanjiabu and Qiujin, respectively. The inflow into d_2, d_3, d_4 *and* d_5, which come from Gangjiang River, is set as 50%, 10%, 20%, 20% of the total observed stream flow at Waizhou station. In Adjusted Scenario, the upper boundary was the summation of the total measured discharge at seven gauging stations and the simulated streamflow in the PLUZ. It will be discussed in the next section.

3.3 Models coupling

The upper boundary condition of the hydrodynamic model in Adjusted Scenario are the summation streamflow from the hillslopes and the PLUZ. The PLUZ includes the land covered area and the water covered area. The streamflow from the hillslopes are represented by the summation observed streamflow of the seven gauging stations. The streamflow from the land covered area in the PLUZ are simulated result by the SWAT model; the streamflow from the water covered area in the PLUZ are estimated by a simplified water balanced equation. In order to determine the upper boundary condition in Adjusted Scenario, we couples the hydrological model and hydrodynamic model in space and time.

To make sure the hydrological model and hydrodynamic model was coupled perfectly, the sub-basins delineation and outlets of each sub-basin definition should satisfy the following constraints. The five major rivers must be delineated flowing from the five sub-catchments (the gauged basins), through the land area of the PLUZ, into the lake at last. The seven gauging stations were set as the outlets of the gauged basins and the inlets of the land covered basin of the PLUZ. The outlets of the land covered basin in the PLUZ must be completely coincided with the inflow points of hydrodynamic model for the lake. The stream flows in the inflow points is the upper boundary of Poyang Lake. The most downstream boundary of the gauged basins and the most upstream boundary of the PLUZ land area basin should be coincided with each other; the most downstream of the PLUZ land area basin and the boundary of the lake are coincided with each other too. Only in this way can the catchment hydrological model be seamless coupled with the lake hydrodynamic model in space.

In this study, the land covered area of the PLUZ was divided to 15 sub-basins (b_1, b_2...b_i...b_{14}), and the ungauged area was divided to 25 sub-basins (b_{15}, b_{16}...b_i...b_{39}). Consequently, 11 outlets of the whole catchment were produced, coinciding with the inflow points—d_1, d_2, d_3, d_4, d_5, d_6, d_7, d_8, d_9, d_{10}, d_{11}. The inflow at the 11 points are the upper boundary in Adjusted Scenario.

In order to calculate the stream flow discharging into each inflow point of the lake, the sub-basins were sorted to 11 groups ($group_1$, $group_2$, $group_3$...$group_i$...$group_{11}$) according to the inflow point (d_1, d_2, d_3...d_i...d_{11}). The sub-basins, of which the stream flow flows into the same inflow point (d_i) at last, are divided into the same group ($group_i$). The gauging station were divided into the same group, as the sub-basins it measures are in. Wanjibu and Qiujing, Waizhou, Lijiadu, Meigang, Hushan, Dufengkeng are in $group_1$, $group_2$, $grourp_6$, $group_7$, $group_8$, $group_9$. The group number and the inflow point number are one-to-one corresponded to each other.

The inflow at point di is the total stream flow produced by the sub-basins in $group_i$, including stream flow produced by the sub-basins in land covered area and water covered of the PLUZ, and the gauged area. The streamflow from the sub-basins in the gauged area was represented by the observed stream flows at the gauging stations in $group_i$. For example, the streamflow produced by the sub-basins flowing into d_1 is the sub-basins of b_{16} and b_{18}. The stream flow flowing into d_1 was presented by the total observed outflow of Qiujing and Wanjiabu gauging stations (Fig. 2). Specially, in the model, 50%, 30%, 10%, 10% of the streamflow from sub-basins in Ganjiang Basin was set as inflows of points d_4, d_5, d_6 and d_7 respectively.

For model coupling in time, the calibration and validation of the SWAT model is conducted at monthly scale. However, the upper boundary conditions of the hydrodynamic model are the daily discharge. The same parameters from the SWAT model were used to perform the streamflow prediction at daily scale.

The daily streamflow produced by the land covered area of the the PLUZ (Q_{ul}), contributing to the lake at the inflow point di, is calculated as the difference between the simulated outflows at the outlets of the whole catchment and outflows at the outlets of the hillslopes. It was calculated by the following formula:

$$Q_{\mathrm{ul}} = Q_{\mathrm{whole\_out}} - Q_{\mathrm{hp\_out}} \tag{2}$$

Where, $Q_{\mathrm{whole\_out}}$ is the simulated outflows at point di, and $Q_{\mathrm{hp\_out}}$ is the total simulated outflows at the gauging station points in $group_i$.

For daily streamflow simulation in the water covered area of the PLUZ, the calculated streamflow was separated to different parts, allocated to the corresponding inflow points. As the lake area is small and almost in the same elevation, the precipitation and evapotranspiration could be considered distributed uniformly in space. So the runoff in the water covered area was divide into 11 parts equally. The streamflow (Q_{uw}) produced by the lake area contributing to the inflow point di is calculated by the following formula:

$$Q_{uw} = (P-E)/n \quad (3)$$

Where P is the daily precipitation, E represents the daily evapotranspiration in the lake, *n*, the total number of inflow points of the lake in lake hydrodynamic model Adjusted Scenario (Fig. 2), equals 11. Long time series precipitation and evapotranspiration data was derived from the nearest meteorological station to the lake, Boyang Station.

The total daily inflow (Q_{total}) contributing to the lake at the inflow point (d_i) produced by the whole watershed is the summation daily streamflow from the hillslopes (Q_{hp_obs}), the land covered area in the PLUZ (Q_{ul}) and water covered area in the PLUZ (Q_{uw}), the sub-basins of which are in $group_i$. Q_{total} is calculated by following formula:

$$Q_{total} = Q_{ul} + Q_{uw} + Q_{hp\_obs} \quad (4)$$

Where, Q_{hp_obs}, the daily streamflow from the hillslopes. It is calculated as the summation daily observed streamflow of the gauging stations in $group_i$. Specially, daily streamflow from the hillslopes contribute to the lake at inflow points d_4, d_5, d_6, d_7 are defined as 50%, 30%, 10%, 10% of the streamflow from sub-basins in Ganjiang sub-catchment, respectively.

The total simulated streamflow produced by the land covered area of the PLUZ (Q'_{ul}) was calculated by subtracting the total streamflow of the hillslopes from the whole catchment. Q'_{ul} is the summation of Q_{ul} at each inflow point. The total daily simulated streamflow produced by the PLUZ (Q'_{ul}) is the summation of streamflow produced the land covered area of the PLUZ (Q'_{ul}) and that produced the water covered area of the PLUZ (Q'_{uw}).

4 Results and discussion

4. 1 Calibration and validation of SWAT model and Delft3D model

In order to adjust the models to be applied in the Poyang Lake Basin availably, we undertake calibration and validation for the SWAT model and the Delft3D model. Table 1 and Fig. 3 shows the calibration and validation result for the SWAT model. The observations and simulations at the six gauging stations (Wanjiabu, Waizhou, Lijiadu, Meigang, Hushan and Dufengkeng,) comes to a satisfactory agreement with R^2 or Ens larger than 0.70 and the absolute value of PBIAS less than 20%, except Wanjiabu Station. The agreement are fourthly supported by the highly consistence between the observation and simulation, in terms of amplitude and phase, although the simulated peak streamflow was not accurately matched the observed producing underestimation and overestimation (Fig. 3). Nevertheless, the calibration and validation result demonstrates that SWAT model is generally capable of simulating streamflow of the catchment.

Table 2 and Fig. 4 shows the calibration and validation result for the Delft3D model. The observations and simulations at the four gauging stations (Xingzi, Duchang, Kangshan, Hukou) comes to a satisfactory agreement with R^2 or Ens larger than 0.70 and the absolute value of PBIAS less than 25%. The agreement are fourthly supported by the highly consistence between the observation and simulation although there is an obvious discrepancy during the low water level period (Fig. 4a, Fig. 4b, Fig. 4c) and high changed flow velocity period (Fig. 4d). This outcome probably arises from the decreased elevation of lake bed from the south to the north and the dynamic variation between wetlands and lake areas. The dynamic variation makes the lake be a river in dry period and turned to be a lake in flood period, which is difficulty to be accurately modelled. Nonetheless, model calibration and validation results demonstrate that Delft3D has the capability to simulate the hydrodynamic characteristics of Poyang Lake.

4.2 Stream flows verification in the ungauged zone

We compared the results of the Adjusted Scenario and that from the Original Scenario, to take a further verification for the stream flows simulation result in the ungauged zone The Adjusted Scenario took the streamflow in the PLUZ into consideration, while Original Scenario neglected the streamflow in the PLUZ. Fig. 4 also shows the comparison of the results from the two scenarios, in terms of the lake water level and outflow. For the lake outflow discharges, the simulated results in Adjusted Scenario produced high value of R^2 (0.81) and low absolute value of PBIAS (10.00%), compared to that in Original Scenario with lower value of R^2 (0.77) and higher absolute value of PBIAS(18.88%). And the discrepancy between the observed and the simulated in Adjusted Scenario is narrower than that in Original Scenario during the most period. For the lake water level, the absolute value of PBIAS is decreased from 0.85%, 3.18%, 1.56% in Original Scenario to 0.48%, 2.67%, 1.21% in Original Scenario. The figures suggests obviously improved simulated result in Adjusted Scenario when the PULZ was taken into consideration, compared to that in Original Scenario when the PULZ was neglected. And the improvement demonstrates the reasonability of the streamflow simulation result in the PLUZ and the significance of the PLUZ on the water balance of the catchment-lake system.

4.3 Stream flows simulation result of the ungauged zone

We calculate the cumulative monthly discharge in the PLUZ from 2000 to 2010. Fig. 5 show the statistic result. Seasonal and inter-annual variations can be seen in the long time series data. The seasonal and inter-annual variations was consist of the change of the precipitation. Monthly water yield reaches maximum in flooding period from March to July, then decrease in the later month. After that, it arrives at the minimum in dry period from December to next January, finally increases. The water yields in 2002, 2003 and 2010 are abundant, indicating rich rainfall and possibility of flood event. Severe drought in 2001, 2006, 2007 and 2009 could be observed indicating relatively deficient precipitation.

The cumulative annual water yield in the PLUZ totals 15.2 billion m^3, occupying 11.24% of that from whole Poyang Lake watershed averagely (Table 3), which is close to the result by Li et al. (2014), where the streamflow produced by the PLUZ land area amount 12%, indicating the hydrological prediction of the PLUZ is reasonable. Such a great contribution to the inflow of Poyang Lake, which has a great influence on drought/flood in the Poyang Lake basin, could make a great effect on the water balance of the catchment-lake system.

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4.4 The impact of the ungauged zone on the water balance

In order to analyse the impact of the PLUZ on the water balance of the lake-catchment system, we compare the consistence of the inflow (or the simulated outflow) and outflow in two cases. In one case, the inflow (or the simulated outflow) incorporated the streamflow produced by the PLUZ; in the other case, the inflow neglected the streamflow produced by the PLUZ. Fig. 6, Fig. 7 and Fig. 8 shows the comparison in yearly, monthly and daily scales, respectively.

In Fig. 6, PBIAS between the Observed and the Estimated is 19.13%; PBISA between the Observed and the Adjusted Estimation1 is 7.94%. The discrepancy between the Observed and the Estimated is narrower than that between the Observed and the Adjusted Estimation1. The Estimated represent the total streamflow of the seven gauging stations, and the Adjusted Estimation1 represent the summation of streamflow in the PLUZ and total streamflow of the seven gauging stations. PBIAS is decreased and the discrepancy is narrowed, when streamflow in the PLUZ neglected. The result suggests the streamflow in the PLUZ improves the water balance of inflow and outflow of the lake, in yearly scale.

In Fig. 7, PBIAS between the Observed and the Estimated is 19.13% while PBISA between the Observed and the Adjusted Estimation1 is 7.94%; the discrepancy between the Observed and the Estimated is narrower than that between the Observed and the Adjusted Estimation1. PBIAS is decreased and the discrepancy is narrowed, when streamflow in the PLUZ neglected. The result suggests the streamflow in the PLUZ improves the water balance of inflow and outflow of the lake, in monthly scale.

However, in monthly scale R^2 is decreased from 0.74 when streamflow in the PLUZ is neglected to 0.72 when streamflow in the PLUZ is taken into account. That seem to get a worse relationship between the inflow and the outflow when the PLUZ is taken into account. The result arise from the water storage and flood regulation function of the Poyang Lake in daily scale. So we built hydrodynamic model for the lake, considering the lake function of water storage and flood regulation. The result was shown in Fig. 8.

In Fig.8, PBIAS between the Observed and the Estimated is 19.13% while PBISA between the Observed and the Adjusted Estimation2 is 7.94%; R^2 between the Observed and the Estimated is 19.13% while R^2 between the Observed and the Adjusted Estimation2 is 7.94%; the discrepancy between the Observed and the Estimated is narrower than that between the Observed and the Adjusted Estimation2 in most period. The Adjusted Estimation2 represent the prediction result from the hydrodynamic model in Adjusted Scenario. The PBIAS is decreased, R^2 is increased and the discrepancy is narrowed when the streamflow in the PLUZ was considered. And for Adjusted Estimation2 when streamflow in the PLUZ is considered, the blocking effects of Yangtze River are reproduced reasonably. In summary, the streamflow in the PLUZ improve the water balance of the lake obviously.

5 Conclusions

Method coupling hydrology and hydrodynamic can be used to simulate and verify stream flows in ungauged zones, solving the simulation and verification problem caused by no streamflow observations.

Ungauged zones lacks stream flow observations for calibration and verification for stream flow simulation. The couple hydrological models for the water body of ungauged zones, can verify the stream flow simulation result of ungauged zones using stream flow observations at the lower boundary of the water body. Due to the verification, the method can demonstrate the reliable of stream flow simulation result of ungauged zone. In the study, discrepancy between the observed and the simulated stream flows of the hydrodynamic model when the ungauged zones was taken into consideration, is narrower than that when the ungauged zones was ignored. The result suggests that the stream flow simulation of the ungauged zone is reliable, verifying the simulation result furtherly.

The hydrological and hydrodynamic models are coupled seamless in both space and time. The method of coupling the models in detail was presented for the first try. Sub-basins in the ungauged zones and the gauged zones must be coupled in space. Inflow to the water body is sum of stream flow from the gauged and ungauged zone in daily scale. The method is applied in the case study successfully.

Using the method, we estimated that the ungauged zone of Poyang Lake produces stream flows of approximately 180 billion m^3; representing about 11.4% of the total inflow from the entire watershed. We also analysed the impact of the stream flows in ungauged zone on the water balance between inflow and outflow of the lake. These results, incorporating the estimated stream flow in ungauged zone, significantly improved the water balance as indicated by R^2 with higher value and percent bias with lower value, as compared to the results when the stream flows in the ungauged zone were not taken into account, R^2 with lower value and percent bias with higher value.

The method can be extended to other lake, river, or ocean basins where stream flow observation data is unavailable, thus producing relatively accurate stream flow simulation results in ungauged zones. Reliable stream flow simulation results in ungauged zones contribute to accurate and reliable water yield predictions, water balance analysis and floods-droughts predictions. The reliable prediction and analysis provide deep understanding of hydrology for hydrological engineers and scientists, and helps a better plan making of water management for governments. Furtherly, as an area of interest of Prediction in Ungauged Basins, stream flow prediction and validation aids in PUB research.

Data availability

All data can be accessed as described in Sect. 2.2.

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Tables

Table 1. Quantitative Assessment of Calibration and Validation for SWAT Model

Gauging Station	Index	Model Calibration (Jan.2000 - Dec.2005)			Model Validation (Jan.2006-Dec.2011)		
		R^2	Ens	PBIAS(%)	R^2	Ens	PBIAS(%)
Wanjiabu	monthly discharge	0.63	0.61	-0.2	0.78	0.76	9.4
Waizhou	monthly discharge	0.94	0.93	3.2	0.95	0.93	6.5
Lijiadu	monthly discharge	0.84	0.82	-9.4	0.88	0.85	-16.8

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Meigang	monthly discharge	0.89	0.89	1.1	0.91	0.90	10.0
Hushan	monthly discharge	0.81	0.78	14.2	0.76	0.75	13.9
Dufengkeng	monthly discharge	0.80	0.80	-4.7	0.83	0.80	9.4

Table 2. Quantitative assessment of calibration and validation for streamflow simulation for the Delft3D model

Gauging Station	Index	Calibration (Jan.2001-Dec.2005)		Validation (Jan.2006-Dec.2010)	
		R^2	PBIAS(%)	R^2	PBIAS(%)
Xingzi	Lake water level	0.99	1.20	0.99	0.45
Duchang	Lake water level	0.97	4.74	0.99	2.78
Kangshan	Lake water level	0.85	2.86	0.88	1.72
Hukou	Lake outflow discharge	0.75	19.46	0.80	21.47

Table 3. Annual water yields produced by the PLUZ (Q_{PLUA}) from 2000 to 2009. The table includes the whole Poyang Lake catchment (Q_{whole}), and the ratio between Q_{PLUA} and Q_{whole}.

Year	$Q_{PLUA}(10^8 m^3)$	$Q_{whole}(10^8 m^3)$	Q_{PLUA}/Q_{whole}(%)
2000	157.18	1421.28	11.06%
2001	141.74	1477.88	9.59%
2002	216.10	1856.29	11.64%
2003	220.90	1404.69	15.73%
2004	113.95	921.54	12.36%
2005	187.83	1471.95	12.76%
2006	155.76	1560.27	9.98%
2007	72.41	1012.19	7.15%
2008	133.71	1291.85	10.35%
2009	115.70	1057.66	10.94%
The Average	151.53	1347.56	11.24%

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Figures

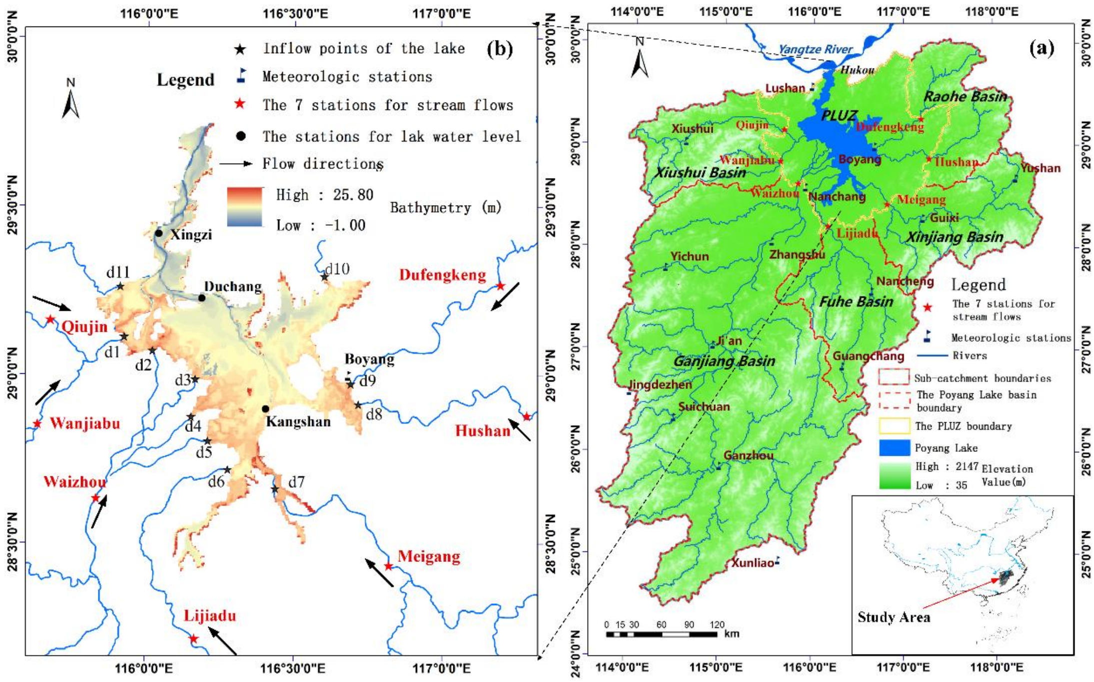


Figure 1. Study area and the related data. (a)The Poyang Lake watershed location, PLUZ location, five major river system, meteorological stations, hydrological stations (b) Lake location, inflow points location, hydrologic stations for lake water level.

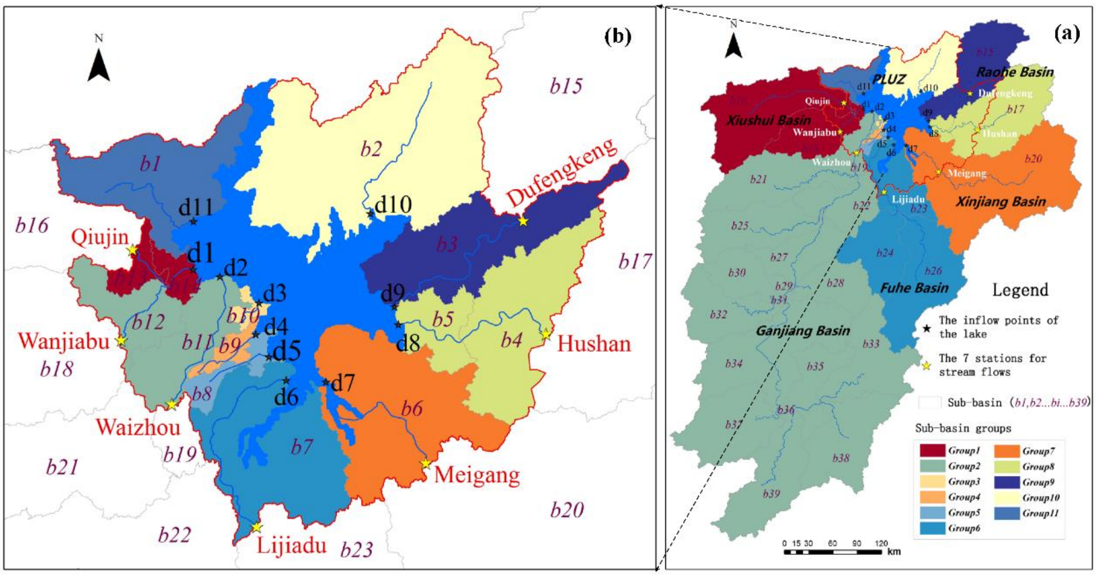


Figure 2. The abridged general view of the coupling between the catchment model and lake model. (a) and (b) shows the sub-basin groups. The streamflow produced by the sub-basins in the same group ($group_i$) flow into the same inflow point (d_i) of the lake. Specially, in the model, 50%, 30%, 10%, 10% of the streamflow from sub-basins in Ganjiang sub-catchment was defined to discharges into inflow points d_4, d_5, d_6, d_7 respectively.

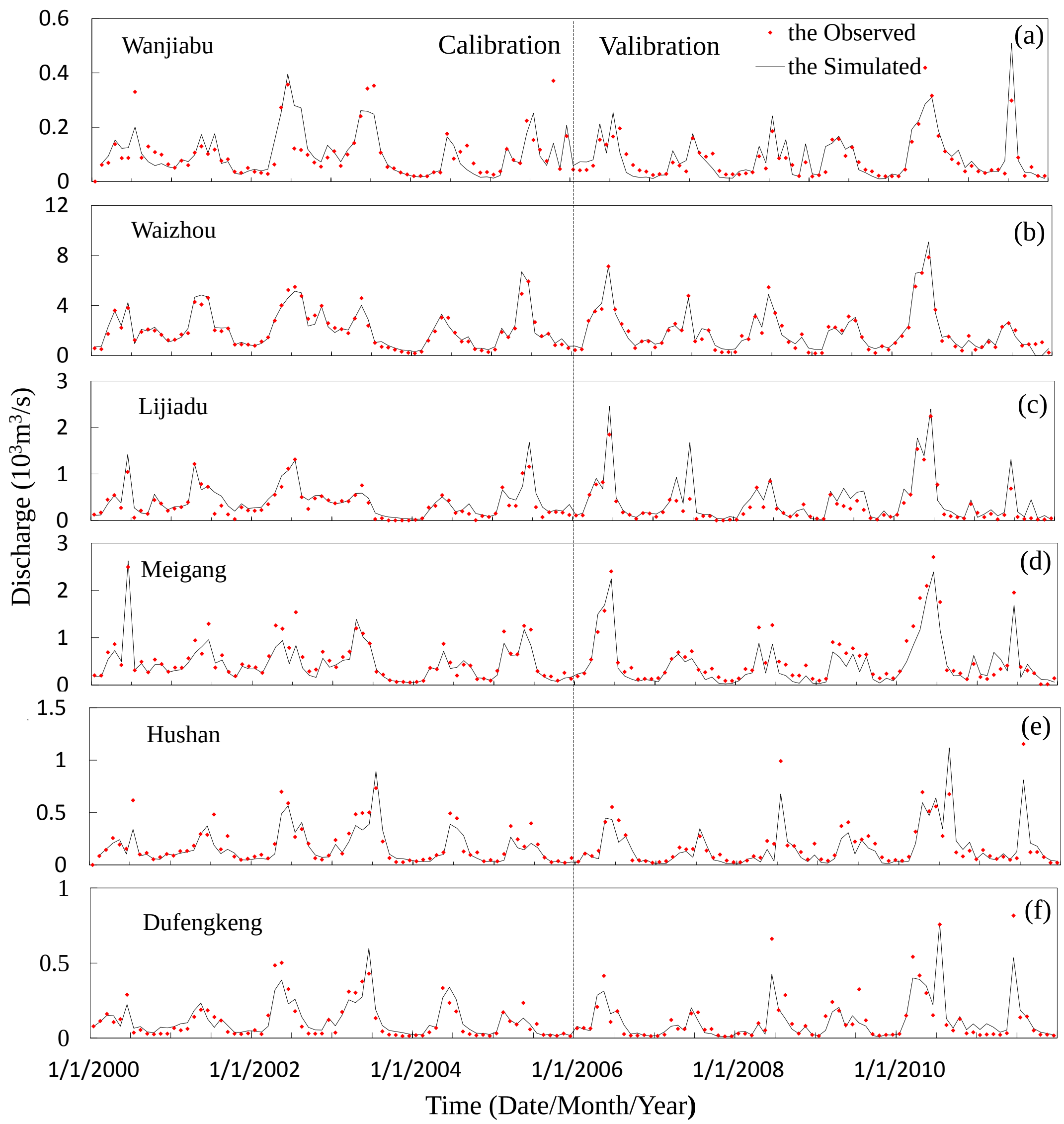


Figure 3. Comparison of the observed and the simulated by SWAT Model for calibration (2000-2005) and validation (2006-2011).

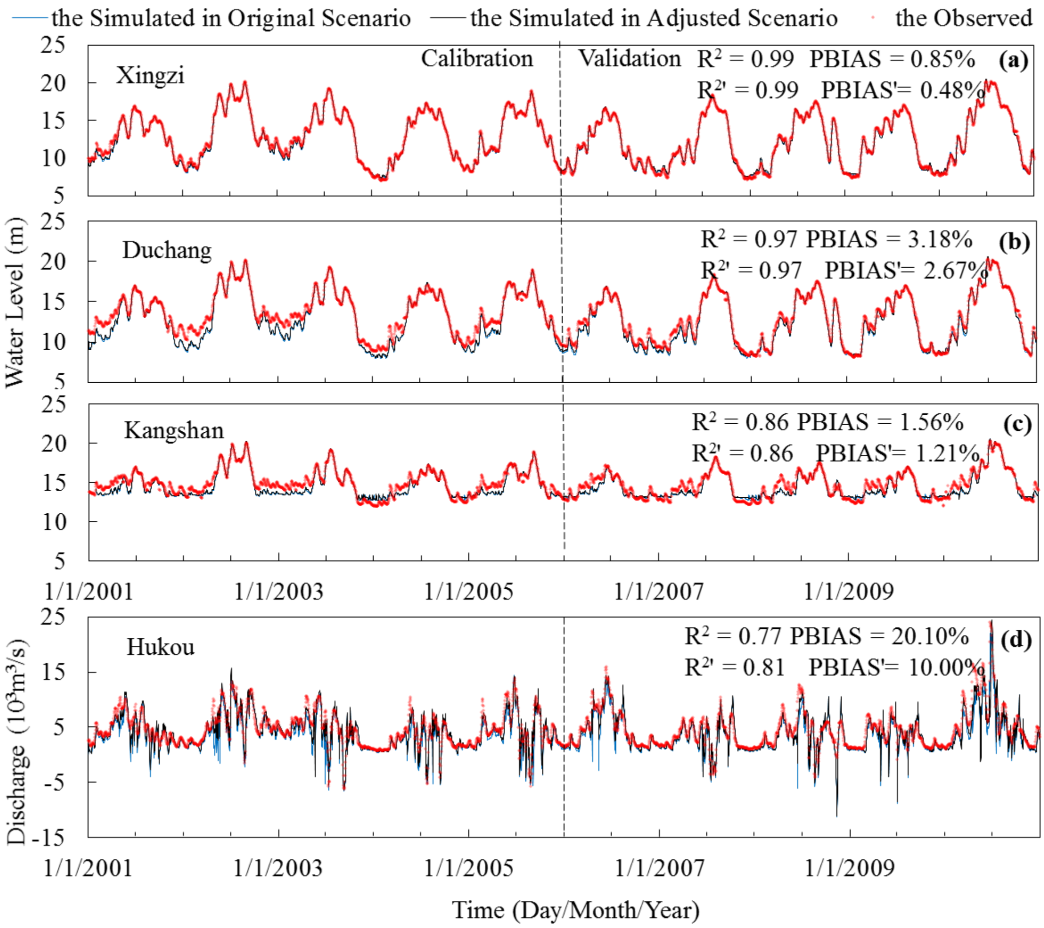


Figure 4. Comparison of the observed (dotted line) and simulated (black solid line for the result in Adjusted Scenario, blue solid line for the result in Original Scenario) lake water level at Xingzi, Duchang, Kangshan station, and lake outflow discharges at Hukou station by Delft3D Model. For the Original Scenario, the calibration period and validation period is from 2001 to 2005, 2006 to 2010, respectively. R^2 and PBIAS, R^{2}', and PBIAS' is the prediction result of Delft3D model in Original Scenario and Adjusted Scenario, respectively.

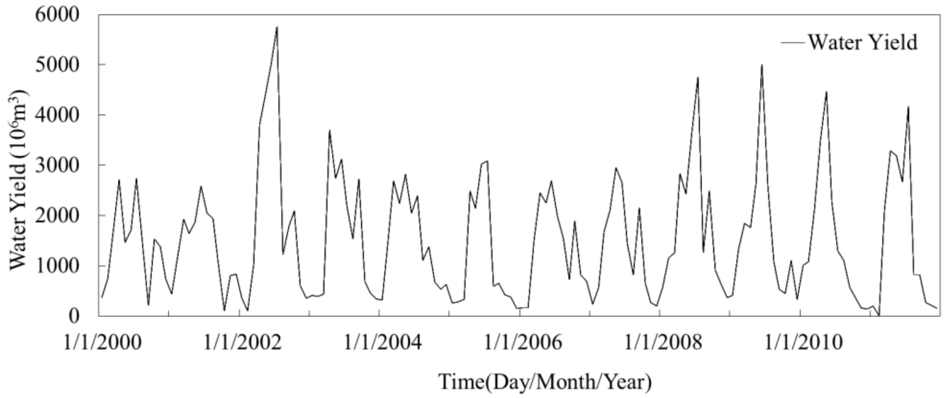
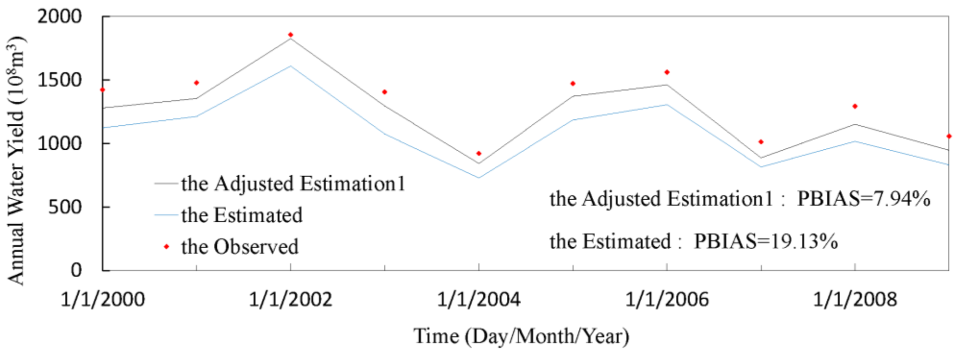


Figure 5. Monthly water yield in the PLUZ from 2000 to 2010.



465 Figure 6. Comparison of the simulated inflow (solid line) and the observed outflow (dotted line) at Hukou gauging station from 2000 to 2009 at monthly scale, where the Estimated represent the total streamflow of the seven gauging stations, and the Adjusted Estimation1 represent the summation of streamflow in the PLUZ and total streamflow of the seven gauging stations. PBIAS presents the percent bias between the Observed and the Estimated (or the Adjusted Estimation1).

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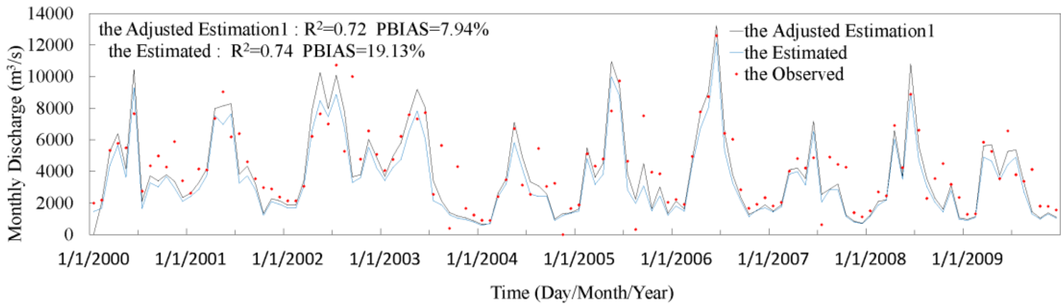

Figure 7. Comparison of the simulated inflow (solid line) and the outflow (dotted line) at Hukou gauging station from 2000 to 2009 at daily scale, where the Estimated represent the total streamflow of the seven gauging stations, and the Adjusted Estimation1 represent the summation of streamflow in the PLUZ and total streamflow of the seven gauging stations. PBIAS presents the percent bias between the Observed and the Estimated (or the Adjusted Estimation1). R^2 presents the determinated coefficient between the Observed and the Estimated (or the Adjusted Estimation1).

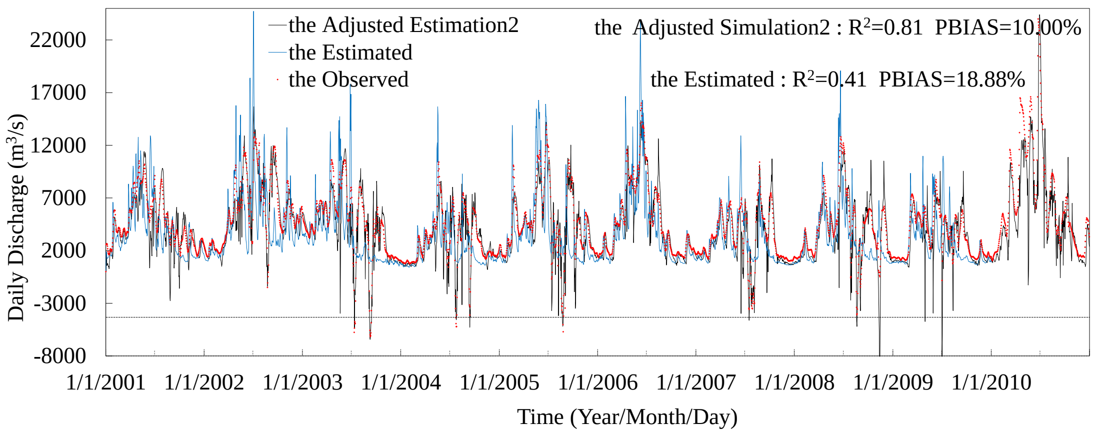

Figure 8. Comparison between the observed (dotted line) and the simulated (solid line) lake outflow discharge at Hukou, where the Estimated represent the total streamflow of the seven gauging stations, and the Adjusted Estimation2 represent the prediction result from the hydrodynamic model in Adjusted Scenario. PBIAS presents the percent bias between the Observed and the Estimated (or the Adjusted Estimation2). R^2 presents the determinate coefficient between the Observed and the Estimated (or the Adjusted Estimation2).