Assessment of the reliability of popular satellite products in characterizing the water balance of the Yangtze River Basin, China
Dan Zhang, Qi Zhang, Adrian D. Werner and Renying Gu

ABSTRACT
This study investigates the water balance of the Yangtze River Basin (YRB) during 2003–2012 using the Tropical Rainfall Measuring Mission precipitation, the Moderate Resolution Imaging Spectroradiometer evapotranspiration and the Gravity Recovery and Climate Experiment total water storage change. The bias, absolute error and correlation coefficient are used to quantify water balance performances at monthly and annual time steps. The results show that the absolute error in the YRB water balance was 18.1 mm/month and 152.5 mm/yr at monthly and annual time steps accounting for 20% and 14% of YRB precipitation, respectively. The three satellite products were combined through a water balance equation to estimate monthly and annual stream flow, which was in error by 19.4 mm/month and 76.7 mm/yr, accounting for 22% and 7% of YRB precipitation, respectively. Trends in YRB water balance components at annual time steps obtained from satellite products were in the range 83–318% of the corresponding trends from alternative datasets (e.g., ground-based measurements, land-surface modelling, etc.), which performed significantly better than monthly time series. The results indicate that the YRB water balance can be evaluated using multiple satellite products to a reasonable accuracy at annual time steps.

Key words | multiple satellite products, water balance changes, water balance closure, Yangtze River Basin

INTRODUCTION
Basin-scale water balance assessment is often subdivided into the following components: precipitation, evapotranspiration, river discharge and total water storage change (TWSC) (Maidment 1992), where TWSC represents changes in the water stored in both surface and subsurface domains. The evaluation of water balance components and their temporal trends is an essential requirement of water resources investigations of river and lake basins, in particular, for the development of effective management strategies for water and ecosystem services (Wilson et al. 2001). Land-based measurements of these variables are restricted by several factors, such as the sparseness of meteorological and hydrological stations for precipitation and evapotranspiration observation, and the spatial heterogeneities inherent in natural systems (Pohl & van Genderen 1998; Lakshmi et al. 2011; Adjei et al. 2014). Further, recording instruments are usually situated in flat areas, and hence regions of steep topography are typically under-represented (Swenson & Wahr 2009). The application of satellite-based methods provides advantages of improved spatial coverage, including for mountainous areas that are...
otherwise difficult to access (e.g., Benz et al. 2004; Sheffield et al. 2009; Finsen et al. 2014; Wu et al. 2015).

The most popular methods for whole-of-catchment water balance studies are often based on satellite products, such as the Tropical Rainfall Measuring Mission (TRMM), the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Gravity Recovery and Climate Experiment (GRACE) (e.g., Armanios & Fisher 2014; Oliveira et al. 2014). The largest component requiring quantification in any catchment is precipitation. Accurate precipitation estimates are critical for reliable water balance evaluations (Al-Mukhtar et al. 2014; Kang & Merwade 2014). TRMM is a research satellite designed to improve the characterization of precipitation distribution across large areas (Kummerow et al. 1998; Huffman et al. 2007; Castro et al. 2015; Xu et al. 2015). Products from TRMM are the most popular and widely used precipitation datasets for application to basin hydrological analysis (e.g., Li et al. 2012, 2014; Yang & Nesbitt 2014). In general, the performance of TRMM precipitation at annual and monthly time steps is very good, whereas higher frequency datasets are less reliable (e.g., Barros et al. 2000; Wolff et al. 2005; Su et al. 2008; Armanios & Fisher 2014; Zhao et al. 2015).

The second-largest component of any catchment water balance is typically the evapotranspiration. The MODIS global terrestrial evapotranspiration dataset (MOD16), established by Mu et al. (2011), is widely used in the evaluation of regional water and energy balances (e.g., Sun et al. 2007; Venturini et al. 2008; Kim et al. 2012; Wang & Dickinson 2012; Corbari et al. 2014). For example, Kim et al. (2012) validated the performance of MOD16 in Asia and concluded that it can estimate actual evapotranspiration with reasonable accuracy at monthly time scales. He & Shao (2014) compared MODIS evapotranspiration with actual evapotranspiration from a water balance method, and found a reasonable match for China at annual time steps (i.e., correlation coefficient \( r \) of 0.91).

Perhaps the most difficult component of a basin water balance to quantify from field measurements is TWSC. In March 2002, NASA launched GRACE satellites to measure earth’s gravitational field with enough precision to infer variations in terrestrial water mass over large regions (Rodell et al. 2004; Tapley et al. 2004). Relative to conventional in situ observations and other remote sensing methods, GRACE products derive integrated information on TWSC in terms of all surface and subsurface water components (Landerer & Swenson 2012). GRACE data are thought to provide a reasonable estimation of TWSC (Moïwo et al. 2015; Long et al. 2014), and have been used in a variety of hydrological studies, ranging from river basins to continental and even global estimates (e.g., Reager & Fiume 2013; Tang et al. 2014; Wang et al. 2014a).

A number of previous basin water balance studies have relied on multiple satellite products (e.g., Sahoo et al. 2011; Armanios & Fisher 2014; Oliveira et al. 2014; Wang et al. 2014a). For example, Sahoo et al. (2011) assessed the water budgets of ten large river basins from across the globe using 2003–2006 data from nine satellite products. They found that errors in precipitation were the main source of non-closure of basin water balances. Armanios & Fisher (2014) used the same three products as adopted in the current study (i.e., TRMM, MODIS and GRACE) to investigate the water budget of Tanzania. They concluded that only the long-term (i.e., 2003–2010) water balance could be evaluated using these products. Oliveira et al. (2014) estimated stream flow for the Brazilian savanna by applying TRMM, MODIS and GRACE data in water balance calculations, and the results were used to detect hydrological drought. However, the accuracy of estimated stream flow was not validated by observed stream flow. Moreover, there is a need to explore the discrepancy between hydrological trends obtained from TRMM, MODIS and GRACE data, relative to ground-based/model-based datasets, given that previous studies have explored the accuracy of these satellite products using comparisons of absolute values only.

The current study uses TRMM, MODIS and GRACE to study the water balance of the Yangtze River Basin (YRB), China. Under the impact of changing climate and human activities, the YRB has experienced a high frequency of extreme hydrological events (i.e. droughts and floods) over the last few decades (e.g., Dai et al. 2008; Huang et al. 2014; Zhang et al. 2014). Previous studies of the YRB have mainly focused on the flow and water level trends of surface water systems, while subsurface water storage changes have received little consideration. In addition, the construction of the Three Gorges Dam (TGD), the largest hydroelectric power station in the world, has significantly modified some of the hydrological components of the YRB (Zhang et al. 2014). However, a comprehensive investigation of the YRB water balance and its temporal trends has not been undertaken, and yet these are critical for YRB water resource management, water project planning and ecosystem protection.
The current study aims to: (i) explore the accuracies of TRMM precipitation, MODIS evapotranspiration and GRACE TWSC based on the data of ground-based measurements and land surface models of the hydrology of the YRB during 2003–2012; (ii) characterize the water balance closure associated with the application of multiple remote sensing products; and (iii) evaluate changes in the YRB water balance during 2003–2012. The results are expected to provide an assessment of the reliability of popular satellite products in undertaking a water balance characterization at the scale of the YRB. The current study also extends previous satellite-based water balance investigations by examining the uncertainty in trends that are obtained by comparing to field-based datasets and model-based datasets.

**STUDY AREA**

The Yangtze River (24°–35° N, 90°–122° E), originating from the Qinghai-Tibetan Plateau, flows from west to east and then discharges to the East China Sea. The YRB experiences subtropical and temperate climates, with a mean temperature of 14 °C, and average annual precipitation of about 1,100 mm, of which 76% occurs during April to September (based on meteorological observations during 1960–2010). The average stream flow is about $9.5 \times 10^{11}$ m$^3$/yr, which accounts for 35% of China’s total (Varis & Vakkilainen 2001). The basin-averaged runoff coefficient, i.e., ratio of average stream flow to average precipitation (multiplied by catchment area), is approximately 0.5.

For the purposes of the current study, the YRB is subdivided into three main sub-basins, referred to here as the upper reaches (upstream of Yichang station; Figure 1), the middle reaches (between Yichang and Datong stations; Figure 1) and the lower reaches (downstream of Datong station). Yichang and Datong are two major hydrological stations for the YRB, and Datong station is the last hydrological station which has stream flow observations for the entire upstream catchment of the YRB. Only the upper and middle reaches were considered in the current analysis. The TGD is about 44 km upstream of Yichang station (Guo et al. 2015; Lai et al. 2017). The upper reaches of the YRB has a drainage area of approximately $1.0 \times 10^6$ km$^2$, and the middle reaches of the YRB has a drainage area of approximately $0.7 \times 10^6$ km$^2$. The lower reaches of the YRB is flat, creating a complex river network lacking in flow gauging stations, and as such, water balance analysis was not undertaken for this part of the YRB.

**Figure 1** | YRB showing topography and ground-based measurement sites.
DATA AND METHODS

Satellite products

Three satellite products were employed in this study (Table 1), including precipitation from TRMM 3B43 Version 7, evapotranspiration from MODIS MOD16, and TWSC from GRACE, using observations from the period January 2003 to December 2012.

The TRMM precipitation product \( P_{\text{TRMM}}, \text{mm/month} \) is a combination of 3-hourly merged high-quality infrared estimates and the latest spatial distributions of gauged precipitation from the Global Precipitation Climatology Center (Huffman et al. \( \text{2007} \)). There were several important changes in Version 7 of the TRMM series of data products, such as additional output fields, uniformly reprocessed input data using current algorithms, and a new infrared brightness temperature dataset. The TRMM dataset covers the latitude band 50° N-S (Huffman et al. \( \text{2007} \)). The spatial resolution of TRMM is 0.25° (approximately 25 km) and the temporal resolution is monthly.

The MODIS global terrestrial evapotranspiration product \( \text{ET}_{\text{MODIS}}, \text{mm/month} \) was updated based on a new algorithm by Mu et al. \( \text{2011} \), including vegetation cover fraction, daytime and night time evapotranspiration, soil heat flux, wet surface fraction and evaporation from wet canopy surfaces. The spatial resolution of MODIS is 1 km and the temporal resolution is monthly. Evapotranspiration from four land surface models (Noah model, VIC model, MOSIC model and CLM model) of the Global Land Data Assimilation System (GLDAS) was employed to compare with the MODIS data, in a similar manner to previous evapotranspiration studies by Reichle et al. \( \text{2004} \), Peters-Lidard et al. \( \text{2011} \) and Cai et al. \( \text{2014} \).

The Release-05 GRACE data provided by the GeoForschungsZentrum Potsdam were employed in this study. Since GRACE observations tend to be attenuated during sampling and post-processing at small spatial scales, the true signal amplitude was adjusted by the scaling factors based on the Community Land Model V4.0 (Landerer & Swenson \( \text{2012} \)). The spatial resolution of GRACE TWS is 1° (approximately 110 km) and the temporal resolution is monthly.

Ground-based observations

Precipitation data \( P_{\text{OBS}}, \text{mm/month} \) in the form of monthly totals from 160 meteorological stations in the YRB were provided by the National Climatic Centre of China Meteorological Administration for the period 2003–2012.
These were used to test the accuracy of TRMM precipitation. The only evapotranspiration observation station, Qianyanzhou, is located in the southeast of the YRB (Figure 1). Daily evapotranspiration data, based on the eddy covariance method, were summed to monthly totals \( (ET_{OBS}, \text{mm/month}) \) from the observation record of 1st January 2003 to 31st December 2004. \( ET_{OBS} \) was compared to \( ET_{MODIS} \) and GLDAS evapotranspiration (at the grid containing Qianyanzhou station).

Daily stream flow records from Yichang and Datong hydrological stations were obtained from the Yangtze River Hydrological Bureau of China for 2003–2012. The runoff into the middle reaches of the YRB was considered as the difference in stream flow at Datong and Yichang stations. Records of daily stream flow were summed to monthly totals and converted to specific discharge \( (Q_{OBS}, \text{mm/month}) \) by dividing by the respective basin areas. The locations of meteorological and hydrological stations are shown in Figure 1.

**Water balance analysis for the YRB**

The water balance analysis of this study equates water storage changes to the sum of water fluxes entering and leaving a particular region, for the purposes of evaluating basin-scale water balance trends. That is, TWSC is compared to the residual of incoming precipitation, outgoing evapotranspiration and stream discharge (i.e., groundwater discharge into and out of the region of interest is neglected), which can be expressed as:

\[
P - ET - Q = \Delta S
\]

where \( P \) is precipitation (mm/month); \( ET \) is evapotranspiration (mm/month); \( Q \) is stream discharge (mm/month); \( \Delta S \) is TWSC (mm/month).

TWSC can be determined from GRACE measurements \( (\Delta S_{GRACE}) \), expressed as the difference between GRACE total water storage (TWS) for two consecutive months \( (L. \text{et al.} 2014) \):

\[
\Delta S_{GRACE}(t) = TWS(t) - TWS(t - 1)
\]

The GRACE TWS signal exhibited significant noise, and so a temporal three-point average window for the TWS time series, in a similar manner to \( W. \text{et al.}(2014b) \), was used in the current study.

The error in the implementation of Equation (1) using remotely sensed data is explored by comparing the left side components with \( \Delta S_{GRACE} \). That is, the difference in water balance components on the left side of Equation (1) is firstly calculated by substituting \( P_{TRMM}, ET_{MODIS} \) and \( Q_{OBS} \) for the respective Equation (1) variables, to obtain the residual \( \Delta S_{WB}(t) \) of water balance fluxes. Then, the water balance error \( \epsilon(t) \) (mm/month) is estimated as the difference between this and the GRACE-based TWSC, as

\[
\epsilon(t) = \Delta S_{GRACE}(t) - (P_{TRMM}(t) - ET_{MODIS}(t) - Q_{OBS}(t))
\]

simplified as

\[
\epsilon(t) = \Delta S_{GRACE}(t) - \Delta S_{WB}(t)
\]

The average absolute error \( (\bar{\epsilon}, \text{mm/month}) \) for a given period of \( n \) months is calculated as

\[
\bar{\epsilon} = \frac{1}{n} \sum_{t=1}^{n} |\epsilon(t)|
\]

The bias \( (\bar{\epsilon}_b, \text{mm/month}) \) is simply the time-averaged error:

\[
\bar{\epsilon}_b = \frac{1}{n} \sum_{t=1}^{n} \epsilon(t)
\]

Bias offers insight into over- and underestimation relative to alternative methods. The average \( P_{TRMM} \) error \( (\bar{\epsilon}_{TRMM}, \text{mm/month}) \) and bias \( (\bar{\epsilon}_{TRMM,b}, \text{mm/month}) \) are estimated by Equations (4) and (5), except using the difference between \( P_{TRMM} \) and \( P_{OBS} \) as the error time series. The average \( ET_{MODIS} \) error \( (\bar{\epsilon}_{MODIS}, \text{mm/month}) \) and bias \( (\bar{\epsilon}_{MODIS,b}, \text{mm/month}) \) are estimated in a similar manner, i.e. using Equations (4) and (5) and the difference between \( ET_{MODIS} \) and GLDAS evapotranspiration. The error in GRACE TWSC \( (\bar{\epsilon}_{GRACE}, \text{mm/month}) \) is estimated by the GRACE measurement error and leakage error \( (Landerer & Swenson 2012) \), which is provided with the GRACE TWS data.
Equation (1) can be modified to make stream flow the dependent variable, allowing for an estimate of the spatial distribution in stream discharge $Q_{RS}$ (mm/month) for the YRB based on $P_{TRMM}$, $ET_{MODIS}$ and $\Delta S_{GRACE}$. The resolution of $Q_{RS}$ is 1' (the coarsest resolution among the three products). Then, the error in $Q_{RS}$, $\varepsilon_Q$ (mm/month), can be estimated as:

$$
\varepsilon_Q = (\varepsilon_{TRMM}^2 + \varepsilon_{MODIS}^2 + \varepsilon_{GRACE}^2)^{0.5}
$$

(6)

The error in $Q_{RS}$ is also estimated by Equations (4) and (5), except using the difference between $Q_{RS}$ and $Q_{OBS}$ as the error time series, expressed as $\varepsilon_Q$. Correlation coefficient $r$ is used to analyze the errors in water balance comments and their trends. Trends in water balance components are estimated using linear regression, and the T-test (Sun et al. 2014) is conducted to determine whether trends are significant at 95% ($P < 0.05$) and 90% ($P < 0.1$) confidence levels.

RESULTS AND DISCUSSION

Accuracy of TRMM, MODIS and GRACE water balance components

The accuracy of $P_{TRMM}$ was evaluated by comparison with the time series of $P_{OBS}$ from 160 meteorological stations in the YRB. Figure 2 shows that the resulting value of $r$ for the match between $P_{TRMM}$ and $P_{OBS}$ was greater than 0.9 at 67% of stations, which indicates that $P_{TRMM}$ reproduces reasonably well $P_{OBS}$ across over 2/3 of the YRB. $\varepsilon_{TRMM}$ was lower than 10 mm/month at 74% of stations. As given in Figure 3, the YRB $P_{TRMM, b}$ value of 4.4 mm/month indicates that TRMM over-estimated ground-based precipitation. At annual time steps, $\varepsilon_{TRMM}$ was 54.3 mm/yr for the YRB (shown in Table 2), accounting for 5% of the corresponding $P_{OBS}$. $\varepsilon_{TRMM}$ in the middle reaches of the YRB was larger than that in the upper reaches of the YRB at both monthly and annual steps. Scheel et al. (2011) reported that precipitation is higher in the lower latitude and altitude areas (e.g., the monthly $P_{OBS}$ averages 72.8 and 107.1 mm/month in the upper and middle reaches, respectively), which tended to lead to larger $\varepsilon_{TRMM}$. Nonetheless, $\varepsilon_{TRMM}$ for the two sub-basins was lower than 8% of the corresponding $P_{OBS}$, and therefore $P_{TRMM}$ is considered to be reliable for application to the YRB at monthly and annual time steps.

Figure 4 and Table 3 show the relationships between $ET_{MODIS}$ and the four GLDAS evapotranspiration datasets (monthly time steps) from 2003 to 2012. $r$, $\varepsilon_{MODIS}$ and $\varepsilon_{MODIS, b}$ were 0.99 ($P < 0.05$), 10.3 and 4.3 mm/month (i.e., MODIS data under-estimate GLDAS evapotranspiration), respectively, where $ET_{MODIS}$ is compared to the...
average of the four GLDAS datasets. At annual time steps, \( \varepsilon_{\text{MODIS}} \) was 51.9 mm/yr for the YRB, which accounted for 5% of \( P_{\text{OBS}} \) (shown in Table 2). \( \varepsilon_{\text{MODIS}} \) for the upper reaches of the YRB was smaller than that for the middle reaches of the YRB at the two time steps. In addition, \( r = 0.95 \) \((P < 0.05)\) between the monthly \( E_{\text{T MODIS}} \) and \( E_{\text{T OBS}} \) from Qianyanzhou station although the observed time series was short (Figure 4(c)). \( \varepsilon_{\text{MODIS}} \) shows that \( E_{\text{T MODIS}} \) was 13.5 mm/month larger than \( E_{\text{T OBS}} \) on average. \( \varepsilon_{\text{MODIS}} \) was 14.3 mm/month, accounting for 16% of the YRB \( P_{\text{OBS}} \).

The spatial distribution in \( \varepsilon_{\text{GRACE}} \) is illustrated in Figure 5, which shows an error range of 18.1 to 145 mm/month, with most cells smaller than 70 mm/month. The basin average \( \varepsilon_{\text{GRACE}} \) for the YRB, upper reaches and middle reaches were 15.3 mm/month, 16.2 mm/month and 24.1 mm/month, respectively. This highlights the smaller errors that arise from averaging GRACE data over larger areas (Tapley et al. 2004; Horwath & Dietrich 2006).

Figure 6 shows the time series of \( \Delta S_{\text{GRACE}} \) and \( \Delta S_{\text{WB}} \) for 2003–2012, and the accompanying \( r \) values, which were 0.71 \((P < 0.05)\), 0.77 \((P < 0.05)\) and 0.56 \((P < 0.05)\) for the YRB, upper and middle reaches, respectively. These results suggest reasonable correlations between \( \Delta S_{\text{GRACE}} \) and \( \Delta S_{\text{WB}} \), albeit the peak of TWSC values, occurring during the wet season, are clearly underestimated by the water balance results relative to GRACE data. It is interesting that \( \Delta S_{\text{WB}} \) changes preceded \( \Delta S_{\text{GRACE}} \) by approximately one month for the middle reaches of the YRB \((r \text{ between } \Delta S_{\text{GRACE}} \text{ and one-month lagged } \Delta S_{\text{WB}} \text{ was improved to } 0.79, P < 0.05)\). This is likely caused in part by the calculation of \( Q_{\text{OBS}} \) in the water balance equation, as the stream flow difference between Datong and Yichang

Table 2 | Error statistics of satellite products in the YRB

<table>
<thead>
<tr>
<th>Basin</th>
<th>Time steps</th>
<th>( P_{\text{OBS}} )</th>
<th>( \varepsilon_{\text{TRMM}} )</th>
<th>( \varepsilon_{\text{MODIS}}^* )</th>
<th>( \varepsilon_{\text{GRACE}}^* )</th>
<th>( \varepsilon_{Q} )</th>
<th>( \varepsilon_{Q2} )</th>
<th>( \varepsilon )</th>
</tr>
</thead>
<tbody>
<tr>
<td>YRB</td>
<td>Monthly (mm/month)</td>
<td>88.9</td>
<td>6.0</td>
<td>10.3</td>
<td>15.3</td>
<td>19.4</td>
<td>21.4</td>
<td>18.1</td>
</tr>
<tr>
<td></td>
<td>Annual (mm/yr)</td>
<td>1066.2</td>
<td>54.3</td>
<td>51.9</td>
<td>76.7</td>
<td>141.2</td>
<td></td>
<td>152.5</td>
</tr>
<tr>
<td>Upper reaches of the YRB</td>
<td>Monthly (mm/month)</td>
<td>72.8</td>
<td>5.5</td>
<td>12.5</td>
<td>16.2</td>
<td>21.2</td>
<td>26.0</td>
<td>20.4</td>
</tr>
<tr>
<td></td>
<td>Annual (mm/yr)</td>
<td>873.5</td>
<td>47.5</td>
<td>25.2</td>
<td>56.2</td>
<td>182.4</td>
<td></td>
<td>183.2</td>
</tr>
<tr>
<td>Middle reaches of the YRB</td>
<td>Monthly (mm/month)</td>
<td>107.1</td>
<td>8.0</td>
<td>9.5</td>
<td>24.1</td>
<td>27.1</td>
<td>25.5</td>
<td>20.5</td>
</tr>
<tr>
<td></td>
<td>Annual (mm/yr)</td>
<td>1284.6</td>
<td>65.9</td>
<td>84.5</td>
<td>109.8</td>
<td>89.0</td>
<td></td>
<td>110.1</td>
</tr>
</tbody>
</table>

*Calculated between \( E_{\text{T MODIS}} \) and the average values of the four GLDAS datasets.

*Estimated by the GRACE measurement error and leakage error.
stations. These stations are about 900 km apart, and therefore, the significant time lag associated with Yangtze River flood waves will create stream flow differences at the two stations that are not necessarily a product of runoff from the middle reaches.

**Water balance errors by satellite products**

Among the three satellite products, the error of GRACE TWSC was the largest at monthly time steps, followed by MODIS evapotranspiration and TRMM precipitation (see

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**Table 3 | Relationship between MODIS product and GLDAS evapotranspiration**

<table>
<thead>
<tr>
<th>Basin</th>
<th>Relationship</th>
<th>CLM</th>
<th>MOSAIC</th>
<th>VIC</th>
<th>Noah</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>YRB</td>
<td>$r$</td>
<td>0.98**</td>
<td>0.98**</td>
<td>0.99**</td>
<td>0.98**</td>
<td>0.99**</td>
</tr>
<tr>
<td></td>
<td>$\delta_{\text{MODIS}}$ (mm/month)</td>
<td>8.5</td>
<td>16.7</td>
<td>16.1</td>
<td>7.5</td>
<td>10.3</td>
</tr>
<tr>
<td></td>
<td>$\delta_{\text{MODIS}}$ (mm/month)</td>
<td>7.8</td>
<td>-14.0</td>
<td>-8.7</td>
<td>-2.4</td>
<td>-4.3</td>
</tr>
<tr>
<td>Upper reaches of the YRB</td>
<td>$r$</td>
<td>0.99**</td>
<td>0.98**</td>
<td>0.98**</td>
<td>0.98**</td>
<td>0.99**</td>
</tr>
<tr>
<td></td>
<td>$\delta_{\text{MODIS}}$ (mm/month)</td>
<td>10.3</td>
<td>16.2</td>
<td>16.3</td>
<td>9.9</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td>$\delta_{\text{MODIS}}$ (mm/month)</td>
<td>6.2</td>
<td>-10.1</td>
<td>-4.7</td>
<td>0.2</td>
<td>-2.1</td>
</tr>
<tr>
<td>Middle reaches of the YRB</td>
<td>$r$</td>
<td>0.97**</td>
<td>0.97**</td>
<td>0.98**</td>
<td>0.97**</td>
<td>0.98**</td>
</tr>
<tr>
<td></td>
<td>$\delta_{\text{MODIS}}$ (mm/month)</td>
<td>11.2</td>
<td>19.8</td>
<td>17.5</td>
<td>9.0</td>
<td>9.5</td>
</tr>
<tr>
<td></td>
<td>$\delta_{\text{MODIS}}$ (mm/month)</td>
<td>10.4</td>
<td>-18.7</td>
<td>-13.5</td>
<td>-6.3</td>
<td>-7.0</td>
</tr>
</tbody>
</table>

** indicates that the relationship is significant at the level of 0.05 by T-test.
Table 2), while TRMM precipitation had the largest error at annual time steps, followed by MODIS evapotranspiration and GRACE TWSC. It should be noted that GRACE TWSC error is influenced by measurement error and leakage error (the residual errors after filtering and rescaling), because there are no observed TWSC data that cover a reasonable proportion of the respective basins. TRMM and MODIS errors were obtained by comparing directly to ground-based and model-based values, and as such, are not subjected to the same uncertainties as the calculations of GRACE errors. Nevertheless, the error estimation method used in this study offers useful insights into discrepancies in the satellite-based water balance components.

The error in streamflow ($\varepsilon_Q$) arising from combining water budget components from satellite products was 19.4 mm/month and 76.7 mm/yr for the YRB at monthly and annual time steps accounting for 22% and 7% of YRB $P_{OBS}$, respectively. Table 2 shows that $\varepsilon_Q$ for the upper reaches of the YRB was smaller than that of the middle reaches of the YRB, at both monthly and annual time steps. In addition, the estimated streamflow was compared with observed values. $\varepsilon_{Q2}$ for the YRB was 21.4 mm/month and 141.2 mm/yr at monthly and annual time steps and both were larger than $\varepsilon_Q$. $\varepsilon_{Q2}$ for the upper reaches of the YRB was larger than that for the middle reaches of the YRB. The discrepancies between $\varepsilon_Q$ and $\varepsilon_{Q2}$ reflect nonlinearities in the errors in streamflow obtained from the summation of satellite products that detract from the reliability of Equation (6).

Water balance errors ($\varepsilon$) obtained using Equation (4) are shown in Table 2. $\varepsilon$ for the YRB was 18.1 mm/month and 152.5 mm/yr at monthly and annual time steps, accounting for 20% and 14% of YRB $P_{OBS}$, respectively. $\varepsilon$ values for the upper and middle sub-basins were similar at monthly time steps, accounting for 28% and 19% of YRB $P_{OBS}$, respectively. However, $\varepsilon$ for the upper reaches of the YRB was much larger than that for the middle reaches of the YRB at annual time steps, accounting for 21% and 9% of corresponding $P_{OBS}$, respectively. The reason was the larger overestimated TRMM precipitation and underestimated MODIS evapotranspiration in the middle reaches of the YRB than that in the upper reaches.

**Changes in water balance components**

Table 4 shows the relationships between trends in satellite products and ground-based/model-based datasets for the YRB at monthly time steps. The only clear relationships were obtained for precipitation. This suggests that monthly time series of MODIS, GRACE and estimated streamflow were not suitable for identifying temporal trends in these components of the YRB water balance, despite there being good correlations in the absolute values. Table 5 shows the comparison of water balance component trends using annual time series. For the entire YRB, the rates of changes...
in $P_{\text{TRMM}}$, $ET_{\text{MODIS}}$, $\Delta S_{\text{GRACE}}$ and $Q_{\text{RS}}$ are 173%, 318%, 240% and 83%, respectively, of corresponding ground-based/model-based slope. Although the rates of changes in satellite-based water balance components for the upper reaches of the YRB are extremely large due to the slight trends in $Q_{\text{OBS}}$ and $ET_{\text{GLDAS}}$, the rates of changes in satellite-based water balance components for the middle reaches of the YRB are within 129–170%. Generally, the satellite products are more suitable for studying the trends in annual time series compared with monthly time series.

![Figure 6](https://iwaponline.com/hr/article-pdf/47/S1/8/367030/nh047s10008.pdf)

**Table 4** Correlation coefficient between trends in satellite products and ground-based/model-based datasets at monthly time steps

<table>
<thead>
<tr>
<th>Basin</th>
<th>$P_{\text{TRMM}}$ vs. $P_{\text{OBS}}$</th>
<th>$ET_{\text{MODIS}}$ vs. $ET_{\text{GLDAS}}$</th>
<th>$\Delta S_{\text{GRACE}}$ vs. $\Delta S_{\text{WB}}$</th>
<th>$Q_{\text{RS}}$ vs. $Q_{\text{OBS}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>YRB</td>
<td>0.84**</td>
<td>0.60**</td>
<td>0.35</td>
<td>−0.07</td>
</tr>
<tr>
<td>Upper reaches of the YRB</td>
<td>0.80**</td>
<td>−0.15</td>
<td>−0.34</td>
<td>−0.11</td>
</tr>
<tr>
<td>Middle reaches of the YRB</td>
<td>0.90**</td>
<td>0.43</td>
<td>0.51**</td>
<td>0.31</td>
</tr>
</tbody>
</table>

*Calculated by the average values of the four GLDAS datasets.

**Indicates that relationship is significant at the level of 0.05 by T-test.
Table 5 | Trends in water balance components based on satellite products in the YRB from 2003 to 2012 (mm/yr²)

<table>
<thead>
<tr>
<th>Basin</th>
<th>( P_{\text{TRMM}} )</th>
<th>( P_{\text{OBS}} )</th>
<th>( ET_{\text{MODIS}} )</th>
<th>( ET_{\text{GLDAS}} )</th>
<th>( \Delta S_{\text{GRACE}} )</th>
<th>( \Delta S_{\text{WB}} )</th>
<th>( Q_{\text{RS}} )</th>
<th>( Q_{\text{OBS}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>YRB</td>
<td>6.9</td>
<td>4.0</td>
<td>-3.5**</td>
<td>-1.1</td>
<td>7.2*</td>
<td>3.0</td>
<td>1.9</td>
<td>2.3</td>
</tr>
<tr>
<td>Upper reaches of the YRB</td>
<td>-1.4</td>
<td>-3.7</td>
<td>-3.1</td>
<td>0.4</td>
<td>5.3*</td>
<td>2.3</td>
<td>-2.9</td>
<td>0.1</td>
</tr>
<tr>
<td>Middle reaches of the YRB</td>
<td>16.4</td>
<td>12.7</td>
<td>-4.2**</td>
<td>-3.0</td>
<td>9.7</td>
<td>5.7</td>
<td>8.8</td>
<td>5.5</td>
</tr>
</tbody>
</table>

*Calculated by the average values of the four GLDAS datasets.
*Indicates that slope is significant at the level of 0.01 by T-test.
**Indicates that slope is significant at the level of 0.05 by T-test.

Figure 7 illustrates the spatial distributions of trends (determined from annual time series) in satellite-based water balance components. During the period 2003–2012, the slope of \( P_{\text{TRMM}} \) ranged from -55.9 to 97.7 mm/yr² (Figure 7(a)). \( P_{\text{TRMM}} \) in the upper reaches of the YRB decreased slightly at -1.4 mm/yr², while \( P_{\text{TRMM}} \) in the middle reaches of the YRB increased at 16.4 mm/yr². For the entire YRB, \( P_{\text{TRMM}} \) increased at 6.9 mm/yr² from 2003 to 2010.

\( ET_{\text{MODIS}} \) changed at rates ranging from -76.6 to 55.4 mm/yr² (Figure 7(b)) at annual time steps. \( ET_{\text{MODIS}} \) for the middle reaches decreased significantly (\( P < 0.05 \)) at a rate of -4.2 mm/yr², while there was no significant trend in \( ET_{\text{MODIS}} \) in the upper reaches. For the entire YRB, \( ET_{\text{MODIS}} \) decreased significantly (\( P < 0.05 \)) at a rate of -3.5 mm/yr². The decrease in evapotranspiration was a complex result of decreases in air temperature, wind speed, vapor pressure and solar radiation (Figure 8), as reported by Roderick & Farquhar (2002), Liu et al. (2011) and Zhang et al. (2015).

Figure 7(c) shows the spatial distribution of \( \Delta S_{\text{GRACE}} \) trends, which ranged from -1.9 to 28.9 mm/yr². For the entire YRB, \( \Delta S_{\text{GRACE}} \) increased significantly (\( P < 0.1 \)) at a rate of 7.2 mm/yr². The increasing trend in \( \Delta S_{\text{GRACE}} \) for the middle reaches of the YRB was about 1.8 times that for the upper reaches of the YRB. The increased precipitation and decreased evapotranspiration, in combination, resulted in increased \( \Delta S_{\text{GRACE}} \), especially for the middle reaches of the YRB. In addition, the forest cover increased markedly under soil and water conservation policies (Gao et al. 2014; Zhang et al. 2015), which likely also modified the basin’s soil water storage capacity, and thereby affected the TWSC of the YRB.

The slope of \( Q_{\text{RS}} \) (Figure 7(d)), based on the residual of TRMM, MODIS and GRACE results, was between -35.4 and 94.7 mm/yr². \( Q_{\text{RS}} \) decreased for the upper reaches of the YRB at a rate of -2.9 mm/yr², while it increased for the middle reaches of the YRB at a rate of 8.8 mm/yr². For the entire YRB, the rate of changes in \( Q_{\text{RS}} \) was 1.9 mm/yr². Table 2 indicates a somewhat reasonable consistency between stream flow estimated from satellite products and ground-based measurements, at least at annual time steps.

It is difficult to provide definitive explanation of the causes of changes in water balance components, and discrepancies between satellite- and ground-based estimates of trends, because water balance trends are interdependent. For example, decreasing trends in precipitation are expected to produce reducing stream flow, evaporation variations influence the regional climate and subsequently modify the regional precipitation, and water storage changes modify evaporation and stream flow, etc. (Kumagai et al. 2013). In addition, the operation of TGD may have modified several water cycle components of the YRB (Li et al. 2013a, 2013b; Lai et al. 2014; Zhang et al. 2014). TGD impounds water from September to October, and releases water from March to June. If TGD impacts the water cycle of the YRB, the relationships between the upper (considered as the unaffected region of TGD) and middle reaches (considered as the TGD-affected region) of the YRB would be disrupted during the impoundment and release periods. Figure 9 shows the correlations of \( \Delta S_{\text{GRACE}} \) between the upper and middle reaches. There were good relationships of \( \Delta S_{\text{GRACE}} \) between the two sub-basins during the impoundment and release periods, which indicates TGD has limited impact on YRB’s \( \Delta S_{\text{GRACE}} \). This is consistent with the result of Li et al. (2013a, 2013b), who concluded that the hydrological drought at the downstream Yichang station was slightly aggravated by TGD’s operation from 2003 to 2011.

It is important to highlight some of the main uncertainties in the results of this study. For example, given the lack of actual evapotranspiration observations, \( ET_{\text{MODIS}} \) was compared with evapotranspiration by GLDAS to evaluate the
Figure 7 | Spatial distributions of trends in water balance components from 2003 to 2012 for the YRB: (a) TRMM precipitation; (b) MODIS evapotranspiration; (c) GRACE TWSC; and (d) stream flow as the sum of multiple satellite products.
errors in $ET_{\text{MODIS}}$. While employing different measurements to quantify errors in remotely sensed water balance components will impart some inequity in the evaluation of sources of error, there are limited alternatives to the evaluation of water balance errors at the scale of the study area. In addition, the resolutions of satellite products are different, and the different re-sampling methods will influence the resulting $Q_{\text{RS}}$ values (Wald et al. 1997). The different spatial resolutions of satellite products used in this study required re-sampling at the coarsest resolution among the three products (1') to estimate $Q_{\text{RS}}$.

In agreement with previous studies (e.g., Sahoo et al. 2011; Armanios & Fisher 2014; Oliveira et al. 2014), the absolute values of the water balance components are found to be consistent with ground-based/model-based time series. As an extension to earlier investigations, this study demonstrated that there are weak relationships between trends (from monthly time series) in water balance components by satellite products and ground-based/model-based sources, whereas reasonable consistency was obtained in the trends of annual time series.

**CONCLUSIONS**

This study evaluated the water balance of the YRB from 2003 to 2012 by the following three satellite products: TRMM precipitation, MODIS evapotranspiration and GRACE TWSC, and the changes in water balance components were analyzed. TRMM and MODIS products performed well in reproducing monthly precipitation and evapotranspiration obtained from ground-based observation and land surface model datasets, respectively. A good relationship between GRACE TWSC and the residual water storage from a water balance equation was identified (correlation coefficient of 0.71). The water
balance error for the YRB was 18.1 mm/month and 152.5 mm/yr at monthly and annual time steps, accounting for 20% and 14% of YRB precipitation, respectively. The error in GRACE TWS was the largest among the three satellite products at monthly time steps, while the error in TRMM precipitation was the largest at annual time steps. The temporal changes in water balance components based on satellite products performed better at an annual time step compared to a monthly time step. Rates of change in the water balance components for the YRB at annual time steps were in the range 83–318% of the corresponding trends from ground-based and model-based datasets. The estimated stream flow by satellite products for the YRB increased at a rate of 1.9 mm/yr² during 2003–2012, which was consistent with ground-based stream flow changes (the slope of 2.3 mm/yr²).

This study evaluated the reliability of multiple satellite products used in a water balance equation, and found that the three products were more suitable for water cycle investigation at annual, rather than monthly, time steps. The current investigation is an improvement on previous studies that assess the accuracy of basin-scale hydrological components separately. This study demonstrates that water balance investigation using remote sensing products is a practical and informative undertaking that is expected to continue to evolve with refinements to inversion algorithms and the spatial and temporal resolution of datasets.

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