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A study of Bangladesh's sub-surface water storages using satellite products and data assimilation scheme

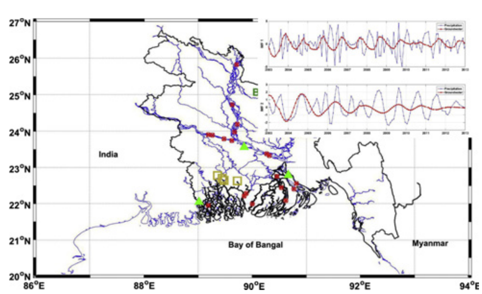
M. Khaki [a,*], E. Forootan [b], M. Kuhn [a], J. Awange [a], F. Papa [c,d], C.K. Shum [e,f]

[a] School of Earth and Planetary Sciences, Discipline of Spatial Sciences, Curtin University, Perth, Australia
[b] School of Earth and Ocean Sciences, Cardiff University, Cardiff, UK
[c] LEGOS, Université de Toulouse, IRD, CNES, CNRS, UPS, Toulouse 31400, France
[d] Indo-French Cell for Water Sciences (IFCWS), IRD-IISc-NIO-IITM Joint International Laboratory, Bangalore 560012, India
[e] Division of Geodetic Science, School of Earth Sciences, The Ohio State University, Columbus, OH, USA
[f] Institute of Geodesy and Geophysics, Chinese Academy of Sciences, Wuhan 430077, China

HIGHLIGHTS

- We assimilate GRACE data to improve a hydrological model estimations over Bangladesh.
- Square Root Analysis (SQRA) filter is used for data assimilation.
- We estimate sub-surface water storage changes within the country.
- Climate impacts on the water storages are investigated.
- Independent in-situ measurements are used to evaluate the results.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change can significantly influence terrestrial water changes around the world particularly in places that have been proven to be more vulnerable such as Bangladesh. In the past few decades, climate impacts, together with those of excessive human water use have changed the country's water availability structure. In this study, we use multi-mission remotely sensed measurements along with a hydrological model to separately analyze groundwater and soil moisture variations for the period 2003–2013, and their interactions with rainfall in Bangladesh. To improve the model's estimates of water storages, terrestrial water storage (TWS) data obtained from the Gravity Recovery And Climate Experiment (GRACE) satellite mission are assimilated into the World-Wide Water Resources Assessment (W3RA) model using the ensemble-based sequential technique of the Square Root Analysis (SQRA) filter. We investigate the capability of the data assimilation approach to use a non-regional hydrological model for a regional case study. Based on these estimates, we investigate relationships between the model derived sub-surface water storage changes and remotely sensed precipitations, as well as altimetry-derived river level variations in Bangladesh by applying the empirical mode decomposition (EMD) method. A larger correlation is found between river level heights and rainfalls (78% on average) in comparison to groundwater storage variations and rainfalls (57% on average). The results indicate a significant decline in groundwater storage (~32% reduction) for Bangladesh between 2003 and 2013, which is equivalent to an average rate of 8.73 ± 2.45 mm/year.

1. Introduction

South Asia, and in particular Bangladesh, is amongst the most water vulnerable regions of the world exhibiting an increase in droughts and floods due to climate change (McCarthy et al., 2001).

* Corresponding author at: Department of Spatial Sciences, Curtin University, Perth, Australia.
E-mail address: Mehdi.Khaki@postgrad.curtin.edu.au (M. Khaki).

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Groundwater is the main source of drinking and irrigation water (almost 90%) in the country (Islam et al., 2013). Any considerable change in climate will, therefore, affect Bangladesh's available water, which is stored in different forms including aquifers, soils, surface waters as rivers, lakes, man-made reservoirs, wetlands and seasonally inundated areas (Papa et al., 2015). Understanding the interaction between precipitation (mainly provided during the Monsoon season) and water storage changes is important to relate climate variability to hydrology. An in-depth understanding of this interaction can be more difficult in Bangladesh due to the changing behavior of monsoonal precipitation (Wang and Ding, 2006) as well as the lack of knowledge on their influence on the hydrology of the region (Shahid, 2010; Rafiuddin et al., 2010).

Groundwater accessibility has made Bangladesh an agro-based country with the main product being rice, making it one of the world's largest rice producer (Abdullah Aziz et al., 2015). The excessive groundwater usage during the last two decades has resulted in serious problems of both rapid falling of groundwater levels and the deterioration of its quality (Qureshi et al., 2015). Groundwater depletion has been reported by Shamsudduha et al. (2009) between 1985 and 2005 within different regions in Bangladesh such as north-central, northwestern, and southwestern parts of the country. This has also been shown by Shamsudduha et al. (2012) for the period of 2003 to 2007. Moreover, Sengupta et al. (2013) reported that groundwater in 63 (out of 64) districts of Bangladesh are seriously contaminated with arsenic, which is partly attributed to its depletion. A number of studies attribute the drop in groundwater level since 1972 to the rainfall decrease and increase in human water usage (see, e.g., Mainuddin, 2002; Ahmed, 2006; McBean et al., 2011; Dey et al., 2011; Adhikary et al., 2013). The Groundwater Monitoring Survey Report of Bangladesh Agricultural Development Corporation (BADC) and Institute of Water Modeling (IWM) showed a three-meter drop of groundwater levels in Dhaka (Sumon and Abul Kalam, 2014). Knappett et al. (2016) claimed that an excess extraction caused the groundwater level to decline more than 1 m near the Buriganga River, which passes in the southwest outskirts of Dhaka resulting in insufficient resources available for the rapidly growing population.

Soil water storage variation is another important factor that worsens the situation and affects agriculture. Furthermore, a considerable amount of surface water from rainfall is consumed by human and thus is not able to recharge the groundwater (e.g., Kanoua and Merkel, 2015; Qureshi et al., 2015; Alimuzzaman, 2017), which can aggravate the conditions mentioned above. Apart from efforts by these studies, a comprehensive study is missing to account for both groundwater and soil moisture variations and their connections to climate variability and change over the entire Bangladesh.

In this regard, hydrological models are important tools for simulating and predicting sub-surface water storages with high saptio-temporal resolutions (e.g., Wooldridge and Kalma, 2001; Döll et al., 2003; van Dijk et al., 2013). However, imperfect modeling of complex water cycle processes, data deficiencies on both temporal and spatial resolutions (e.g., limited ground-based observations), and uncertainties of (unknown) empirical model parameters, inputs and forcing data cause some degrees of deficiencies in them (Vrugt et al., 2013; van Dijk et al., 2011; van Dijk et al., 2014). These limitations are addressed through data assimilation, which is a technique that incorporates additional observations into a dynamic model to improve its state estimations (Bertino et al., 2003; Hoteit et al., 2012). The technique has been widely applied and validated in the fields of oceanography, climate, and hydrological science (Garner et al., 1999; Elbern and Schmidt, 2001; Bennett, 2002; Moradkhani et al., 2005; van Dijk et al., 2014; Reager et al., 2015). Several studies indicate that terrestrial water storage (TWS) derived from the Gravity Recovery And Climate Experiment (GRACE) can play a significant role in better understanding surface and sub-surface processes related to water redistribution within the Earth system (e.g., Huntington, 2006; Chen et al., 2007; Kusche et al., 2012; Forootan et al., 2014; van Dijk et al., 2014). In particular, Shamsudduha et al. (2012) showed a high capability of GRACE measurements for studying water storage variations in the Bengal Basin. A growing number of studies have also assimilated GRACE TWS in order to constrain the mass balance of hydrological models (e.g., Zaitchik et al., 2008; Thomas et al., 2014; van Dijk et al., 2014; Eicker et al., 2014; Tangdamrongsub et al., 2015; Reager et al., 2015; Khaki et al., 2017c; Schumacher et al., 2018).

The present study aims at assimilating GRACE TWS into the World-Wide Water Resources Assessment (W3RA) hydrological model (van Dijk, 2010) to analyze groundwater and soil moisture changes within Bangladesh. While the main focus is on groundwater and soil moisture, surface water as an important water source in Bangladesh is also studied since some surface water sources (e.g., lakes and rivers, except major ones) are not modeled in W3RA. Moreover, since GRACE TWS reflects the summation of all water compartments, for the first time, we use three different scenarios to account for surface water storage changes before data assimilation (see details in Section 3.1). The main reason for using the W3RA model to perform our investigations is to rely on the physical processes implemented in the model equations to consistently separate GRACE TWS (since both model and observation errors are considered) into different water compartments that includes groundwater and soil moisture. As hydrological models are usually better resolved than GRACE data during the assimilation procedure, observations are downscaled, and therefore, higher spatial resolution estimations of water storages will be available within the study region (see, e.g., Schumacher et al., 2016). Here, we use the ensemble-based sequential technique of the Square Root Analysis (SQRA) filtering scheme (Evensen, 2004) to assimilate GRACE TWS into W3RA. SQRA is preferred over the traditional ensemble Kalman filter since it offers a higher computational speed, simplicity, and independence of observation perturbations. Besides, Khaki et al. (2017a) showed that this method is highly capable of assimilating GRACE TWS data into a hydrological model.

After data assimilation, we investigate the connections between the estimated groundwater and soil moisture storages (from improved model) and both surface water level variations and rainfall from multi-mission satellite remote sensing data over Bangladesh. Satellite radar altimetry products of Jason-1 and -2, and Envisat are used in this study to provide 19 virtual river gauge stations for the period 2003 to 2013 distributed across Bangladesh. Since satellite altimetry was initially designed for ocean studies (Fu and Cazenave, 2001), its observations over inland water bodies must be carefully post processed (Birkett, 1998; Calmant et al., 2008; Khaki et al., 2015). Therefore, the Extrema Retracking (ExtR) technique, proposed by Khaki et al. (2014), is applied to retrack satellite waveform data to improve range estimations and consequently derive better water level estimations.

Further, we apply the statistical method of empirical mode decomposition (EMD, Chen et al., 2007) to explore connections between the groundwater and surface water from the model, rainfall data from the Tropical Rainfall Measuring Mission (TRMM), and retracked surface water heights. EMD is an efficient approach to extract cyclic/semi-cyclic components and is preferred over the classical techniques such as the Fourier analysis (Chen et al., 2007; Pietrafesa et al., 2016).

The remainder of this study is organized as follows: in Section 2, the study area, and datasets are presented. Section 3 provides a brief overview of the data assimilation filtering methods, the ExtR retracking method as well as the EMD approach. Results and discussion are presented in Section 4, and the study is concluded in Section 5.