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Large Addition of Freshwater to the Tidal Reaches of the Yangtze (Changjiang) River

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Abstract
Freshwater discharge through the estuarine reach is always affected by tides and often composed of multiple distributary channels. The current estimation of freshwater input to the ocean by large rivers, therefore, is usually based on discharge measured at some distance upstream of the river mouth. Thus, records, however, may not truly reflect the river discharge to the ocean. In this paper, we consider the case of the Yangtze River where the furthest downstream gauging station is some 600 km upstream of the river mouth. Recent gaugings of the flow at Xuliujing, 69 km upstream of the river mouth, are used here to refine the estimate of the Yangtze flow to the sea. Given the errors in flow gauging, we consider only differences between Datong and Xuliujing > 15% as being significant. The results show that flows exceed this threshold on over 120 days with 63% being days when flow is larger at the downstream station. Most of these days with larger flow are in the period July to September, while most of the days when flow is less downstream occur in the period March to June. Annual flow differences between Xuliujing and Datong are only small percentages of the annual flow at Xuliujing for the years for which we have the records (1.78, 2.93, and 4.81% for normal, wet, and dry years, respectively) though these are still significant volumes of water. Local precipitation is the main driver of flow increases between Datong and Xuliujing in the July to September period, while water abstraction for irrigation between March and June appears to be the main cause of water loss in this reach. We recommend that water budgets for the tidal reaches of large rivers around the world are needed to accurately determine freshwater discharges from the rivers to the ocean and their temporal patterns.

Keywords Freshwater discharge to the ocean · Tidal reach · Estuary flows · Water consumption · Yangtze (Changjiang) Estuary

Introduction

The river discharge into the oceans plays an important role in the global hydrological cycle providing a critical linkage between continental freshwater and oceanic salt water (Largier et al. 1997; Lu 2004; Haddeland et al. 2014). An accurate estimation of freshwater flowing to the ocean is crucial in estuarine management, as it directly affects the assessment of material flux towards the ocean, the global biogeochemical budget and estuarine organism populations (Milliman and Farnsworth 2011; Dai et al. 2011b).

In most rivers, the downstream gauging stations are located upstream of the tidal limit. In large rivers, these stations are usually hundreds kilometers upstream of the river's mouth because of the problems involved in gauging where there are tidal flows and delta distributary channels. For example, the gauging station at Obidos is used to record the flow from the Amazon River into the central Atlantic Ocean, and it is ~ 900 km upstream of the mouth (Anthony et al. 2010). Similarly, Kratie, the most downstream station on the Mekong River, is over 500 km away from the mouth (Lauri et al. 2012). Dalles, the control station of the Columbia River, is ~ 300 km upstream of the mouth (Nijssen et al. 2001). Corrientes, the last station on the Parana River, is 550 km from the mouth (Antico and Kröhling 2011). Regions between these gauging stations and the river mouths are areas of high precipitation with local tributary inflows and are likely to significantly increase the freshwater flow into the ocean (Chen et al. 2010; Zhang et al. 2012). Often there are large cities

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located in these tidal areas, such as Macapa on the Amazon Estuary and Shanghai at the mouth of the Yangtze River. As a consequence, intensive human activities, including irrigation, industrial and domestic water consumption, and enhanced runoff from urban areas below the control station, can further impact the discharge entering the ocean (Nguyen et al. 2008; Chen et al. 2013). Thus, it is necessary to evaluate the water budget for the tidal reach to assess the river discharge to the ocean more accurately.

Over the past decade, several attempts have been made to obtain accurate discharge estimations for rivers that interact with ocean tides. For instance, Hoitink et al. (2009) employed Horizontal Acoustic Doppler current profilers to estimate river discharge in the Berau Estuary, Indonesia, by combining the index velocity method and velocity profile method approaches. Kawanisi et al. (2010) used a fluvial acoustic tomography system to continuously monitor discharge in the tidal Ota River Estuary, Japan. In view of the difficulties in measuring discharge in tidal rivers, Moftakhari et al. (2013) estimated monthly average river flows into San Francisco Bay using a tidal discharge estimation method based on tidal constituents, astronomical forcing and the frictional interaction of flow and tides. Similarly, Cai et al. (2014) estimated freshwater discharge in the Yangtze Estuary based on tidal water level observations by accounting for the effects of residual water level slope and tidal damping in the estuary. However, these efforts mainly focused on the feasibility of the proposed methodology but did not produce continuous flow records for the estuaries examined. Thus, they failed to document how the discharge changed downstream of the last gauging station.

In this study, we estimate, for the first time, the real flow from the Yangtze River into the East China Sea on the basis of continuous daily in-situ observations at Xuliujing where an automatic monitoring system has been established that can cope with tidal flows (Fig. 1b). Based on the measured daily discharge at Datong and Xuliujing, we explore in detail the pattern of flows from the Yangtze River to the East China Sea at the daily, monthly, and yearly levels and explore the main causes for the observed flow patterns.

Study Area

The Yangtze River (Changjiang River in Chinese), the longest Eurasian river, is 6300-km long with a catchment area of 1.8×10^6 km^2 (Chen et al. 2001; Mei et al. 2018). It rises on the Qinghai-Tibet Plateau at an elevation of 6600 m above sea level and flows into the East China Sea (Fig. 1a). The Yangtze River is generally divided into three subsections, namely, the upstream section from the source to Yichang, the middle section from Yichang to Hankou, and the lower section from Hankou to Datong (Xu et al. 2006; Mei et al. 2015). Datong station, located at the upstream tidal limit, is recognized as the control station that records the discharge from the river to the sea (Kuang et al. 2017).

However, Datong station is 600 km from the river mouth (Fig. 1b). Along this tidal reach, there are three populous provinces, Anhui, Jiangsu, and Shanghai (Fig. 1b), which significantly affect the river flow by the generation of local runoff, abstraction of water from the river, and waste water discharge (Zhang et al. 2012). Besides, in this section of the river, water is extracted to supply the eastern route of the south to north water transfer project (SNWDP, Fig. 1a). Since the operation of the first phase of the project in 2013, it has delivered over 2.00-billion m^3 water from Jiangsu Province to Shandong Province (CSNWDPC 2017), which further affects the river's flow to the sea. The lower Yangtze River downstream of Datong also receives flow from the 10.00×10^4-km^2 catchment area. Thus, Datong station does not accurately record the terrestrial freshwater discharge into the East China Sea (Yang 2013).

A flow gauging station has now been established at Xuliujing (Fig. 1b) approximately 531 km downstream from Datong and located immediately upstream of the first estuarine branch channel. Xuliujing records the discharge from the Yangtze River to the East China Sea more accurately than Datong though it is still located ~ 100 km upstream of the mouth of the Yangtze as downstream of this point there are channel branches in the estuary that would further complicate flow gauging. Here, the neighboring areas of Jiangzu and Shanghai have further unmeasured effects on the total freshwater flow entering the sea.

Along the Datong-Xuliujing Reach (DX Reach, 117° 37′ E–121° 59′ E and 30° 46′ N–31° 00′ N, Fig. 1b), there are several small tributaries that discharge water into the main stream, and together, they are equal to 1.20% of Datong's annual discharge. The largest tributary downstream of Datong, the Qingyi River (Fig. 1), has the largest yearly discharge of these tributaries, 4.93 billion m^3 annually on average, which is around 0.55% of the discharge through Datong station.

The DX Reach experiences a subtropical monsoon climate, characterized by four distinct seasons and abundant rainfall. Average annual rainfall for the DX Reach catchment is 1100 mm, with around 85% of the total occurring between May and October. Mean annual water surface evaporation over the region ranges from 950 to 1100 mm, ~ 50% occurring from May to August.

Owning to the effects of both highly varying river discharge and strong tides, a certain number of key interfaces exist along the DX Reach. Specifically, Datong and Zhenjiang are the upper limit of tidal backwater influence in the dry season and the flood season, respectively; Nanjing and Jiangyin are the upper limit of tidal currents in the dry and flood seasons, respectively; Xuliujing is the upper limit of saltwater intrusion in the dry season (the locations of these interfaces are indicated on Fig. 1b).

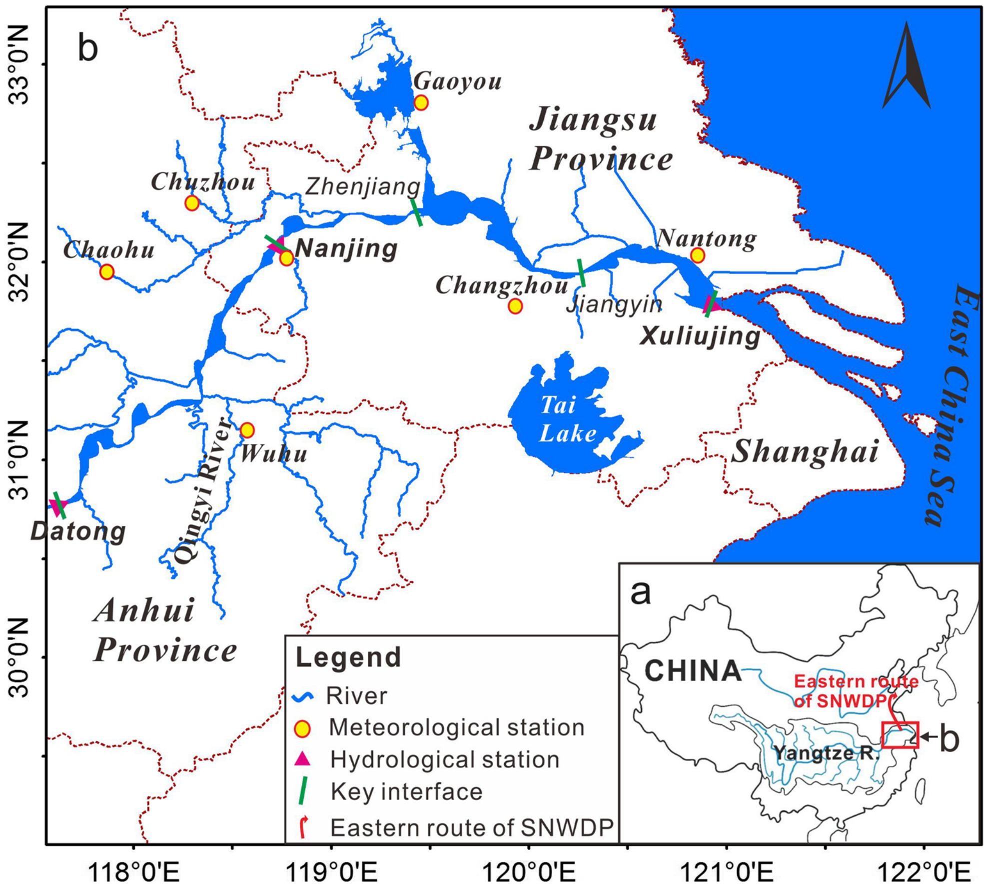

Fig. 1 The tidal reach of the Yangtze River, showing the hydrological stations and the meteorological stations used in this study

Data and Methods

Data Sources

Daily discharge records from 1950 to 2013 at Datong hydrological station and daily discharge in 2006, 2008, and 2010–2012 at Xuliujing hydrological station were provided by the Changjiang Water Conservancy Committee (CWCC) (Figs. 1b and 2). We were only able to get access to data for these 5 years because of restrictions in the data management system in China. However, these years do cover flood, normal, and dry hydrological years and are therefore suitable for our purposes.

Flow velocity data for 2006–2013 at Nanjing hydrological station (Fig. 1b), in the central DX Reach, were also sourced from the CWCC. Daily precipitation records at seven meteorological stations, Chaohu, Chuzhou, Wuhu, Nanjing, Changzhou, Gaoyou, and Nantong (Fig. 1b) in 2006, 2008, and 2010–2012 were provided by the National Climatic Centre of the Chinese Meteorological Administration. Water abstraction and consumption information in Jiangsu and Anhui for 2005–2012 were collected from the Jiangsu Province water resources bulletins and Anhui Province water resources bulletins.

Real-Time Discharge Measurement at Xuliujing Station

Real-time discharge at Xuliujing station was obtained based on water level measurements and flow velocity array data across a river transect. When the mean velocity of a cross section can be related to the depth-averaged velocity of a representative vertical line, the real-time discharge can be obtained directly as the product of cross-sectional area and mean velocity:

$$q = VA \tag{1}$$

where q is the measured discharge, V is the average velocity of the cross section, and A is the cross-sectional area.

When a cross section has a complicated geometrical shape, the cross-sectional mean velocity can not be well represented by the mean velocity at one vertical. The cross-section then should be divided into several sub-sections. For each sub-section, its mean cross-sectional velocity and segment area need to be identified first to compute the panel discharge. Thereafter, the total discharge can be obtained by summing the discharges in each subsection:

$$q = \sum_{i=1}^{N} V_i A_i \tag{2}$$

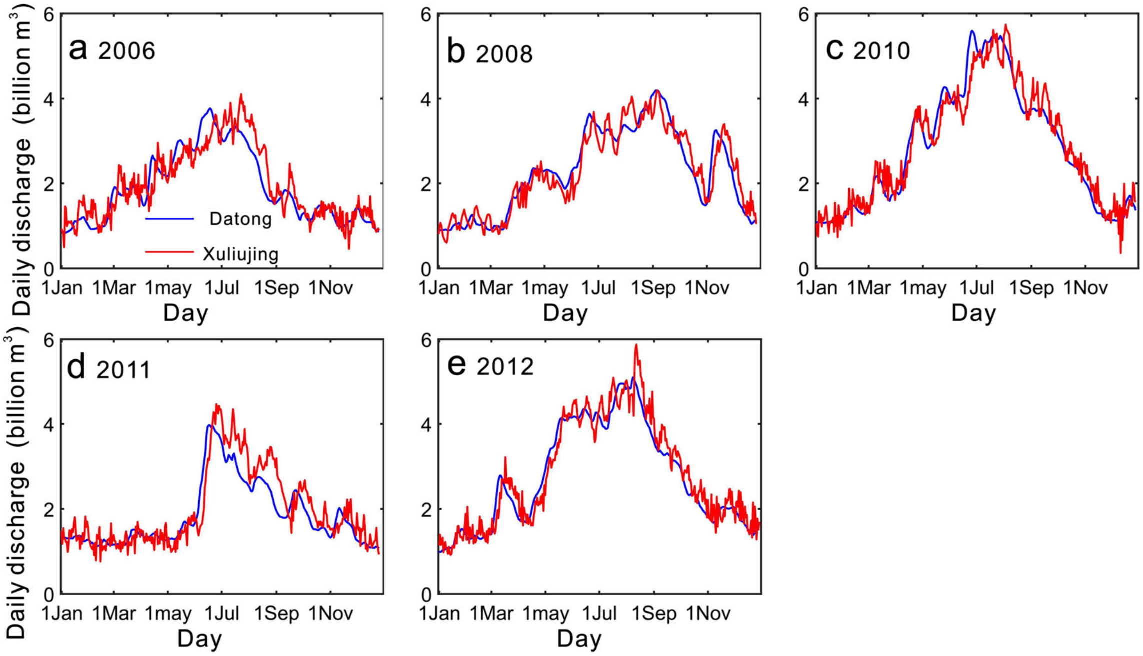

Fig. 2 Daily discharge hydrographs for Datong and Xuliujing stations

where q is the total discharge through the cross-section, V_i is the mean velocity at the ith vertical of the sub-cross-section i with sub-cross-sectional area A_i, and N is the number of sub-cross-sections.

The Xuliujing cross section is 5900 m wide (Fig. 3). The maximum depth of the cross section is 55 m. Tidal discharge through the Xuliujing cross section is compiled separately for the edge areas and the main channel. Following the code for hydrologic data processing in China (MWRPRC 2012), five velocity verticals were set at different intervals to cover the central area of the cross section (Fig. 3). A vertical velocity profile on a representative line is measured every half hour with acoustic Doppler current profilers (ADCP), which apply the Doppler principle to measure velocity profiles from near the water surface to near the bed (Simpson 2001; Morse et al. 2010). ADCPs in vertical 1 to vertical 4 are in buoys and looking downward, while the ADCP in vertical 5 is bottom moored and looking upward. The unmeasured area at the top and bottom of each vertical is obtained by extrapolation (Lee et al. 2014). Tidal discharge through the main stream is computed by the combined representative vertical line method in view of it being a complicated geometrical feature, while edge discharges are calculated through the single representative vertical line method (Fig. 3), which together constitute the total discharge through the entire cross section.

$$q = a_{\mathrm{left}} V_1 A_1 + \sum_{i=2}^{5} V_i A_i + a_{\mathrm{right}} V_5 A_6 \tag{3}$$

where q is the total tidal discharge through Xuliujing cross section, α is the edge coefficient. The mean velocity through CS-1 and CS-6 can respectively be related to the depth-averaged velocity of vertical 1 and vertical 5 (Fig. 3).

Each sub-cross-section can be treated as a trapezoidal shape when calculating the section area:

$$A_i = \frac{Z_i + Z_{i+1}}{2} b_i \tag{4}$$

where Z is the depth of the sub-cross-section's boundary (left and right), and b_i is the width between the two boundaries.

In view of the time and effort required for this measurement approach, stable velocity-discharge relationships have been established respectively for the flood and ebb tide periods at Xuliujing based on the measured data. Therefore, tidal discharge at Xuliujing station is obtained through the velocity profile and corresponding velocity-discharge relationship.

Net Daily Discharge Measurement

The Yangtze Estuary is dominated by the lunar semidiurnal internal tide. Daily discharge through Xuliujing is therefore obtained as the average net flow through the cross-section within two tidal cycles to remove the tidal signal:

$$Q = \frac{\sum_{i=1}^{n} \left[\frac{q_i + q_{i+1}}{2} (t_{i+1} - t_i) \right]}{t_n - t_1} \tag{5}$$

where Q is the daily net discharge through Xuliujing, q_i is the tidal discharge at time t_i, $t_{i+1} - t_i$ is the time interval between two adjacent measurements (half an hour), and $t_n - t_1$ is the time covering two tidal cycles (24 h and 50 min).

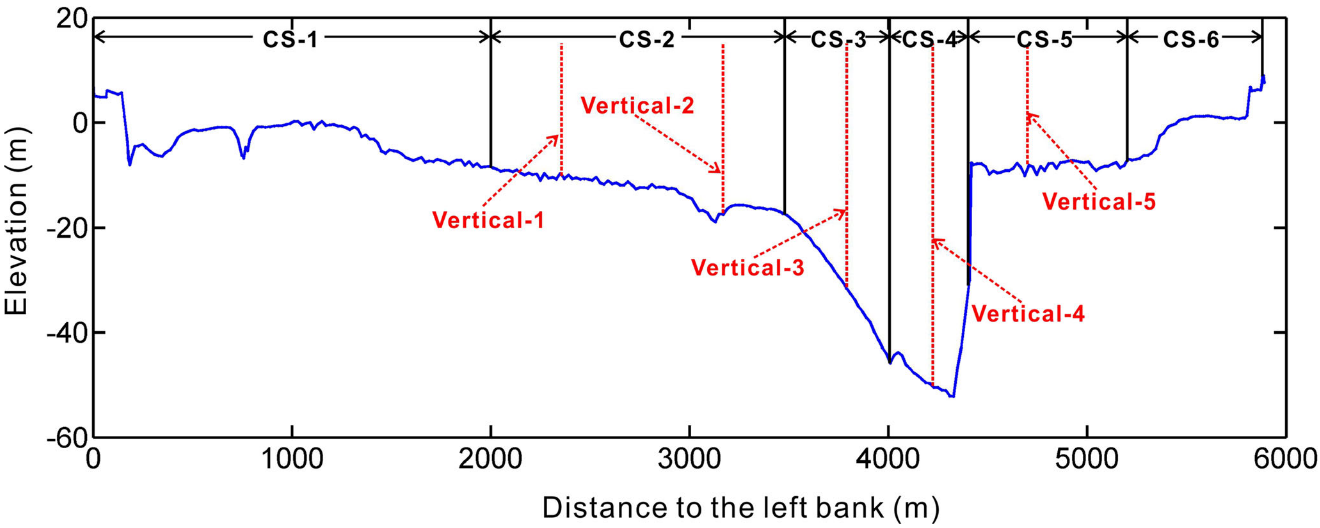

Fig. 3 Cross section with representative vertical line locations, with CS-1 and CS-6, respectively, indicating the left and right floodplain area while the area from CS-2 to CS-5 indicating the main channel

Analysis Methods

In order to determine the actual freshwater flow from the Yangtze River to the East China Sea in response to different hydrological scenarios, three types of hydrological year are designated based on their frequencies of occurrence (Bonsal et al. 2001). Specifically, for an ascending ranked annual discharge sequence $Q_1 < Q_2 < \ldots < Q_n$, the probability that a random value is less than or equal to Q_m could be expressed in a general formula as follows (Gringorten 1963):

$$P_m = \frac{m-a}{n+1-2a} \tag{6}$$

Normally, a ranges from 0 to 0.5. In this paper, a is set as 0.5. Accordingly, the percentile for a percent value can be obtained through linear interpolation. In this study, thresholds for dry years and wet years are respectively defined as the 12.5 percentile and the 87.5 percentile of the yearly discharge series at Datong (IPCC 2007). Specifically, the years with discharge smaller than the 12.5 percentile are defined as dry years, while the years with discharge larger than 87.5 percentile are defined as wet years. The years with discharge between the 12.5 percentile and the 87.5 percentile are taken as normal years.

The daily flow difference (FD) between Xuliujing and Datong is calculated as: $Q_{\text{Xuliujing}} - Q_{\text{Datong}}$. Accordingly, a positive value means that the discharge at Xuliujing is larger than Datong, indicating that extra water is supplied to the tidal reach, while a negative value indicates water loss. Time of travel from Datong to Xuliujing is calculated according to the distance between the two stations and the flow velocity at the Nanjing hydrological station.

Areally averaged precipitation over the tidal reach is calculated based on the observed point precipitation through the classical Thiessen polygon method, as described by the following functions (Fielder 2003):

$$P = \sum_{i=1}^{n} W_i P_i \tag{7}$$

$$W_i = A_i / A \tag{8}$$

where P is the areal average precipitation (mm), P_i is the point precipitation (mm), W_i is the Thiessen weight, A_i is the area represented by each meteorological station (km^2), A is the total watershed area (km^2), and n is the total number of precipitation stations in the DX Reach basin.

To estimate the precipitation-induced runoff over the DX Reach, the yearly runoff ratio (runoff/precipitation, the proportion of drainage basin rainfall that becomes runoff) for the middle-lower Yangtze was calculated. Yearly precipitation and runoff for the middle-lower Yangtze River catchment were obtained from Chen et al. (2016).

Measurements of river discharge are known to be subject to uncertainties (Di Baldassarre and Montanari 2009). Under the assumptions that (1) the ADCP is operated in ideal conditions, without any systematic uncertainty and in the absence of significant wind; (2) the errors are independent and normally distributed; and (3) the distribution of discharge along the river cross subsections are even, the uncertainty affecting the river discharge measurement at Xuliujing derived by the velocity-area method is given by:

$$u(Q) = \pm\left[u_m^2 + \frac{1}{m}\left(u_b^2 + u_d^2 + u_v^2\right)\right]^{1/2} \tag{9}$$

where $u(Q)$ is the relative (percentage) combined standard uncertainty in discharge; u_m is the uncertainty due to the limited number of verticals; u_b, u_d and u_v are the relative standard uncertainties in the width, depth, and mean velocity measured at each vertical; m is the number of verticals. Component uncertainties can be obtained from the Ministry of Transport of the People's Republic of China (2015) and European ISO EN Rule 748 (2007).

Results

Variations in Daily Flow Differences Between Xuliujing and Datong

At Datong, based on the definitions of dry, normal, and wet years set out above, 2006 and 2011 were dry years, 2010 and 2012 were wet years, while 2008 was a normal year (Fig. 4a). Since flow velocities at Nanjing hydrological station in dry, normal, and wet periods are respectively 1.04, 1.28, and 1.65 m/s, daily discharge at Xuliujing corresponding to the record at Datong indicates 6-day lag, 5-day lag, and 4-day lag in dry years, normal years, and wet years, respectively.

The daily cumulated differences in flow between Datong and Xuliujing for each of the 5 years are shown in Fig. 4b–f. Where a difference existed, it began to appear in August and then gradually increased. The most significant difference occurred in the dry years, followed by the wet years. Both dry and wet years showed that the river gained water in the DX Reach. Conversely, in the normal year, 2008, the reach lost a relatively small amount of flow.

Daily FDs in the DX Reach (Fig. 5a–e) were characterized by significant fluctuations between positive and negative values. By calculating the uncertainty in river discharge measurement at Xulijiujing, it was found that the measurement was affected by an uncertainty of 15% of discharge at Xuliujing at the 95% confident level, which was therefore set as the threshold to detect the significant daily FD along the XD Reach. The FD values that exceeded the threshold were highlighted with red circles in Fig. 5. It can be seen that

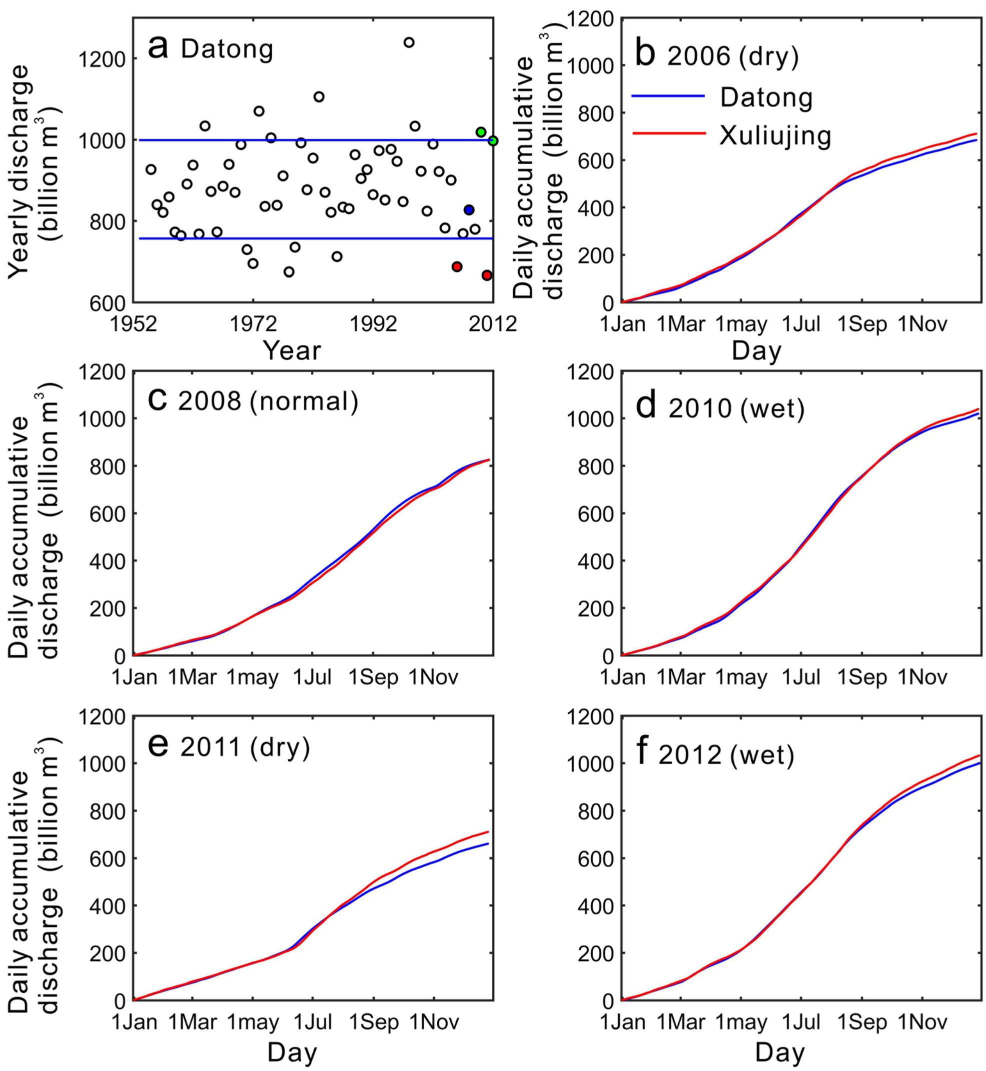

Fig. 4 **a** Yearly discharge at Datong, and **b**–**f** cumulated daily discharge at Datong and Xuliujing. The two blue lines in **a** represent the 12.5 and 87.5 percentile threshold of the yearly discharge series at Datong. Colored dots in **a** are the years used in this study

a significant number of daily FD in the tidal reach were above the threshold. Specifically, in 2006, 2008, 2010, 2011, and 2012, there were respectively 176, 87, 97, 152, and 91 days exceeding the threshold level (Fig. 5a–e) with the majority being positive: 61% in 2006, 68% in 2008, 64% in 2010, 63% in 2011, and 62% in 2012. In 2006 and 2011 (dry years), water gains were concentrated between July and September (Fig. 5a, d), while a significant number of water losses were detected between March and June in all years (Fig. 5).

Characteristics of Monthly Flow Differences Between Xuliujing and Datong

Monthly FD between Xuliujing and Datong varied substantially over the hydrological years (Fig. 6). In dry years, water losses started in March and lasted until June, which was followed in each case by observable gains for the remainder of the year (Fig. 6a, d). In the normal year, a water loss occurred from April to July, with a slight loss in September and varying gains in all other months (Fig. 6b). In the wet years, monthly FD between Xuliujing and Datong differed between the 2 years. In 2010, water losses occurred in the 4 months from April to August (Fig. 6c). In 2012, however, losses occurred only in April and May (Fig. 6e). Generally, water losses mainly occurred in March to June in dry years, which shifted to April to July during wet and normal years. There was around 1 month of time delay in water loss/gain in wet/normal years in comparison with dry years. Moreover, the maximum monthly water gains in dry years were dramatically larger than those in normal and wet years, an increase from 8.04 billion m^3 in wet and normal years to around 18.75 billion m^3 in dry years, while the maximum monthly water losses had no apparent variation between different hydrological years.

Estimation of Yearly Flow Differences Between Xuliujing and Datong

Annual flow at Xuliujing was greater than at Datong in all years (Fig. 7). Specifically, the XD Reach gained an additional 27.06- and 50.30-billion m^3 flow in 2006 and 2011, 19.30 and 33.05 billion m^3 in 2010 and 2012, and 12.74 billion m^3 in 2008. On average, local water supply to the DX Reach was 12.74, 26.18, and 38.68 billion m^3 in normal, wet, and dry years, respectively. These are significant volumes of water but represent only 1.78, 2.93, and 4.81% of the annual flow at Xuliujing, much less than the uncertainty threshold of 15% at the 95% confidence level. This means that flow gained in the DX Reach appears to have limited effects on discharge into the East China Sea at the annual scale. Moreover, the

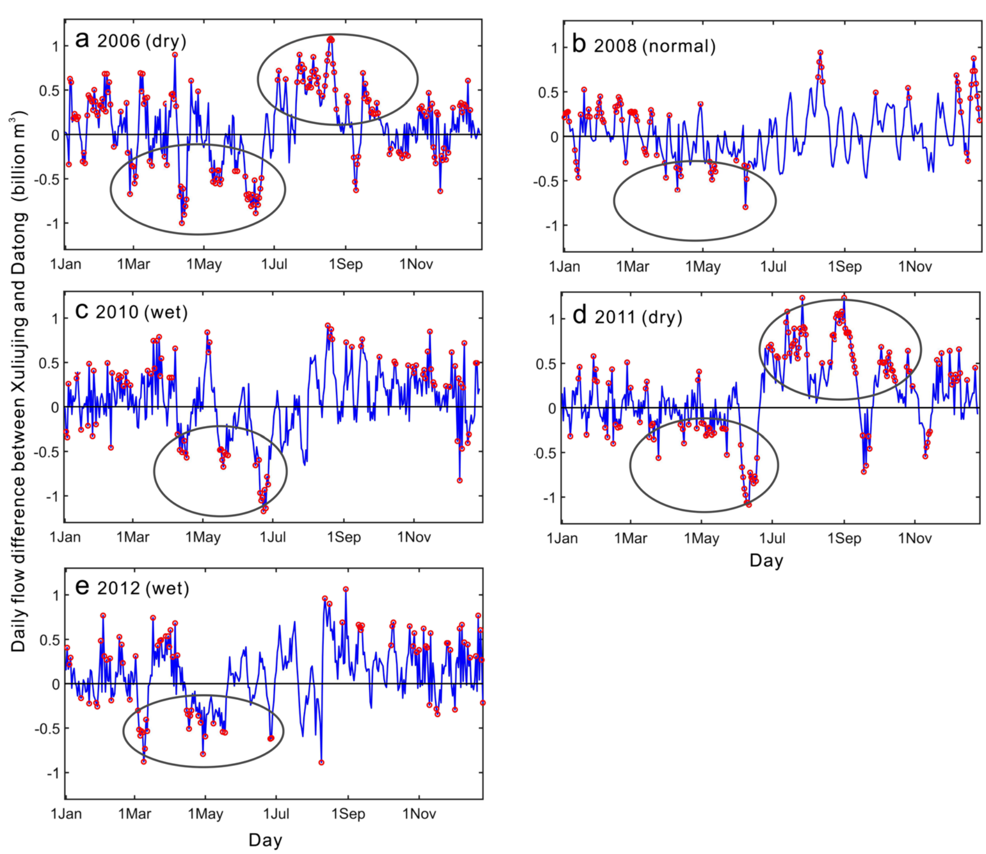

Fig. 5 Daily flow differences between Xuliujing and Datong for the study years. Red points indicate the flow exceeds the threshold (±15% of daily gauged discharge through Xuliujing). The flow difference between Xuliujing and Datong is calculated as: $Q_{\mathrm{Xuliujing}} - Q_{\mathrm{Datong}}$

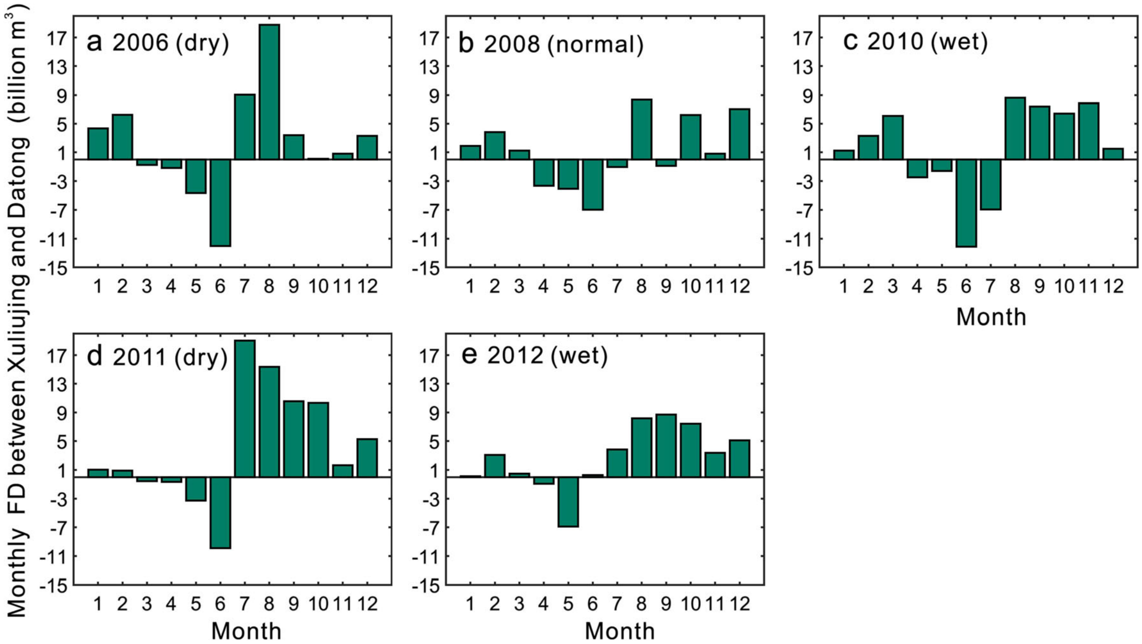

Fig. 6 Monthly flow differences between Xuliujing and Datong over the study years. The flow difference between Xuliujing and Datong is calculated as: $Q_{\text{Xuliujing}} - Q_{\text{Datong}}$

DX Reach obtained 12.51 and 25.94 billion m^3 more water in the dry years than the wet and normal years, respectively, indicating that the tidal reach downstream of Datong was likely to adjust the regional water budget to balance the riverine flow to the East China Sea among different hydrological years.

Discussion

Freshwater in the tidal reach can be controlled by local climate and anthropogenic activities (Xu and Wu 2006; Nepal et al. 2014; Nepal 2016). Human activities along the Yangtze tidal region affect the river flow mainly through water abstraction/input (Li et al. 2015). Accordingly, the dominant forces that control freshwater in the DX Reach can be considered as local climate and water abstraction/input, which are further analyzed in this section. Meanwhile, the impacts of the FD on estuarine water resources are discussed.

Local Climate

Precipitation over the DX Reach has a consistent seasonal pattern. 52.20% of the annual average precipitation occurs in June, July, and August (Fig. 8a), coinciding with the flow gains in summer (Fig. 6). In view of the difficulty in obtaining actual evaporation data along the DX Reach, the runoff ratio of 48.86% for the middle-lower Yangtze basin was used to provide a general estimate of yearly runoff from the area between Datong and Xuliujing. Using the areal precipitation, the catchment area of the DX Reach and the runoff ratio, the yearly flows that were generated along the DX Reach were calculated. Local runoff calculated this way was generally larger than the observed FD between Datong and Xuliujing (Fig. 8b–c). For instance, the FD between Xuliujing and Datong was 12.74 billion m^3 in the normal year (2008), while the runoff calculated from local precipitation was over 50 billion m^3, suggesting a high water loss of 75%. In other words, processes that consume or divert the local runoff had significantly altered the water balance along the DX Reach.

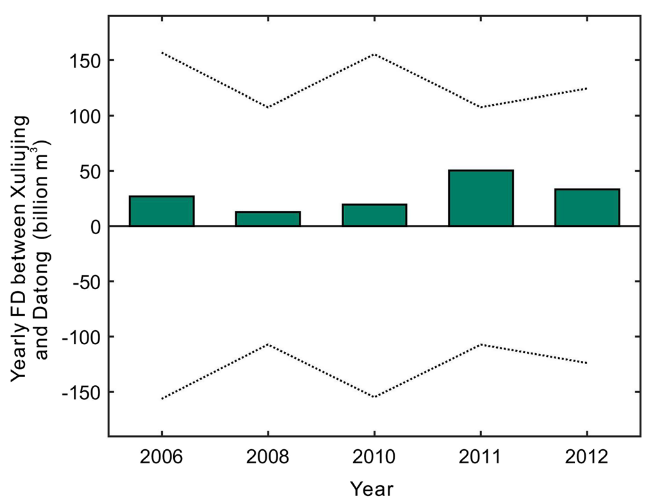

Fig. 7 Yearly flow difference between Xuliujing and Datong. The dotted line represents the threshold level (±15% of annual discharge through Xuliujing). The flow difference between Xuliujing and Datong is calculated as: $Q_{\text{Xuliujing}} - Q_{\text{Datong}}$

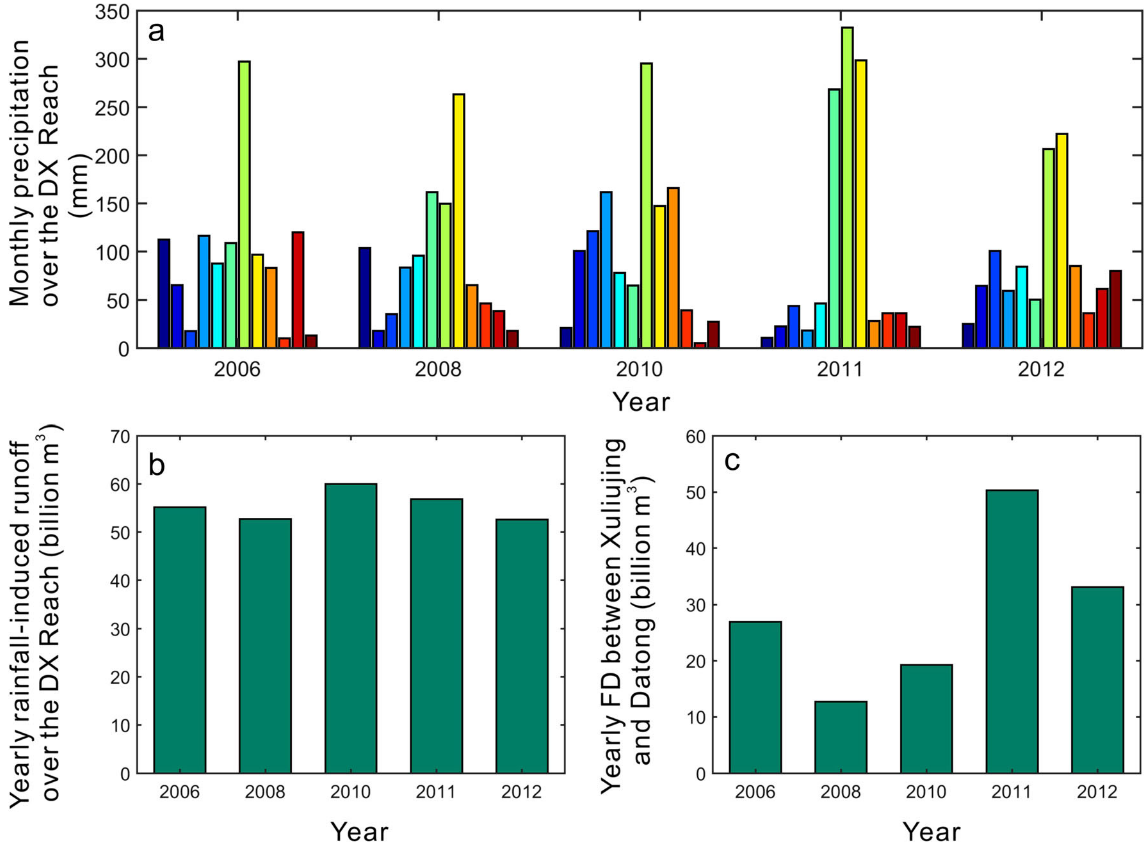

Fig. 8 **a** Monthly precipitation over the Datong-Xuliujing Reach. **b** Yearly rainfall-induced runoff over the Datong-Xuliujing Reach. **c** Yearly flow differences between Xuliujing and Datong. The flow difference between Xuliujing and Datong is calculated as: $Q_{\text{Xuliujing}} - Q_{\text{Datong}}$

Sub-Catchment Water Abstraction between Datong and Xuliujing

Two densely populated provinces, Jiangsu and Anhui, surround the DX Reach. Lying along the Yangtze River, the two provinces abstracted 24.89, 27.18, 28.00, 27.83, and 28.32 billion m^3 of water from the Yangtze River in 2006, 2008, 2010, 2011, and 2012, respectively (Fig. 9a). Around half of the extracted water was used for irrigation, with a yearly average ratio of 47.06 and 49.42% in Jiangsu and Anhui, respectively (Fig. 9). As mentioned above, large flow losses in this reach were in March–June (Fig. 6), which corresponds with the spring freshwater extraction for rice farming along the Yangtze River (Dai et al. 2011a). While there were no significant differences in water abstraction between the various hydrological years, it is the case that, as might be expected, the water extraction proportion for the two provinces was higher in the dry year than in the normal and wet flow years.

It is important to note that if the water is abstracted for irrigation, then it is effectively lost to the system (mostly through evaporation). Besides, the eastern route of SNWDP of China, completed in 2013, has transferred over 2-billion m^3 water from Jiangsu Province to Shandong Province (Fig. 1a), further reducing the freshwater discharge of the DX Reach. However, water extracted for power station cooling, domestic use, and a lot of industrial uses will eventually be returned to the river. There are large urban areas along the DX Reach. Urban areas return about five times as much runoff from rainfall as do rural areas due to the extensive impervious areas in cities consisting of buildings, roads, and other impervious infrastructures (Dawson et al. 2008; Isidoro et al. 2012). Consequently, the reach gets a lot of extra input from these cities, which immediately becomes part of the flow of the river, as does rain falling directly into the river.

In summary, the flow budget along the Yangtze tidal reach is determined by the contest between the water supply from local precipitation and urban water drainage, and water loss, particularly through irrigation and the SNWDP. As Fig. 6 indicates, flow losses occur between March and June, which means that the effects of irrigation on the flow were likely significantly larger than the water being supplied by local runoff. On the other hand, the monthly flow analyses indicated water gains from July to September, which reveals that heavy precipitation and extra water input from cities negated the influence of irrigation and dominated the runoff budget between Datong and Xuliujing. Besides, groundwater compensation, especially in dry water years, can also significantly

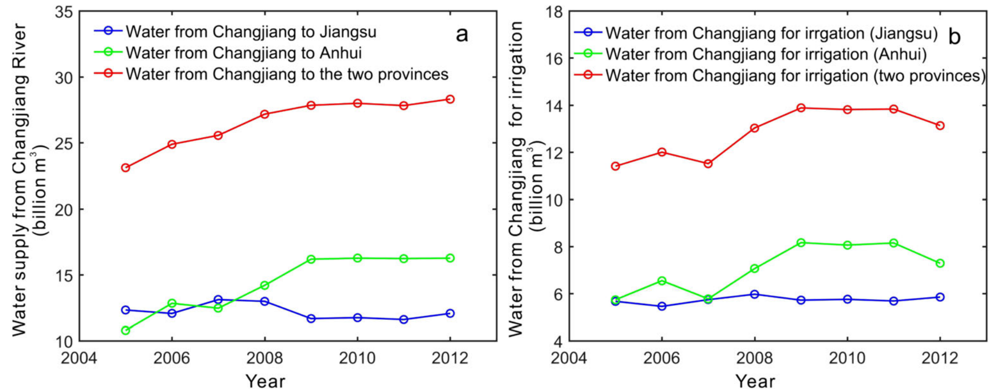

Fig. 9 **a** Water abstraction from the tidal reach of the Yangtze River to Jiangsu and Anhui provinces and **b** the corresponding water volume used for irrigation

affect the water budget along the DX Reach (Dai et al. 2011a), an issue still needing further research.

Environmental Consequences

At the daily time scale, a certain number of days indicated significant flow gain/loss in the DX Reach by exceeding the threshold of ± 15% of gauged discharge at Xuliujing, which can dramatically affect the accurate estimation of freshwater from the Yangtze River to the East China Sea. As river runoff is responsible for the pollutants entering to the sea (Nixon 1995), the evaluation of the estuarine and marine environment is closely related to the level of river discharge. During July to September, the additional water downstream of Datong carries more dissolved chemical compounds to the sea, while less freshwater discharge during March to June enhances pollutant concentrations. Both over- and under-estimation of the freshwater discharge into the sea have significant effects on the estimation of sea water composition. Furthermore, salt water intrudes far into the estuary during periods of high tide and low river discharge. Underestimation of freshwater discharge may lead to exaggeration of salt water intrusion, while overestimation of water flow can underestimate the magnitude of salinity intrusion (Savenije 1988; Stofberg et al. 2017), both of which may drastically affect the security of water supply to the estuarine cities, particularly Shanghai (Dai et al. 2011a). It is important to note that the months when there is less water passing Xuliujing do not include the low flow winter months from November to February. In these cases, Datong would not be a good guide to when low flows in the estuary are a problem for the quality of raw water going to the Shanghai treatment plants (Finlayson et al. 2013).

Globally, there are a significant number of large rivers facing the same problem, such as the Amazon, Mekong, and Columbia; their most downstream gauging stations are respectively 900, 500, and 300 km upstream of the river mouths. Downstream of these stations are usually fertile delta areas with densely populated socio-economic centers (Giosan et al. 2014; Tessler et al. 2015). Water gains and losses along these ungauged reaches may significantly affect the flow into the sea and thus misrepresent the real hydrological features, especially at the daily scale. In this study, we firstly reevaluate the daily flow from the Yangtze River to the East China Sea by considering the water budget in the tidal reach based on in-situ observations at Datong and Xuliujing stations. We have been able to assess flow at the daily, monthly and annual time scales and show that the situation varies across these scales. Now that there is technology available to carry out gauging in these estuarine areas, we recommend that it should be more widely used. Such knowledge provides a new insight on accurate estimation of freshwater discharge with global implications, especially to the developing world, where urban growth rates are high (Mcdonald et al. 2011).

Conclusions

Freshwater transport to the ocean plays a critical role in river-ocean interaction. Knowledge about the real amount of freshwater discharge into the ocean, and how it varies at different time scales, especially for large river basins, is important for understanding the global hydrological cycle. In this study, estimation of actual freshwater flux from the Yangtze River to the East China Sea was carried out through considering the water budget along the tidal reach. The main conclusions can be summarized as follows:

1) Annually 76 and 45 days exceeded the upper and lower thresholds respectively by passing + 15 and − 15% of Xuliujing's daily gauged flow when compared to corresponding flow at Datong. Water losses mainly occurred during March to June, while water gains were concentrated between July and September.
2) Yearly freshwater discharge from the Yangtze River to the East China Sea was underestimated by 12.74, 26.18, and 38.68 billion m^3 in normal, wet, and dry years. When expressed as a percentage of the annual flow at Xuliujing, these differences were 1.78, 2.93, and 4.81%, respectively, significantly less than the uncertainty threshold in flow gauging, indicating that the underestimation

of flow to the East China Sea at the yearly scale is not as serious as some believe, though in such a large river these are still large volumes of water.

3) Freshwater inputs/extractions along the Yangtze River tidal reach were dominated by local precipitation and water consumption. Local precipitation was directly responsible for the water gains in the DX Reach from July to September, and over 12.83 billion m^3 of water annually extracted from the Yangtze River to Jiangsu and Anhui Provinces for irrigation dominated the water losses, especially the significant water reduction during March to June.

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