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Research papers

Influences of reservoir operation on terrestrial water storage changes detected by GRACE in the Yellow River basin

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ABSTRACT

The implementation of water–sediment regulation scheme (WSRS) in the Yellow River can induce instantaneous water redistribution over regions through frequent reservoir operation. In this study, we attempt to detect the signal of changes in terrestrial water storage (TWS) induced by reservoir operation during WSRS based on GRACE data. Meanwhile, a modified index is proposed to further assess the contributions of human activities and climatic variability to annual changes in TWS. The results indicated that the impounding or releasing events in the XLD reservoir and the LYX reservoir during WSRS can be well detected by monthly GRACE CSR solutions with the DDK3 filter. In addition, there exists a significant correlation between annual changes in TWS and reservoir water storage changes within both the catchment area above the LYX reservoir ($r_s = 0.88$, $p < 0.01$) and the catchment area above the XLD reservoir ($r_s = 0.86$, $p < 0.01$). The modified index proposed in this study, which is an attribution index based on a variation analysis, showed that reservoir operation contributes significantly to changes in TWS especially for heavily reservoir-regulated regions.

1. Introduction

Reservoir operation is one of the most representative anthropogenic activities to influence environments, which can result in a regional mass redistribution through the water release or impoundment (Wang et al., 2011). Since 2002, the water–sediment regulation scheme (WSRS) has been implemented by the Yellow River Conservancy Commission (YRCC) with the goal of regulating flood flow and alleviating the problem of sediment accumulation in reservoirs and the lower reaches of the Yellow River via multi-reservoir operations (Bai et al., 2019; Ji et al., 2018). This scheme can be regarded as an unprecedented human-designed "controlled experiment" (Miao et al., 2016). The volume of water stored in different reservoirs, which is one of the most important components of surface water, has tremendously changed during the process of WSRS. As a result, terrestrial water storage (TWS) for heavily reservoir-regulated regions may be affected with the frequent release or impoundment of water. However, the effects of reservoir operation on regional TWS have long been unknown because an accurate estimation of regional TWS for regions with intensive human activities is difficult.

The successful launch of GRACE satellite in 2002 has provided an unprecedented opportunity to directly quantify the monthly variation of TWS in real time globally. Since then, GRACE data have been widely adopted to monitor variations in TWS for different regions especially for those with intensive human activities which are generally difficult to measure based on traditional methods, such as in situ measurements (Long et al., 2017) and hydrologic model simulations (Rodell et al., 2004; Scanlon et al., 2018). For example, various attempts have been made to detect water storage changes in large lakes or reservoirs such as the Lake Victoria of East Africa (Swenson and Wahr, 2009), Three Gorges Reservoir (TGR) of China (Wang et al., 2011), and Lake Nasser of Egypt (Longuevergne et al., 2013) using GRACE data, since these signals of water storage changes are so strong that they can be much more likely captured by GRACE data (Table 1). However, GRACE data are poorly applied to detect water storage changes in reservoirs across the Yellow River basin, whose spatial extents are much smaller and such changes are less likely to be captured (Tangdamrongsub et al., 2019; Xie et al., 2019a). More insights into the influence of reservoir operation on changes in regional TWS are expected to help better understand the regional water cycle under intensive human activities.

As one of the most typical human activities across the Yellow River basin, reservoir operation has undoubtedly posed substantial impacts on hydrological cycles in this region. Apart from this, the results from our

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previous study (Xie et al., 2019a) have further demonstrated that reservoir operation can influence inter-annual variations in TWS over the whole Yellow River basin especially for heavily reservoir-regulated regions. Given the above reasons, we attempt to detect the signal of changes in TWS around the Longyangxia (hereafter, LYX) reservoir and the Xiaolangdi (hereafter, XLD) reservoir, both of which are much smaller than the TGR reservoir (shown in Table 1), and then quantify the contributions of different items including reservoir operation and climatic variability to changes in TWS based on a new modified indicator. The conclusions drawn from this study not only can provide a deep insight into the influences of human activities on hydrological processes but also can be useful in helping make appropriate policies for regional water resources management.

The following main objectives are achieved in this study:

1. Validating the feasibility of GRACE data to detect the signal of water storage changes caused by reservoir operation around the LYX reservoir and the XLD reservoir;
2. Evaluating the hydrological influences of reservoir operation on changes in regional TWS by the joint use of GRACE data and in-situ ground observations during WSRS;
3. Analyzing the relationship between regional discharge and terrestrial water storage anomaly (TWSA) under reservoir operation in different regions;
4. Assessing the contribution of reservoir operation to changes in regional TWS for regions where large reservoirs are located.

The other parts of this paper are organized as follows. Firstly, an introduction is made to the study region in Section 2. Then, the materials and methods used to evaluate the hydrological influences of reservoir operation on changes in TWS are described in Section 3. Section 4 and Section 5 display the results and discussions regarding the feasibility of GRACE data to detect the signal of variations in water stored in reservoirs and changes in TWS during WSRS for different regions. Meanwhile, the contributions of different factors including climatic variability and human activities to changes in regional TWS have been assessed in this section. Finally, all conclusions drawn from this study are summarized in Section 6.

2. Study area

The Yellow River (shown in Fig. 1) is the second longest river in China (after the Yangtze River) with a length of more than 5,400 km (Dong et al., 2015). The Yellow River basin, which has a drainage area of 79.50×10^4 km^2, has been viewed as one of the most important basins in China due to hosting a population of over 120 million people and irrigating more than 200,000 km^2 arable land (Lin et al., 2019; Zhang et al., 2017; Wang et al., 2012). The topography in the Yellow River basin generally declines from west to east with a mean elevation of ~ 1900 m above the sea level. This region is a typical semi-arid river basin (a long-term mean annual PET/P of 2.1), with annual mean precipitation ranging from 900 ~ 1050 mm and annual mean temperature ranging from 15 ~ 18 ℃. To ensure water supply for various human activities including irrigation and hydropower generation, many large or small-sized reservoirs were constructed in the mainstream of the Yellow River with a total capacity of over 68 km^3 (Bi et al., 2019). According to the statistics data published by the Yellow River Conservancy Commission of the Ministry of Water Resources and Deng et al. (2020), over 3000 reservoirs have been constructed in the entire Yellow River basin. Up to 2018, 219 major or middle-sized reservoirs were distributed in the Yellow River basin including 34 major reservoirs. Therefore, the Yellow River is regarded as a river with intensive reservoir regulation. In this study, the LYX reservoir and the XLD reservoir have been investigated because the mean annual changes in water stored in these two reservoirs can account for over 90% of that occurred in all reservoirs located in the Yellow River basin during 2003–2015 (shown in Section 4.1).

Located at the entrance of Longyangxia canyon in Qinghai Province, the LYX reservoir is viewed as the first cascaded project on the mainstream of the upper part of the Yellow River. This reservoir has an average elevation of above 2,700 m, with a distance of 3,778 km from entrance to the sea. The LYX reservoir has comprehensive functions after its completion in 1989, such as flood and ice control, power generation and irrigation etc. As one of the main reservoirs involved in WSRS, this reservoir has a maximal storage capacity of 27.63 km^3. Meanwhile, the catchment area above the LYX reservoir has a total area of 12.91×10^4 km^2.

Completed in 2001, the XLD reservoir mainly aims at mitigating flood risk and satisfying water demands for irrigation and industry at first (Hu et al., 2012). The catchment area controlled by the XLD reservoir accounts for over 92.5% of the total area of the Yellow River basin, with a total area of 77.21×10^4 km^2. With the increasing amount of sediment deposited in the reservoir and downstream reach of the Yellow River, the problem of imbalance between water and sediment grows to be more and more severe in recent years (Wang et al., 2017a). Therefore, the XLD reservoir is becoming the main control for WSRS because it is the last reservoir before the Yellow River emptying into the Bohai Sea with a distance of only 800 km from entrance to the sea (Kong et al., 2015). According to the statistical data published by Chinese National Committee on Large Dams, the XLD reservoir has a maximal capacity of 12.65 km^3 which is$<$1/2 compared to the LYX reservoir.

The Yellow River basin features high sediment loads and heavy soil erosion but relatively low water discharge to the sea. As a result of land use changes and other anthropogenic influences, massive sediments and soil have eroded from landscapes, with subsequent transport into rivers, reservoirs or lakes, and finally resulted in serious river siltation (Bai et al., 2019). River sedimentation can cause the emergence of extreme

Table 1
Detailed information about the different study regions in related literature.

Literature	Study regions	Maximum surface area (km^2)	Maximum capacity (km^3)	Study period	Data sources
Swenson and Wahr (2009)	Lake Victoria	67,197	2760[a]	2003–2007	CSR
Wang et al. (2011)	Three Gorges Reservoir	976	39.3	2002–2010	CSR
Longuevergne et al. (2013)	Lake Nasser	6200	162	2003–2009	CSR, GRGS
Moore and Williams (2014)	Lake Volta	9190	148[b]	2003–2011	CSR
Zhou et al. (2017)	Dongting Lake	2124	16.7[c]	2003–2016	HUST, CSR, JPL, GFZ
	Poyang Lake	3601	27.6[d]	2003–2016	
Ferreira et al. (2018)	Lake Volta	9190	148[b]	2002–2016	CSR, JPL
Wang et al. (2019)	Three Gorges Reservoir	976	39.3	2003–2012	CSR
This study	LYX Reservoir	383	27.6	2006–2015	CSR
	XLD Reservoir	277	12.7	2002–2012	

[a] The maximal capacity of the Lake Victoria can refer to Tong et al. (2016);
[b] The maximal capacity of the Lake Volta can refer to Jin et al. (2018);
[c] The maximal capacity of the Dongting Lake can refer to Yu et al. (2018);
[d] The maximal capacity of the Poyang Lake can refer to Liu et al. (2020).

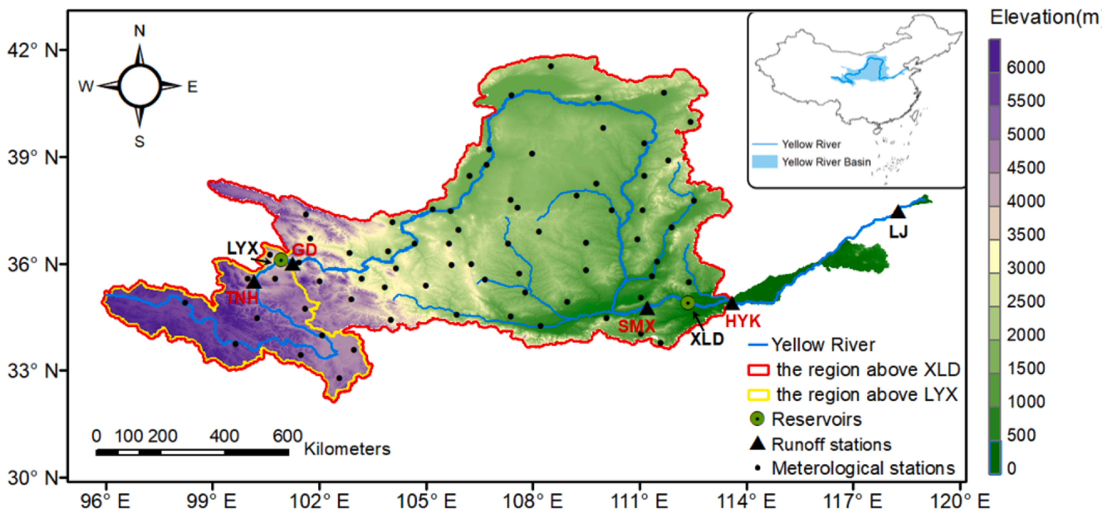

Fig. 1. Spatial distribution of study reservoirs, meteorological stations and hydrological stations across the Yellow River basin. LYX: Longyangxia; XLD: Xiaolangdi; TNH: Tangnaihai; GD: Guide; SMX: Sanmenxia; HYK: Huayuankou; LJ: Lijin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

floods, which further pose threats to residents' lives, property and economic development in the lower reaches of the Yellow River (Wang et al., 2015). To build a harmonious water–sediment relationship and reduce the risk of floods, the WSRS has been implemented since 2002. Under the implementation of WSRS, large amounts of water will be stored by some major reservoirs (e.g. the LYX and the XLD) several months in advance and then released within a short period, to say about 10–20 days (Wang et al., 2010). By creating such artificial flood peaks, the WSRS can effectively scour river channels in the lower reaches. During each controlled event, the instantaneous rate of dam-regulated artificial water can reach up to 4,000 m^3/s, which is nearly ten-fold higher than normal releases of floodwater from reservoirs during non-WSRS periods (about 300 m^3/s) (Xu et al., 2016). Since unusually large amounts of water are often released or stored by the reservoirs during WSRS, surface water storage, which is an important component of terrestrial water storage, will correspondingly change and significantly affect hydrological cycles and regional environments around these reservoirs. More basic information for the LYX reservoir and the XLD reservoir also can refer to Table 2.

3. Materials and methods

3.1. Materials

3.1.1. Water level records and reservoir water storage data

In-situ observations of water level and reservoir water storage are provided by the Yellow River Conservancy Commission of the Ministry of Water Resources. In this study, we collect monthly time series of water level and reservoir water storage about the LYX reservoir from April 2006 to December 2015 and the XLD reservoir from January 2002 to December 2012 respectively. These data are jointly used to characterize the variations in water stored in the LYX reservoir and the XLD reservoir involved in the implementation of WSRS. Some monthly observations about reservoir water storage are not available, and they can be reconstructed by the water level records based on a water level-storage relationship (Lei et al., 2018; Wang et al., 2011).

Given the limited period of reservoir water storage data available, we further collect annual water storage variations in the LYX reservoir and the XLD reservoir during the period of 2003–2015 according to the information published by the Water Resources Bulletin of the Yellow River (https://www.yrcc.gov.cn/zwzc/gzgb/gb/szygb/). After comparing reservoir water storage data derived from different sources, we find that water storage variations in the LYX reservoir and the XLD reservoir published by the Water Resources Bulletin of the Yellow River are consistent with that calculated from the Yellow River Conservancy Commission of the Ministry of Water Resources (Supplement Figure S1) at annual scales. Therefore, both the annual water storage variations in the LYX reservoir and the XLD reservoir from 2003 to 2015 are further applied to evaluate the influence of human activities, such as reservoir operation, on changes in regional TWS in the following section.

3.1.2. GRACE data

TWS mainly refers to the summation of different forms of water stored above and beneath the earth including surface water (e.g. water stored in reservoirs, lakes, rivers, wetlands, snow, glacier etc.), soil moisture and groundwater (Cazenave and Chen, 2010). Since launched in 2002, the Gravity Recovery and Climate Experiment (GRACE) satellite have been providing high quality observations of the temporal variations in Earth's gravity field, which are primarily the combined result of changes in surface water, soil water and groundwater (Chao, 2016). Therefore, GRACE-observed TWS has been usually provided as an integrated monthly averaged water storage change (Tian et al., 2017), sometimes also termed as TWSA, which represents the surface mass anomaly relative to the baseline average over January 2004 to December 2009.

To detect the influence of reservoir operation on changes in regional TWS during WSRS, the products of monthly GRACE solutions from April 2002 to December 2015, published by the Center for Space Research (CSR, at the University of Texas, Austin), are applied in this study. The latest Release-06 GRACE Level-2 data products are expressed as

Table 2
Basic information for the LYX reservoir and the XLD reservoir.

Reservoirs	Longyangxia (LYX)	Xiaolangdi (XLD)
Year complected	1989	2001
Type	Arch dam	Rockfill dam
Dead storage level (m)	2560	225
Normal pool level (m)	2600	275
Installed capacity (MW)	1280	1800
Annual power generation (10^6 kW/h)	5924	5100
Maximal capacity (km^3)	27.63	12.65
Maximal mass change (Gt)	9.9[a]	5.9[b]

[a] From July 2009 to November 2009;
[b] From August 2003 to October 2003.

dimensionless spherical harmonic coefficients (SHC) of the geopotential up to degree 60 (or 96), which can be freely downloaded from the website of https://www2.csr.utexas.edu/grace/RL06.html. It is worth mentioning that GRACE data in some months are not available because of the battery problem. As suggested by Long et al. (2015a), these missing data have been well interpolated by averaging the values of their adjacent months in this study, which can maintain the average seasonal cycle at monthly scale (Xie et al., 2019b).

3.1.3. In-situ runoff data and auxiliary data

In-situ observations of runoff are mainly collected from four different gauging stations, namely Tangnaihai (TNH), Guide (GD), Sanmenxia (SMX) and Huayankou (HYK) (shown in Fig. 1). The former two gauging stations are the inlet and outlet of the LYX reservoir respectively while the left two gauging stations are the inlet and outlet of the XLD reservoir. In this study, daily runoff records of the SMX and the HYK spanning from 2003 to 2015 are provided by the Yellow River Conservancy Commission of Ministry of Water Resources of China and then aggregated to monthly values. Meanwhile, daily runoff records of the TNH and the GD are only available from 2006 to 2013. Mean monthly observed runoff (m^3/s) obtained from these runoff stations are further converted to depth units (mm per month) by cumulating flow rates for each month during the study period and dividing by the total drainage area upstream of each site (shown in Fig. 1) in order to better analyze the possible impact of reservoir operation on the TWSA-runoff relationship.

To investigate the influence of climatic variability on changes in regional TWS, daily records of precipitation are collected from 71 meteorological stations (shown in Fig. 1), all of which are provided by China Meteorological Administration (CMA). The region-averaged precipitation can be estimated by the observations from different meteorological stations based on a Thiessen polygon method that is widely used in many studies (Chao et al., 2021; Spencer et al, 2019; Strauch et al., 2012). Similar to runoff data, daily precipitation is aggregated to monthly values during the study period. In addition to climatic variability, changes in regional TWS can also be influenced by some human activities, such as reservoir operation and water withdrawals (Rodell et al., 2009; Scanlon et al., 2018). Therefore, we further collect annual water withdrawals data besides annual water storage variations in the LYX reservoir and the XLD reservoir across the Yellow River basin during the study period. These data can freely be acquired from the Water Resources Bulletin of the Yellow River (https://www.yrcc.gov.cn/zwzc/gzgb/gb/szygb/). More information about the datasets used in this study also can refer to Table 3.

Table 3
Overview of datasets used in this study.

Variable	Temporal resolution	Period	Data Source
Water Level	Monthly	April 2006 to December 2015 (LYX)	Yellow River Conservancy Commission of Ministry of Water Resources of China
	Monthly	January 2002 to December 2012 (XLD)	
Reservoir water storage	Monthly	April 2006 to December 2015 (LYX)	
	Monthly	January 2002 to December 2012 (XLD)	
Runoff	Daily	January 2006 to December 2013 (LYX)	
	Daily	January 2003 to December 2015 (XLD)	
Reservoir water storage	Annual	January 2003 to December 2015	Water Resources Bulletin of the Yellow River
Water withdrawals	Annual	January 2003 to December 2015	Water Resources Bulletin of the Yellow River
TWSA	Monthly	April 2002 to December 2015	Center for Space Research (CSR)
Precipitation	Daily	January 2003 to December 2015	China Meteorological Administration (CMA)

3.2. Methods

3.2.1. GRACE-based analysis method for TWSA and changes in TWS

Based on time-variable GRACE SHC, mass changes on the Earth's surface for a specific period can be represented in equivalent water heights (Wahr et al., 1998; Seo et al., 2006). This method can be described as follows:

$$\Delta h(\theta,\varphi)=\frac{R\rho_E}{3\rho_w}\sum_{l=0}^{N}\frac{2l+1}{1+k_l}\sum_{m=0}^{l}\widetilde{P}_{lm}\cos\theta(\Delta C_{lm}\cos(m\varphi)+\Delta S_{lm}\sin(m\varphi)) \quad (1)$$

where Δh is equivalent water heights (mm) for each month derived from GRACE SHC, R is the radius of the Earth (6,378 km),ρ_E is the average density of the earth (5,515 kg/m^3),ρ_w is the average density of water (1,000 kg/m^3), k_l is the set of load Love number of degree l,$\widetilde{P}_{lm}$ are the fully normalized Legendre functions, C_{lm} and S_{lm} are the monthly GRACE SHC after subtracting the temporal mean. Degrees in Equation (1) can range from 0 to higher values, which generally denote spatial resolution ranging from global to regional. The results from previous study (Lander and Swenson, 2012) indicated that a degree over 60 in SHC will lead to a higher uncertainty or error. Therefore, the degree of SHC is truncated at 60 in this study ($N = 60$). To obtain accurate TWSA across the study regions, various methods of processing GRACE data have been proposed in previous work (Chen et al., 2006; Chen et al., 2021; Geruo et al., 2013; Han et al., 2005; Luthcke et al., 2006). In this study, several techniques are applied to reduce the error and noise induced by satellite measurements. As suggested by Werth et al. (2009), the DDK3 anisotropic decorrelation filter is used to relieve such errors before estimating monthly terrestrial water storage fields of the study regions (Kusche et al., 2009). We also replace the geocenter terms (degree one coefficients) with solutions using the method from Swenson et al. (2008) because they are missing in the original datasets. In addition, the C20 coefficients are replaced by results from satellite laser ranging (SLR) with the goal of reducing uncertainty (Cheng and Tapley, 2004). Finally, we compute the GRACE solutions on a 0.5°×0.5° grid after converting the SHC into equivalent water height anomalies (Wahr et al., 1998). The scaling method suggested by Long et al. (2015b) has been applied in this study to consider the bias and leakage effects on GRACE data.

Changes in regional TWS are defined as the difference between TWSA in the initial month and that in the final month for a specific period. For example, changes in TWS during the impounding (or releasing) event for the reservoir can be estimated by calculating the difference between TWSA in the initial month and that in the final month for this impounding (or releasing) event. Similarly, annual changes in TWS can be estimated by calculating the difference between TWSA in January and that in December for a specific year.

3.2.2. Spearman's rank correlation analysis

In this study, the Spearman's rank correlation coefficient (r_s) (Vachaud et al., 1985) is applied to analyze the relationship between reservoir water storage changes and changes in TWS within the catchment area above the XLD reservoir and the catchment area above the LYX reservoir at annual time scales respectively. The Spearman's rank correlation coefficient can be calculated as:

$$r_s=1-\frac{6\times\sum_{i=1}^{n}d_i^2}{n(n^2-1)}\ (-1\leq r_s\leq 1) \quad (2)$$

where d_i denotes the difference between the ranks of two variables; n represents the number of alternatives;r_s is the Spearman's rank correlation coefficient ranging from −1 to 1. A value of r_s near 1 denotes a perfect positive association of rank while a value of r_s near −1 denotes a perfect negative association of rank. The closer the value of r_s to 0, the weaker is the association between the ranks of two variables. Additionally, we evaluate the significance level of the Spearman's rank correlation coefficient based on the Student's T-test. The significance test is accepted when the p value associated with r_s is less than the significance level (commonly, 0.01).

3.2.3. GRACE derived TWSA-runoff hysteresis

The study about relationship between discharge and TWS over regions has been a focus of the hydrological sciences because it is crucial for water resources management and assessment. In addition, it can help us better understand the complex underlying mechanism for hydrological processes over catchments under the joint effects of human activities and climate changes. The study of Macedo et al. (2019) revealed that regional water storage can increase with little variations in river discharge for the reason that water is being stored in large lakes or reservoirs, especially in some human-regulated systems. In this study, we aim to characterize the relationship between the regional discharge and its TWSA based on the joint use of GRACE data and ground-based observations. To better build the relationship with regional TWSA (mm), mean monthly observations of runoff data (m^3/s) is converted to water depth (mm) by cumulating flow rates for each month and then dividing by the drainage area of different study regions. Following work by Tourian et al. (2018) and Sproles et al. (2015), the relationship between regional discharge and TWSA for regions generally can be represented as hysteresis loops, which can present the variations in both TWSA and regional discharge with different seasons.

3.2.4. Contributions of different factors to changes in regional TWS

Changes in TWS (ΔTWS) can be significantly influenced by human activities (Tapley et al., 2019; Huang et al., 2015a; Huang et al., 2015b), which mainly refer to reservoir operation and water withdrawals in this study. We can describe this change as:

$$\Delta TWS_H = \Delta TWS_R + \Delta TWS_W \tag{3}$$

where ΔTWS_H refers to the part of ΔTWS induced by human activities;ΔTWS_R refers to the part of ΔTWS induced by reservoir operation; ΔTWS_W refers to the part of ΔTWS induced by different forms of water withdrawals (e.g., agricultural, industrial and domestic).

Since GRACE satellite detects the total changes in regional TWS resulted from the joint effects of human activities and climatic variability, we can estimate the climate-driven changes in regional TWS through:

$$\Delta TWS_C = \Delta TWS_{GRACE} - \Delta TWS_H = \Delta TWS_{GRACE} - (\Delta TWS_R + \Delta TWS_W) \tag{4}$$

where ΔTWS_C is the climate-driven ΔTWS under the joint effects of different climatic factors (e.g. precipitation, evapotranspiration and outflow); ΔTWS_{GRACE} is the total ΔTWS derived from GRACE data.

Furthermore, changes in regional TWS induced by climatic variability (ΔTWS_C) can be further divided into three parts, i.e., evapotranspiration-induced ΔTWS (ΔTWS_{ET}), precipitation induced ΔTWS (ΔTWS_P) and outflow-induced ΔTWS (ΔTWS_O). It has been widely acknowledged that ET is extremely hard to measure or quantify through direct observations, especially in some regions with intensive human activities (Xie et al., 2021; Long et al., 2014). Given that an accurate estimation of regional ET across the Yellow River basin is not available due to intensive human activists, such as massive water withdrawals and reservoir regulation (Lv et al., 2017), we can estimate ΔTWS_{ET} as follows:

$$\Delta TWS_{ET} = \Delta TWS_C - \Delta TWS_P - \Delta TWS_O \tag{5}$$

To better present the fractional contribution rates of different factors to the total ΔTWS under the joint effects of human activities and climatic variability, we propose a modified contribution indicator (η) by considering the water balance equation and with reference to our previous study (Xie et al., 2019a), which can be computed as follows:

$$\eta_R = \frac{\Delta TWS_R}{\Delta TWS_{Total}} \times 100\% \tag{6}$$

$$\eta_W = \frac{\Delta TWS_W}{\Delta TWS_{Total}} \times 100\% \tag{7}$$

$$\eta_P = \frac{\Delta TWS_P}{\Delta TWS_{Total}} \times 100\% \tag{8}$$

$$\eta_{ET} = \frac{\Delta TWS_{ET}}{\Delta TWS_{Total}} \times 100\% \tag{9}$$

$$\eta_O = \frac{\Delta TWS_O}{\Delta TWS_{Total}} \times 100\% \tag{10}$$

$$\eta_H = \frac{\Delta TWS_R + \Delta TWS_W}{\Delta TWS_{Total}} \times 100\% \tag{11}$$

$$\eta_C = \frac{\Delta TWS_P + \Delta TWS_{ET} + \Delta TWS_O}{\Delta TWS_{Total}} \times 100\% \tag{12}$$

where $\Delta TWS_{Total} = |\Delta TWS_R| + |\Delta TWS_W| + |\Delta TWS_P| + |\Delta TWS_{ET}| + |\Delta TWS_O|$ is the sum of absolute ΔTWS derived from all factors; η_R, η_W, η_P, η_{ET}, η_O represent the contribution of reservoir operation, water withdrawals, precipitation, evapotranspiration and outflow to the total ΔTWS for a specific region respectively; η_H and η_C denote the contribution of human activities and climatic variability to the total ΔTWS. When η is a positive value, it indicates a positive influence on the total ΔTWS; otherwise, a negative influence can be found. For example, precipitation can pose a positive effect on the total ΔTWS while evapotranspiration usually has a negative effect on the total ΔTWS. According to the above assumptions, we can quantify the contributions of different factors including climatic variability and human activities to inter-annual changes in regional TWS during 2003–2015.

4. Results

4.1. Contributions of the LYX reservoir and the XLD reservoir to total reservoirs water storage changes under WSRS

The Yellow River basin has been regarded as one of the most reservoir-regulated regions. Fig. 2 presents the inter-annual changes in water stored in different reservoirs across the Yellow River basin spanning from 2003 to 2015, according to the statistical data collected from the Yellow River Water Resources Bulletin. As shown in this figure, annual changes in water stored in all reservoirs ranged from −7.8 km^3/yr to 11.9 km^3/yr during the period from 2003 to 2015. The maximum value occurred in 2003 when the annual precipitation in the Yellow River basin was 30.1% higher than the average of annual precipitation from 1980 to 2015. In contrast, a minimum value was observed in 2006 due to a loss of massive water in order to maintain the water supply for various human activities. The lowest record of water storage in reservoirs occurred in 2006 due mostly to the large precipitation deficit accompanied with an obvious increase in water withdrawals across the Yellow River basin in this year (shown in Supplement Figure S2). Overall, annual changes in water stored in all reservoirs across the entire Yellow River basin were almost overlapped with that derived from the sum of the XLD reservoir and the LYX reservoir. In other words, the LYX reservoir and the XLD reservoir can be regarded as the two most important reservoirs engaged in WSRS. In fact, more than 90% of the annual water stored in reservoirs across the Yellow River basin are regulated by the above mentioned two reservoirs. Considering the above reasons, these two reservoirs (i.e. the LYX reservoir and the XLD

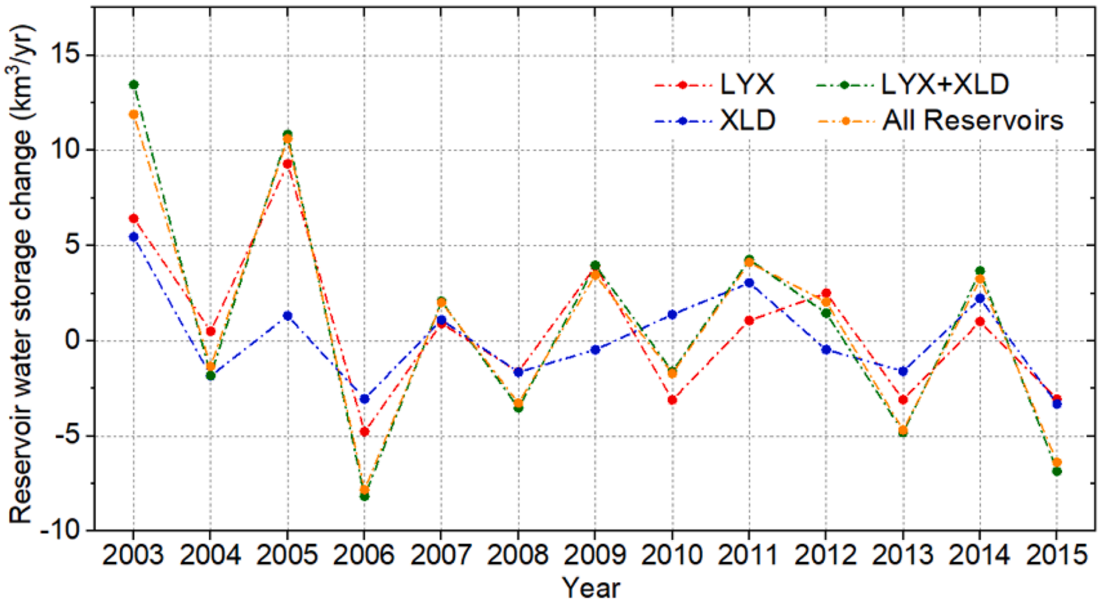

Fig. 2. Inter-annual changes in water stored in the LYX reservoir, the XLD reservoir and all reservoirs across the entire Yellow River basin during 2003–2015. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

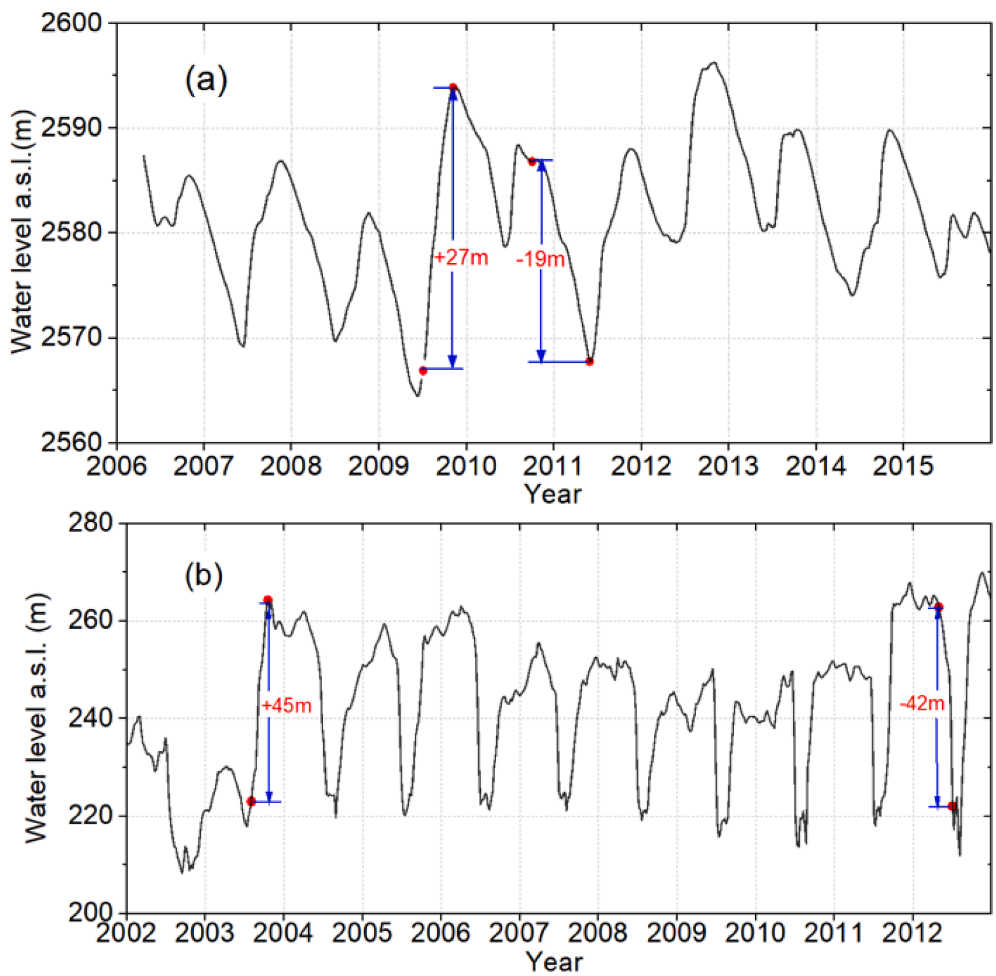

Fig. 3. Monthly water level records above sea level (a.s.l.) for two major reservoirs including (a) the LYX reservoir and (b) the XLD reservoir that are engaged in WSRS. The above data are collected from the Yellow River Conservancy Commission of Ministry of Water Resources (http://www.yellowriver.gov.cn). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

reservoir) will serve as the examples for the influence assessment of reservoir operation on hydrological cycles in the following analysis.

4.2. Variations in reservoir water storage under WSRS

Water level records of the LYX reservoir and the XLD reservoir are presented in Fig. 3. As seen from Fig. 3(a), the most rapid rise in water level for the LYX reservoir occurred in July 2009. After continuously impounding water for five months, there was a total rise of ~ 27 m during this period, with an impounded water volume of 9.9 km^3, which accounted for approximately 75% the volume of water emptied into the Bohai Sea from the Yellow River in 2009 (shown in Supplement Figure S3). Apart from the rising events, we also notice that there was a rapid decrease in the water level from October 2010 to May 2011 for the LYX reservoir. As a result, water stored in the LYX reservoir had experienced a drastic reduction over the past nine months, with a loss of 6.0 km^3 water in total. Compared to the LYX reservoir, the XLD reservoir is generally easier to reach a high water level, because the latter has a smaller capacity (Table 2). As presented in Fig. 3(b), a rapid water level rise was identified in the XLD reservoir, the magnitude of which can quickly reach up to 45 m spanning from August 2003 to October 2003. Correspondingly, the amount of water stored in the XLD reservoir increased from 0.5 km^3 to 6.4 km^3 over the past three months. The releasing event for the XLD reservoir occurred in April 2012, and over 5.6 km^3 water had been continuously discharged in just three months.

Fig. 4 shows the multi-year averages of monthly precipitation within the catchment area above the LYX reservoir (2006–2015) and the catchment area above the XLD reservoir (2002–2012) under WSRS. Dominated by an arid and semiarid continental monsoon, the precipitation in the flood season (from July to October) accounts for more than 65% of the total annual precipitation in the Yellow River basin (Wang et al., 2020). As expected, monthly precipitation within the catchment area above the LYX reservoir reached its maximum in July during 2006–2015, with an average value of 117.5 mm (Fig. 4(a)). Similarly, the maximum of monthly precipitation within the catchment area above the XLD reservoir was up to 86.3 mm in July during 2002–2012. With respect to extreme flood induced by massive precipitation, water regulation by reservoir was generally considered an effective measure to reduce the risk of flood in the Yellow River. As reported by Guo et al. (2018), seasonal cycles in precipitation were supposed to be highly correlated with periodic variations in the frequency of reservoir operation in a year.

Fig. 5(a) and 5(b) show the multi-year averages of water levels of the LYX reservoir and the XLD reservoir respectively. For the LYX reservoir, the mean monthly water levels showed an obvious seasonal cycle with a maximum value in November and a minimum value in June respectively (Fig. 5(a)). During the wet season from July to October, massive water had been stored in the XLD reservoir with high precipitation during this period (Fig. 4(b)). As a result, water level peaked in April (Fig. 5(b)) and then experienced a sharp decrease until July with a minimum value for the XLD reservoir. The discrepancies in monthly water level records between the LYX reservoir and the XLD reservoir mainly occurred in Summer. The minimum value of mean monthly water levels of the LYX reservoir (June) arrived more early than that of the XLD reservoir (July), because the LYX reservoir was located in the upstream of the Yellow River. The LYX reservoir may usually release the majority of water stored in reservoir with the goal of better regulating flood during the flood season (from July to October). In general, both of monthly water levels in the LYX reservoir and the XLD reservoir seem to fluctuate from month to month, which can be mainly attributed to an integrated effect of natural precipitation and artificial controls.

4.3. Influences of reservoir operation on changes in TWS detected by GRACE

To investigate the influences of reservoir operation on changes in TWS around the reservoirs and its surrounding areas, we estimate the difference between TWSA in different periods, that is to say, before and after impounding (or releasing) water with the corresponding reservoirs based on GRACE data. The events discussed in this section are mainly selected based on magnitudes of monthly water level fluctuations in the LYX reservoir and the XLD reservoir respectively, which has been shown in Section 4.2. Fig. 6(a) shows the spatial pattern of GRACE-derived mass anomaly around the LYX reservoir and its surrounding areas before and after impounding water from July 2009 to November 2009. In general, it shows an overall positive trend in GRACE-derived mass

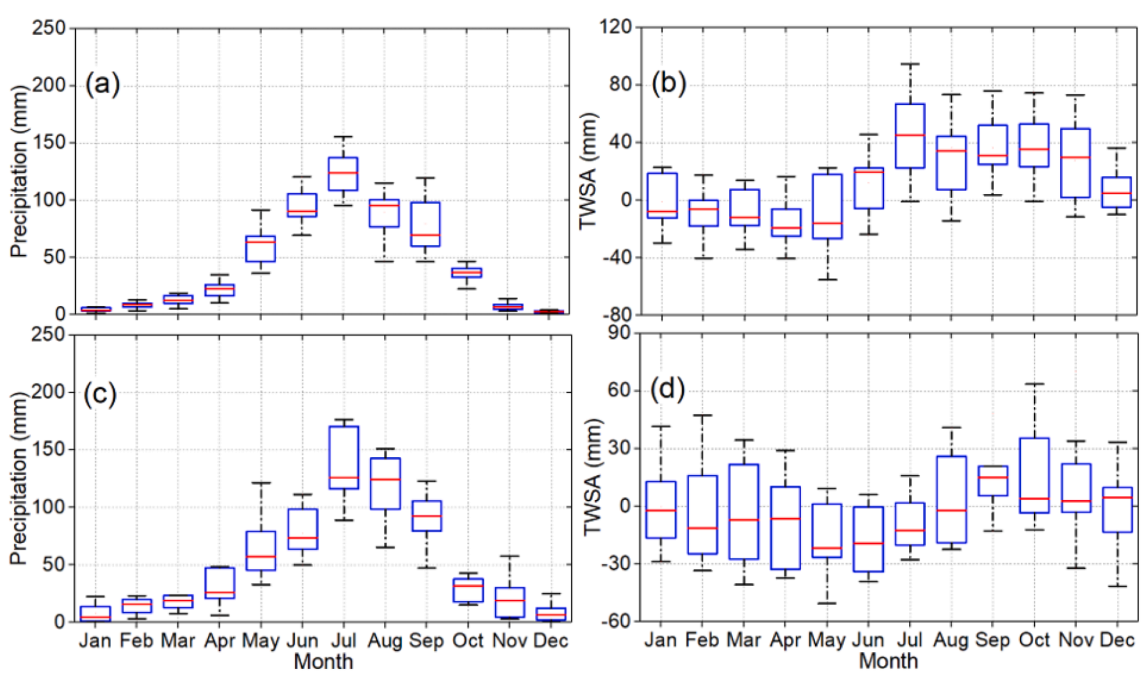

Fig. 4. Multi-year averages of monthly precipitation and monthly GRACE-derived TWSA within (a-b) the catchment area above the LYX reservoir (2006–2015) and (c-d) the catchment area above the XLD reservoir (2002–2012) under WSRS.

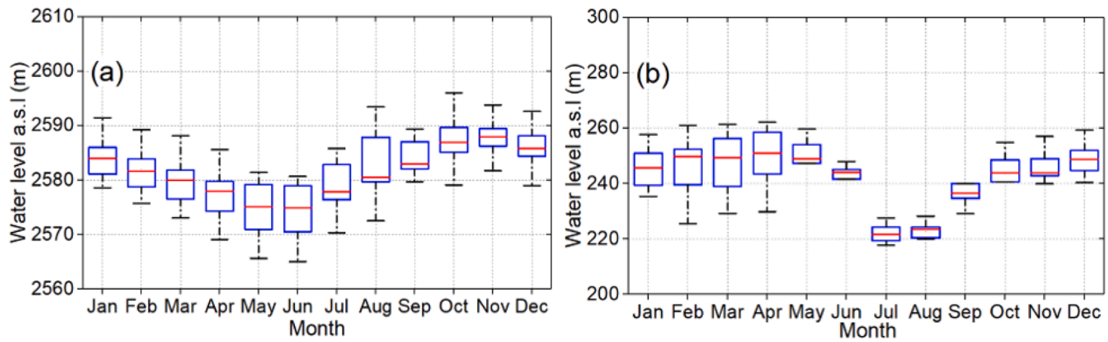

Fig. 5. Multi-year averages of monthly water level records in (a) the LYX reservoir (2006–2015) and (b) the XLD reservoir (2002–2012) under WSRS.

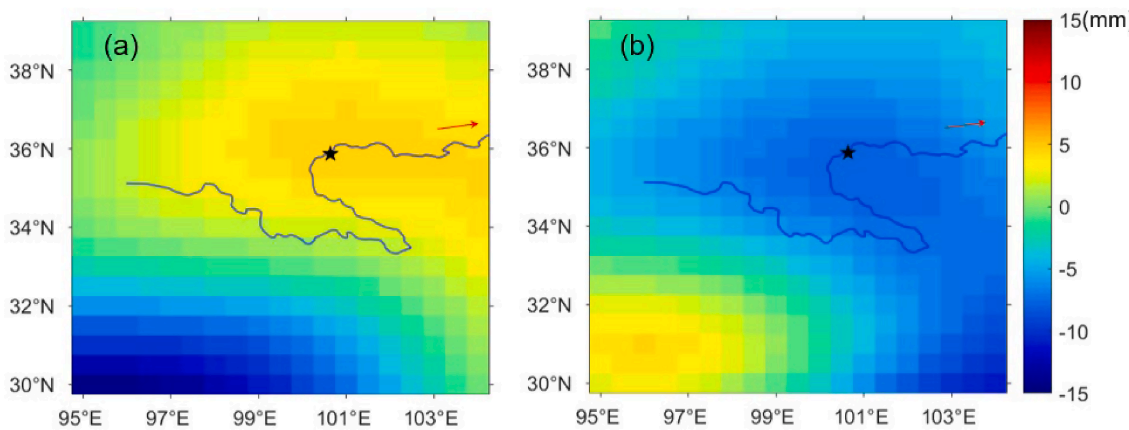

Fig. 6. GRACE-derived mass anomaly differences at 0.5°×0.5° grid between (a) July 2009 and November 2009 (impounding), (b) October 2010 and May 2011 (releasing) respectively within the LYX reservoir area. The pentagram it the location of the LYX reservoir, and the blue lines are streams. Water level records spanning from two different periods have been presented in Fig. 3(a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

anomaly over the surrounding area of LYX reservoir. On the contrary, a negative trend is found in most of the surrounding area of LYX reservoir during the period from October 2010 to May 2011 when massive water has been discharged from the LYX reservoir, and the most obvious negative trend is found in the LYX reservoir as shown in Fig. 6(b).

Compared to the LYX reservoir, the XLD reservoir shows more obvious changes in TWSA before and after impounding (Fig. 7(a)) (or releasing (Fig. 7(b)) water. As displayed in Fig. 7(a), GRACE data are used to estimate the equivalent water height changes during the period from August 2003 to October 2003 when massive water stored in the XLD reservoir drastically increase. The results indicate that changes in TWS over the past three months is more than 10 mm in most of the

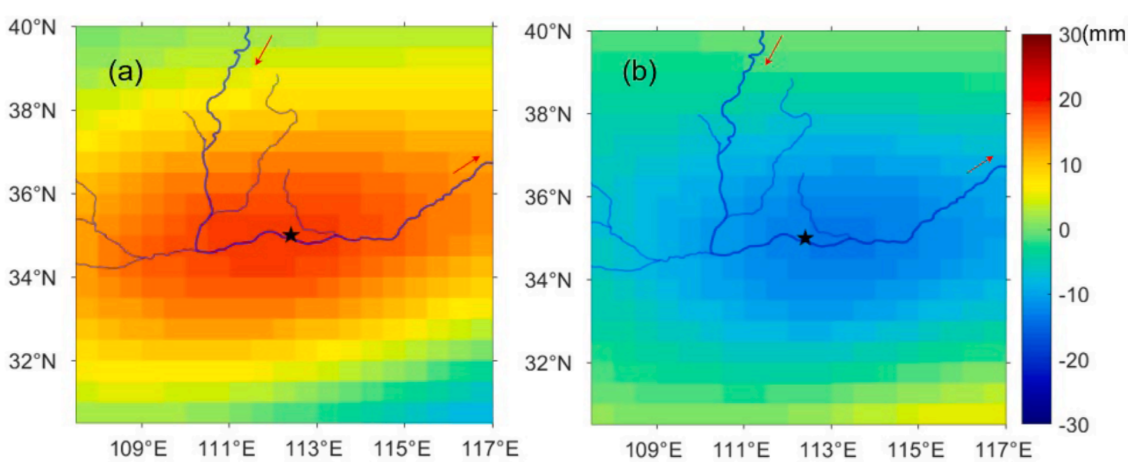

Fig. 7. GRACE-derived mass anomaly differences at 0.5°×0.5° grid between (a) August 2003 and October 2003 (impounding), (b) April 2012 and June 2012 (releasing) respectively within the XLD reservoir area. The pentagram it the location of the XLD reservoir, and the blue lines are streams. Water level records spanning from two different periods have been presented in Fig. 3(b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

surrounding area of XLD reservoir, especially in the location of the XLD reservoir with a maximum value over 20 mm. In comparison, a strong negative signal has been detected around the surrounding area of XLD reservoir as expected from April 2012 to June 2012 during which over 5.6 km^3 water has been discharged from the XLD reservoir in just three months. These consecutive observations from GRACE data indicate that the evolutions of TWS in different regions are mainly as a consequence of water impoundment or discharge induced by reservoir operation.

Reservoir operation including water impoundment and discharge can directly lead to a water storage redistribution over regions. To further understand the hydrological influences of reservoir operation under WSRS on changes in TWS at regional scales, we analyze the relationships between annual changes in TWS and reservoirs water storage changes based on the Spearman's rank correlation analysis. The units of variations in regional TWS derived from GRACE data should be converted into cubic meters (km^3) by multiplying the area of catchments with the goal of keeping consistent with the reservoir water storage changes. As shown in Fig. 8(a) and 8(b), we find a significant correlation between changes in TWS and reservoir water storage changes on annual timescales both within the catchment area above the LYX reservoir and the catchment area above the XLD reservoir. Notably, the performance of the catchment area above the LYX reservoir (with $r_s = 0.88, p < 0.01$) is better than that of the catchment area above the XLD reservoir (with $r_s = 0.86, p < 0.01$). This phenomenon can arise from the discrepancies in their dominated human activities within two regions. Human activities within the catchment area above the LYX reservoir are mainly controlled by reservoir operation while human activities within the catchment area above the XLD reservoir may have more water withdrawals besides reservoir operation. In general, the results shown in Fig. 8 indicate that reservoir operation both within the LYX reservoir and the XLD reservoir can exert an obvious influence on changes in regional TWS at annual scales.

4.4. Relationship between regional discharge and terrestrial water storage

In addition to the direct analysis of changes in regional TWS due to reservoir operation events, we analyze here the possible impact of reservoir operation on the TWSA-runoff relationship. Such relationships can be represented as hysteresis loops which show the variations both in TWSA and regional runoff in different months (Sproles et al., 2015; Tourian et al., 2018). Hysteresis is a phenomenon related to input–output relationships where the output does not only depend on the value of the input at the same instant, but also on the history of the input. Fig. 9 shows the relationships between TWSA and runoff (R) at selected stations in the Yellow River basin. Four hydrological stations along the main river are used to present the relationships, namely Tangnaihai (TNH), Guide (GD), Sanmenxia (SMX) and Huayuankou (HYK). TNH and GD are located before and after the LYX reservoir while SMX and HYK are located before and after the XLD reservoir (shown in Fig. 1). We calculate TWSA for the upstream basin of the four stations.

As shown in Fig. 9, monthly mean GRACE-derived TWSA versus monthly mean runoff over the Yellow River basin show hysteresis loops during 2006–2013. The shape and size of the loops are often controlled by many natural factors including climate, topography and geology of the watershed (Sproles et al., 2015; Tourian et al., 2018). However, in the Yellow River basin, strong human activities are significantly affecting the shape and size of the loops as well. As we can see, the hysteresis loops observed at four stations along the river are rather irregular and very different from other studies (Sproles et al., 2015; Tourian et al., 2018) where loops were mainly controlled by natural factors. We speculate that regional runoff and TWSA generally will not show a simple linear or exponential relationship as others (Kirchner, 2009), due to intensive human activities especially in human-dominated regions like the Yellow River basin.

Among four stations, TNH is the most upstream station, where the runoff is less affected by large reservoirs which are located more downstream. A typical hysteresis loop in 2009 (Fig. 9(d)) begins at the start of the calendar year. TWSA decreases slightly till March while runoff increases. From March to July, both TWSA and runoff increases significantly. This is clearly due to the melting of snow in the upstream part of the river basin and increasing precipitation (shown in Supplement Figure S4). From July to September, runoff slightly decreases with decreasing precipitation while TWSA continues to increase. Starting from September, both TWSA and total runoff decrease with a sharper decrease of total runoff, indicating decreasing groundwater together with very limited amount of precipitation. The different shapes of the loops in different years at TNH and the other stations indicates the large inter-annual variability of runoff and TWSA. Complex shapes can be observed in some years such as 2006, showing the highly complex natural dynamics of the regions.

From upstream to downstream, the hysteresis loops of four stations become narrower and narrower, indicating that the reservoirs along the river are storing water or there are strong water supply demands from riverside users, including irrigation and domestic water use. The Yellow River basin is well-known for its intensive human activities (Wang et al., 2015) and large-scale agricultural irrigation is the main source of water

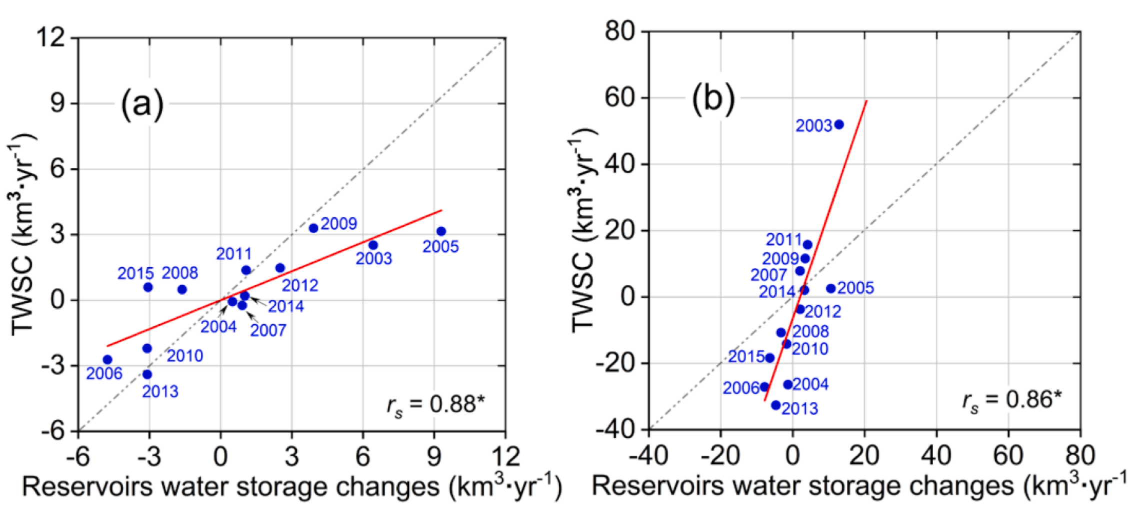

Fig. 8. The relationships between annual changes in TWS and reservoir water storage changes within (a) the catchment area above the LYX reservoir and (b) the catchment area above the XLD reservoir from 2003 to 2015 based on the Spearman's rank correlation (r_s). Annotations represent the Spearman's rank correlation coefficient (r_s), with significance at 0.01 marked by "*". The number in the scatter indicates the corresponding year, and the line is the straight-line fitting.

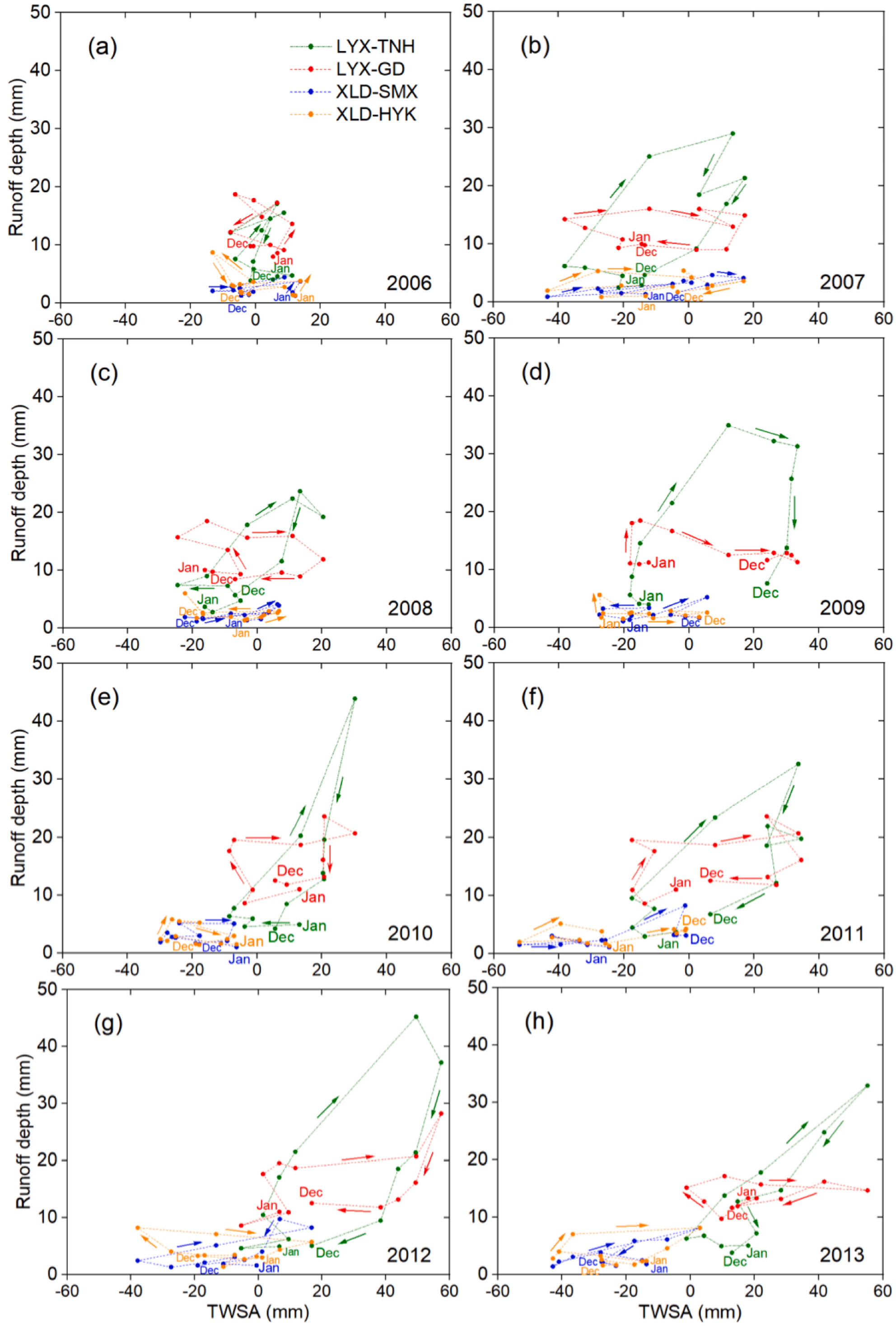

Fig. 9. Monthly GRACE-derived TWSA (*x* axis, in mm) versus runoff depth (*y* axis, in mm) over the catchment area above the XLD reservoir and the catchment area above the LYX reservoir during (a-f) 2006–2013. TNH: Tangnaihai station; GD: Guide station; SMX: Sanmenxia station; HYK: Huayuankou station; LYX: Longyangxia reservoir; XLD: Xiaolangdi reservoir.

consumption in the lower stream (Bai et al., 2017). The decrease of loop heights from the TNH station to the GD station indicates that the LYX reservoir stored water (e.g. in 2009), since these two stations are just before and after the LYX reservoir. The sharp decrease from the GD station to the HYK station can be attributed to different human factors including reservoir storage and riverside water use. There are many other reservoirs along the river, which may have effects on total runoff. However, as shown in Fig. 2, such effects induced by other reservoirs can be small if compared to those of the two large reservoirs.

4.5. Contributions of different factors to changes in regional TWS

The above analysis is mostly qualitative. The previous studies indicate that both climatic variability and human activities may have an important role in triggering TWS changes (Xie et al., 2019a; Zhang et al., 2019). Important human activities including water withdrawals, check dams in the middle stream of the basin, and large reservoirs along the river are producing a profound effect on changes in regional TWS across the Yellow River basin. Fig. 10 shows the annual precipitation, ET, outflow (or runoff), water withdrawals and reservoir water storage changes over regions during the study period. As depicted in Fig. 10, the annual ET has a wide range from 298 mm to 434 mm within the catchment area above the LYX reservoir during the period from 2006 to 2013. From 2003 to 2015, the annual ET ranges from 297 mm to 386 mm within the catchment area above the XLD reservoir, showing a slight increasing trend at a rate of + 0.8 mm/yr during this period. Under the joint effects of climatic variability and human activities, there exist some discrepancies between the water balance-derived ET and that simulated by hydrological models (Figure S5), which is consistent with the findings shown in Pan et al. (2017) and Syed et al. (2014).

To separate the contribution of reservoir operation to changes in regional TWS from other factors and have a clearer idea of the role of reservoir operation, we propose a new indicator (η) to quantify the contributions of climatic variability and human activities, in particular that of reservoir operation (shown in Section 3.4). Fig. 11 shows the contributions of different factors including human activities and climatic variability. For the whole basin, water withdrawals and reservoir operation are the two most important factors affecting TWS while revegetation due to the 'Grain to Green' revegetation program and check dams are only important for the middle part of the basin (Wang et al., 2015; Xie et al., 2019a; Feng et al., 2016), which is temporarily not our concern. Therefore, here we only show the contributions in the catchment area above the LYX reservoir and the catchment area above the XLD reservoir.

We find that large differences exist between the two regions in terms of the computed indicator (η), demonstrating that the contributions of different factors to annual changes in TWS may vary from one region to another. Fig. 11(a) shows that water withdrawals are only important for the catchment area above the XLD reservoir. Fig. 11(b) presents the similar role of reservoir operation, with slightly stronger impacts on the catchment area above the LYX reservoir. Climatic variability represented by evapotranspiration (ET), outflow (O) and precipitation (P) is the dominant factor that affects annual changes in TWS across these regions (Fig. 11(c), 11(d) and 11(e)), but they have a complementary role on the TWS for regions. Both evapotranspiration and outflow have a negative effect while precipitation has a positive effect on changes in TWS. Fig. 11(f) and 11(g) show us that human activities can even have more significant impacts on changes in TWS than climate variability, especially for the catchment area above the XLD reservoir with a very important role on changes in TWS from water withdrawals and intense reservoir operation. In general, we can see that for both the catchment area above the LYX reservoir and the catchment area above the XLD

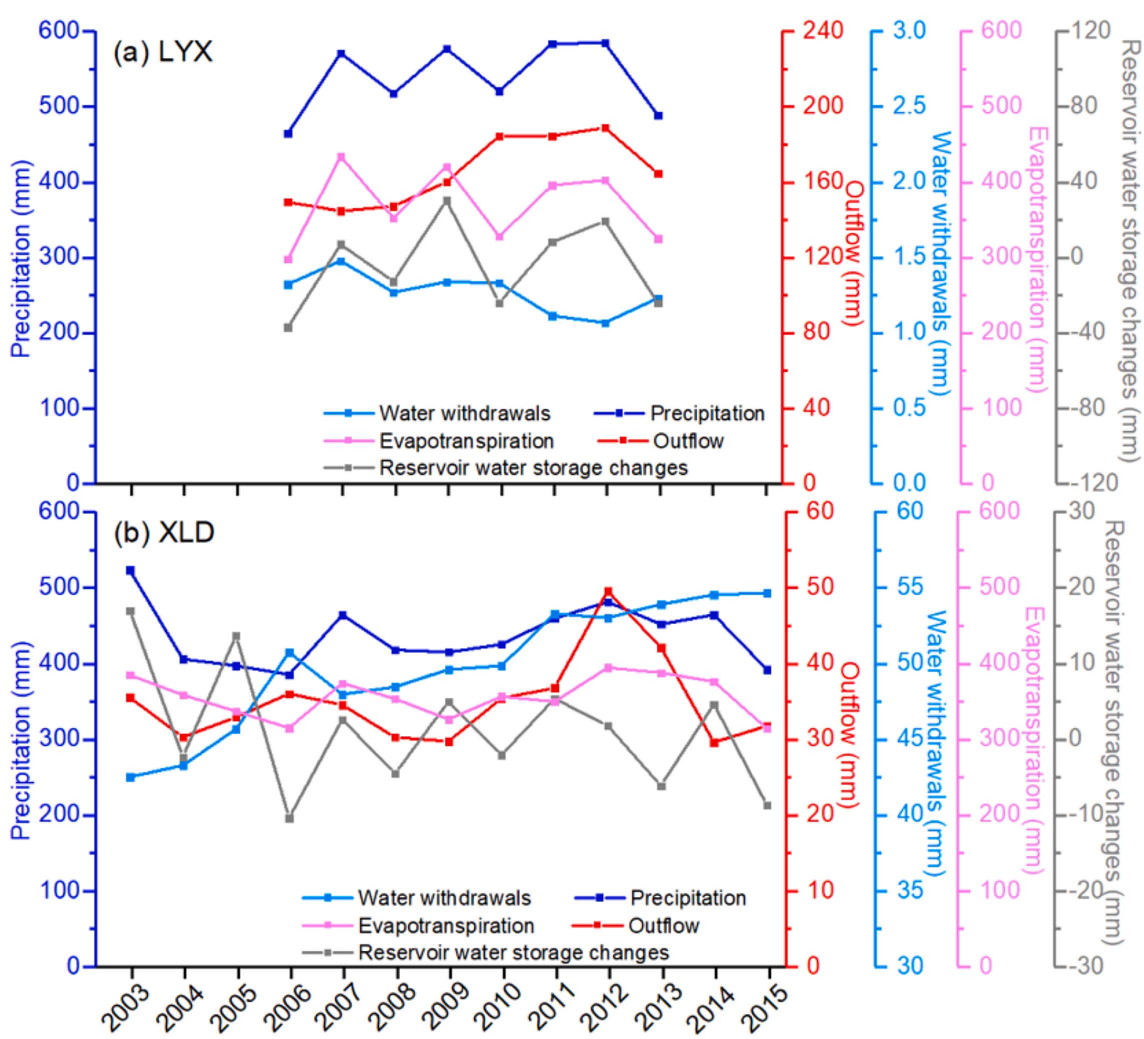

Fig. 10. Annual precipitation, ET, outflow (or runoff), water withdrawals and reservoir water storage changes within (a) the catchment area above the LYX reservoir (2006–2013) and (b) the catchment area above the XLD reservoir (2003–2015) respectively. Note that all variables have been converted to depth units (mm per year) after dividing by the total drainage area upstream of each site (shown in Fig. 1) in order to keep consistent with TWSA. The positive values of reservoir water storage changes shown in this figure denote water impoundment while negative values denote water discharge.

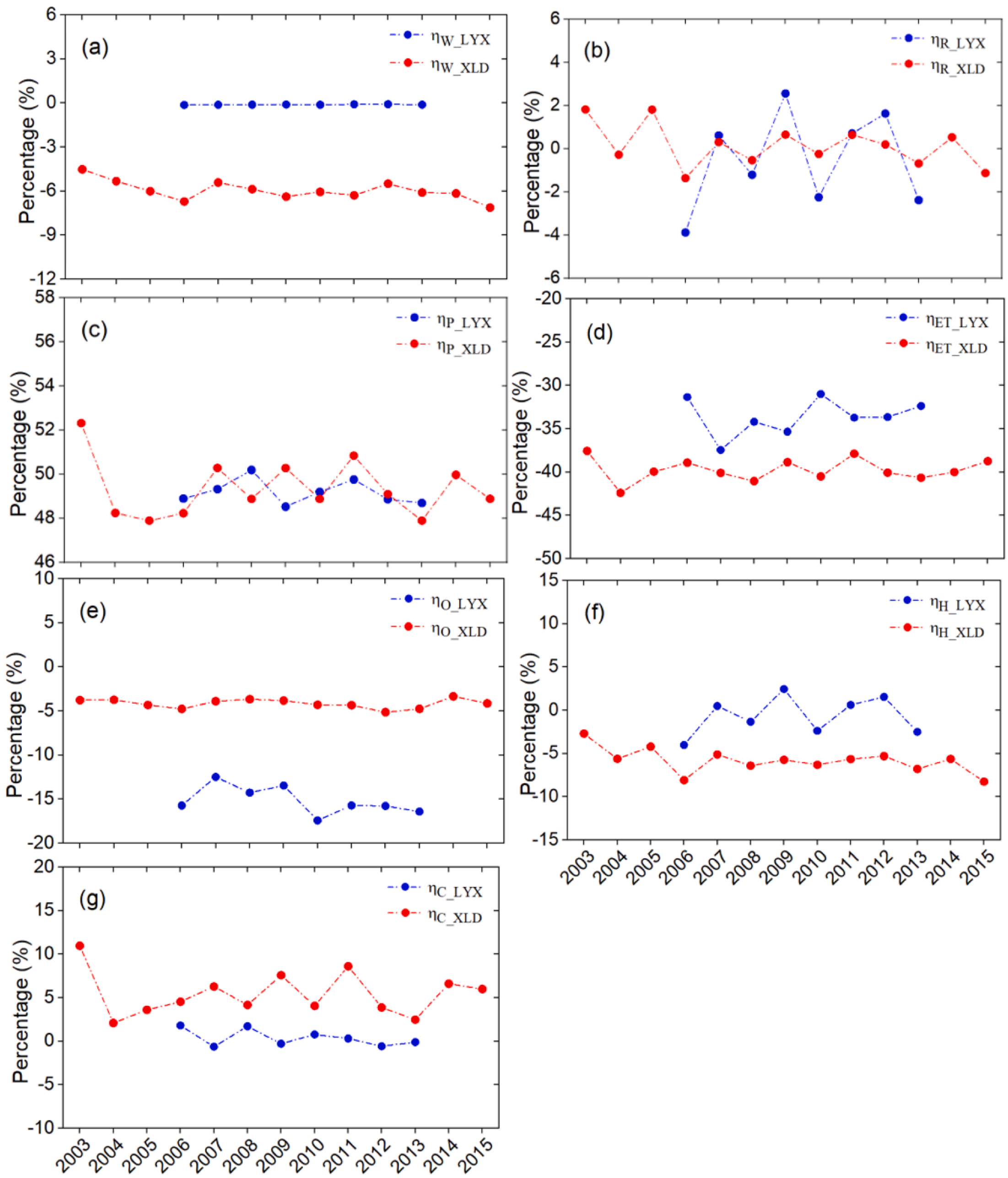

Fig. 11. Contributions of different factors from human activities and climatic variability including (a) water withdrawals (η_w); (b) reservoir operation (η_R); (c) precipitation (η_P); (d) evapotranspiration (η_{ET}); (e) outflow (η_O); (f) human activities (η_H) and (g) climatic variability (η_C) to annual changes in TWS within the catchment area above the LYX reservoir and the catchment area above the XLD reservoir.

reservoir, the contributions of reservoir operation to annual changes in TWS are substantial.

5. Discussion

The previous studies (Longuevergne et al., 2013; Wang et al., 2011) have indicated that massive water variations including impoundment and discharge indeed produced a profound effect on the hydrological or geophysical environment of study regions and its surrounding regions. As described in Section 2, it is supposed to be more difficult in detecting water storage changes based on GRACE data in the XLD reservoir owing to its smaller capacity and variations in water storage. However, we found that the signal from the XLD reservoir detected by GRACE data is more significant than that from the LYX reservoir after comparing the results shown in Fig. 6 and Fig. 7. According to the data shown in Table 1, the surface area of the XLD reservoir is less than that of the LYX reservoir, which means that variations in equivalent water heights is higher in the XLD reservoir than that in the LYX reservoir when the same amount of water was released from these two reservoirs. Their large discrepancies in water level variations during WSRS can also account for this point (shown in Fig. 3). Therefore, it is deemed as reasonable that more obvious signals have been captured by GRACE in the XLD reservoir. In other words, the huge mass variation occurred in a small region can also be captured by GRACE from space probably.

Various studies have been implemented to evaluate groundwater (Zhao et al., 2019), ice mass loss (Wang et al., 2017b), and soil moisture (Tian et al., 2017; Tian et al., 2019) based on GRACE data. However, the influences of reservoir operation on regional TWS have been rarely investigated. In this study, high correlations (r_s greater than 0.85) between annual reservoirs water storage changes and GRACE-derived changes in regional TWS were found both within the catchment area above the LYX reservoir and the catchment area above the XLD reservoir (Fig. 8). These high correlations indicate the direct effects of water storage changes induced by reservoir operation on the temporal variability of regional TWS. To summarize, we demonstrate that the variations in TWS across the study regions can be, to a large extent, induced by human activities.

Due to the implementation of WSRS for the Yellow River basin, large amounts of water will be stored by major reservoirs several months in advance and then released within a short period. Meanwhile, the LYX reservoir and the XLD reservoir always implement frequent reservoir operation acting as an important source for the local and downstream water system of the Yellow River basin during the wet season (shown in Fig. 4). Accordingly, we can find that both of the water level records of the LYX reservoir and the XLD reservoir show a strong inter-annual variation during WSRS (shown in Fig. 5). Previous studies have indicated that the cumulative influences on local TWS arising from the water impoundment (or release) of major reservoirs or lakes will significantly change the gravity signal (Ferreira et al., 2018; Wang et al., 2019). Therefore, the estimated effects of reservoir operation on GRACE along with TWS changes can be explained by the frequent impoundment or release implemented by reservoirs during WSRS, which cause the corresponding changes in available water stored in these reservoirs and eventually influence the regional TWS.

In this study, the latest Release-06 GRACE Level-2 data products have been applied to detect the variations in TWS induced by reservoir operation during WSRS. Although many techniques have been taken in this study to reduce the error or uncertainties induced by satellite measurements, cautions should be still mentioned when applying GRACE data to detect changes in regional TWS because of its coarse spatial resolution. Therefore, more accurate data that can reflect actual variations in TWS should be acquired based on the method of downscaling or new dataset.

Sproles et al. (2015) found that there were hysteresis relationships between water storage and discharge which could be represented by hysteresis loops in three regional-scale watersheds of the Columbia River Basin, USA and stated that a series of dams and reservoirs may create obvious effects on the directions of these hysteresis loops. The results in our study indicated that the magnitude and direction of hysteresis loops may vary with different conditions especially in human-dominated regions such as the Yellow River basin, which is consistent with the findings in Sproles et al. (2015). The previous studies speculated that the shape and size of the hysteresis loops were decided by the character of topography, climate, lands type, and geology over study regions (Macedo et al., 2019). Considering the physical processes underlying these hysteresis relationships between storage and discharge are complex and unknown, therefore, more efforts should be made in our future study to investigate aspects inherent in the hysteresis loops.

In the study of Xie et al. (2019a), the contribution of reservoir operation and water withdrawals (representing human activities) to changes in TWS has been analyzed based on the traditional contribution indicator while the contribution of different factors from climatic variability, which is usually represented by precipitation and evapotranspiration, has not been thoroughly investigated. In this study, the modified contribution indicator could fully assess the contributions of precipitation and evapotranspiration (representing climatic variability) to annual changes in TWS respectively besides the reservoir operation and water withdrawals (representing human activities) by considering the water balance equation and with reference to the study of Xie et al. (2019a). As a result, the contributions of different factors from climatic variability and human activities to changes in TWS in the study region have been thoroughly quantified and compared (Fig. 11). Furthermore, the massive water redistribution induced by reservoir operation at sub-yearly time scales can be well detected by the GRACE CSR solutions with the DDK3 filter. In conclusion, our analysis shows that the effects of reservoir operation implemented by major reservoirs on TWS changes is significant especially at sub-yearly time scales. Although reservoir operation can be an effective way to solve water supply, flooding and sediment problems in the Yellow River basin, it changes the hydrological cycle dramatically. This study emphasized the significant role of reservoir operation without ignoring the impacts of other factors including precipitation and evapotranspiration. As a matter of fact, observed changes of TWS are a result of complex human-natural dynamics of the basin. Water managers must be cautious to avoid possible negative effects of such TWS changes, including earthquake and landslides etc. (Talwani, 1997; Sayão et al., 2020), caused by large-scale reservoir operation. Especially, it may produce a profound effect on the hydrological or geophysical environment of study regions and its surrounding regions, which should be taken into account in water infrastructure design and management.

6. Conclusions

The implementation of WSRS has caused profound hydrological effects in the Yellow River basin. In this work, we investigated the feasibility of GRACE data to detect water storage changes induced by reservoir operation during WSRS. Meanwhile, the influences of reservoir operation on hydrological process have been well analyzed by using hysteresis loops. According to a modified index, which is an attribution index based on a variation analysis, the contributions of human activities and climatic variability on changes in TWS were further quantified. The main conclusions drawn from this study are:

1. The impounding or releasing events around the XLD reservoir and the LYX reservoir during WSRS can be well detected by the GRACE CSR solutions with the DDK3 filter. To our knowledge, the XLD reservoir may be the smallest signal source ever detected by GRACE satellite in terms of surface area. This indicates that GRACE can be a useful tool to observe the massive water redistribution induced by human activities, such as reservoir operation, even if the size is smaller than its original coarse spatial resolution;
2. According to the Spearman's rank correlation analysis, we find that reservoir water storage changes are closely correlated with changes in TWS for heavily reservoir-regulated regions at annual time scales from 2003 to 2015. The results demonstrate that there exists a significant correlation between reservoirs water storage changes and annual changes in TWS within the catchment area above the XLD reservoir (with $r_s = 0.88$, $p < 0.01$) and the catchment area above the LYX reservoir (with $r_s = 0.86$, $p < 0.01$) respectively;
3. By a comparison of the TWSA-runoff hysteresis loops observed at four stations along the Yellow River spanning from 2006 to 2013, we postulate that reservoir operation has a direct effect on the shapes and sizes of hysteresis loops over the study regions. While the magnitude of the hysteresis loops varies from region to region, they generally show a narrower shape from upstream to downstream along the Yellow River due to reservoir operation. We also highlight the important role of other human activities, such as water withdrawals, in the hydrological process;
4. Our results show that the proposed contribution indicator offers a good alternative for quantifying the contributions of different items included in human activities and climatic variability to changes in TWS for a specific region. We have applied this contribution indicator to two different basins which are controlled by insensitive reservoir operation. The results indicate that the contribution of reservoir storage changes to changes in TWS can be profound across the Yellow River basin, which has been poorly reported in previous studies. Especially, the contribution of reservoir water storage changes to annual changes in TWS can reach up to −3.89% and 1.81% within the catchment area above the LYX reservoir and the catchment area above the XLD reservoir respectively, indicating that the effects of reservoir operation on changes in TWS cannot be neglected in heavily reservoir-regulated regions.

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CRediT authorship contribution statement

Jingkai Xie: Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing - original draft, Visualization, Funding acquisition. **Yue-ping Xu:** Conceptualization, Resources, Data curation, Writing - review & editing, Supervision, Funding acquisition. **Martijn J. Booij:** Conceptualization, Writing - review & editing, Supervision. **Yuxue Guo:** Conceptualization, Methodology, Writing - review & editing, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2022.127924.

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