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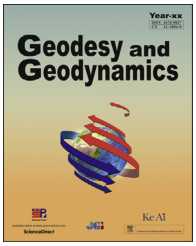

GRACE-based estimates of water discharge over the Yellow River basin

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ABSTRACT

As critical component of hydrologic cycle, basin discharge is a key issue for understanding the hydrological and climatologic related to water and energy cycles. Combining GRACE gravity field models with ET from GLDAS models and precipitation from GPCP, discharge of the Yellow River basin are estimated from the water balance equation. While comparing the results with discharge from GLDAS model and in situ measurements, the results reveal that discharge from Mosaic and CLM GLDAS model can partially represent the river discharge and the discharge estimation from water balance equation could reflect the discharge from precipitation over the Yellow River basin.

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1. Introduction

Global warming expedites the global water cycle process, and leads to the intensity variations of the regional precipitation and evapotranspiration as well as the water discharge. Water discharge is also a kind of important water resource, and the temporal and spatial variations of regional water discharge result in difficult exploitation of surface water and watershed management. As the critical component of hydrologic cycle, basin discharge is a key issue for understanding the hydrological and climatologic related to the water and energy cycles [1]. Currently the seasonal and inter-annual variability of land-scale surface water changes, including water discharge, relying on sparse in situ gauge measurement and partially verified hydrological models. In

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situ gauge measurements could quantify the value of the river channel runoff, but little information about subsurface runoff [2]. Thought mostly hydrological model driving by real-time hydro-meteorological data such as precipitation, surface temperature, lacking of spatially measurement of regional basin characteristic make the hydrological model unable to estimate the water cycle component including water discharge properly.

The Gravity Recovery and Climate Experiment (GRACE) mission, launched on March 17, 2002, provides a unique opportunity to detect continental water storage variations [3]. GRACE's temporal gravity field has been used to detect the water storage changes at a global or very large scale, and to quantify fluxes and storages for the validation and improvement of the terrestrial water balance in global land surface hydrological models [4–7]. Syed et al. [8] proposed a method for estimating monthly river basin outflows based on GRACE satellite measurements in a coupled water balance equation, which was tested on the Amazon and Mississippi River basin showing good correlation with observed streamflow. Syed et al. [9] used the same method to estimate monthly fresh water discharge from continents, drainage regions, and global land, and the comparisons to observations indicate that the method shows important potential for global-scale monitoring discharge at near-real-time. Sproles et al. [10] used GRACE measurements to estimate runoff in three regional-scale watersheds of Columbia River basin, USA and Canada, and discussing the hysteresis loops between runoff and terrestrial water storage, subsurface water and groundwater.

The Yellow River (Huanghe) is the second largest river in China, and the annual runoff accounts for 2% of the whole country but offers 12% water consumption in china. As the most important water resource in the Yellow River basin, the variations of the water discharge in Yellow River affects the personal life directly and restricted the development of social economy. In this paper, we estimate the Yellow River discharge combined with the monthly terrestrial water storage based on GRACE observation, precipitation and evapotranspiration from space observation. The GRACE-based estimates of water discharge are compared with the in situ gauge station observation over the sub-streams of the Yellow River basin.

2. Data and methods

2.1. *GRACE data and TWS*

137 approximately monthly average gravity field models from April 2002 to December 2014 are used in the paper, provided by RL05 solutions from the Center for Space Research (CSR), University of Texas at Austin. Each monthly gravity field consists of fully normalized spherical harmonic coefficients $\overline{C}_{lm}$ and $\overline{S}_{lm}$ to degree and order 96. Though comparing with CSR RL04, the degree-2 zonal harmonic C_{20} of RL05 have been improved, it is still of relatively low quality, due in part to the orbital geometry and the short separation between the satellites. The time series of C_{20} from satellite laser ranging (SLR) will be used to substitute for the C_{20} series from GRACE in the study [11].

Owing to the hybrid effects of the satellite orbit errors, ocean and atmospheric mode errors and the correlated errors of Stokes coefficients, the surface mass variations exhibit obvious N–S strip and high-frequency errors while calculate without filtering. In this paper, a hybrid filtering scheme with the combination of de-correlation filter P3M6 [12] and 300 km Fan filter [13] is taken in the subsequent calculations. Their calculation models are as follows:

$$\Delta h(\theta,\lambda)=\frac{2a\pi\rho_{ave}}{3\rho_{water}}\sum_{l=0}^{\infty}\frac{2l+1}{1+k_l}\cdot W_l\sum_{m=0}^{l}\overline{P}_{lm}(\cos\theta)\cdot W_m\Big(\Delta\tilde{C}_{lm}\cos(m\lambda)+\Delta\tilde{S}_{lm}\sin(m\lambda)\Big) \tag{1}$$

where W_l and W_m are the smoothing kernel related to order and degree respectively, namely $W_0=1$, $W_1=\frac{1+e^{-2b}}{1-e^{-2b}}-\frac{1}{b}$, $W_{n+1}=-\frac{2n+1}{b}W_n+W_{n-1}$, $b=\frac{\ln 2}{1-\cos(r/a)}$, r is the filtering radius, and $\Delta\tilde{C}_{lm}$ and $\Delta\tilde{S}_{lm}$ are the variations of Stokes coefficients after de-correlated filtering respectively.

2.2. *Estimation of terrestrial freshwater discharge*

The basic water balance equation can be described as:

$$\frac{dS}{dt}=P(t)-R(t)-ET(t) \tag{2}$$

where t is the time, S is the terrestrial water storage inferred by GRACE, P and ET are the basin-wide totals of precipitation and evapotranspiration, R represented as total basin discharge, or the net surface and groundwater outflow [8].

The TWS variations recovered from GRACE Spherical Harmonic solutions were converted into the anomaly with respect to a mean gravity field of a selected period, so called terrestrial water storage anomaly (TWSA). While estimating the GRACE-based ET by water balance method, $\frac{dS}{dt}$ is referred to a monthly scale value, or so called terrestrial water storage change (TWSC). We used a briefly and efficient way to calculate the TWSC following the method provided in Ramillien et al. [14]. The TWSC of month ith could be denoted as:

$$\mathrm{TWSC}(i)=\frac{\mathrm{TWSA}(i+1)-\mathrm{TWSA}(i-1)}{2} \tag{3}$$

We used ten years monthly gravity field model covering the period from 2003 to 2013, with six month data missing due to technical failure. The TWSA missing data were retrieved by interpolation for calculating TWSC as integrated as possible.

Here the Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (version 2) is used to obtain monthly estimates of precipitation averaged over the Yellow River basin and several sub-streams respectively. The GPCP produces global analyses of monthly precipitation available from 1979 to the present on a 2.5° × 2.5° grid. It is a merged analysis that incorporates precipitation estimates from microwave-based data from the Special Sensor Microwave Imager (SSM/I), geosynchronous-orbit satellite infrared data and surface rain gauging data from over more than 6000