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Wei Feng, Min Zhong, Jean-Michel Lemoine, Richard Biancale, Hou-Tse Hsu, et al.. Evaluation of groundwater depletion in North China using the Gravity Recovery and Climate Experiment (GRACE) data and ground-based measurements. Water Resources Research, American Geophysical Union, 2013, 49, pp.2110-2118. 10.1002/wrcr.20192 . insu-03620497

HAL Id: insu-03620497

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WATER RESOURCES RESEARCH, VOL. 49, 2110–2118, doi:10.1002/wrcr.20192, 2013

Evaluation of groundwater depletion in North China using the Gravity Recovery and Climate Experiment (GRACE) data and ground-based measurements

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Received 14 July 2012; revised 4 March 2013; accepted 8 March 2013; published 24 April 2013.

[1] Changes in regional groundwater storage in North China were estimated from the Gravity Recovery and Climate Experiment (GRACE) satellites data and ground-based measurements collected from 2003 to 2010. The study area (~370,000 km^2) included the Beijing and Tianjin municipality, the Hebei and Shanxi province, which is one of the largest irrigation areas in the world and is subjected to intensive groundwater-based irrigation. Groundwater depletion in North China was estimated by removing the simulated soil moisture changes from the GRACE-derived terrestrial water storage changes. The rate of groundwater depletion in North China based on GRACE was 2.2 ± 0.3 cm/yr from 2003 to 2010, which is equivalent to a volume of 8.3 ± 1.1 km^3/yr. The groundwater depletion rate estimated from monitoring well stations during the same time period was between 2.0 and 2.8 cm/yr, which is consistent with the GRACE-based result. However, the estimated groundwater depletion rate in shallow plain aquifers according to the *Groundwater Bulletin of China Northern Plains* (*GBCNP*) for the same time period was only approximately 2.5 km^3/yr. The difference in groundwater depletion rates estimated from GRACE and *GBCNP* data indicates the important contribution of groundwater depletion from deep aquifers in the plain and piedmont regions of North China.

Citation: Feng, W., M. Zhong, J.-M. Lemoine, R. Biancale, H.-T. Hsu, and J. Xia (2013), Evaluation of groundwater depletion in North China using the Gravity Recovery and Climate Experiment (GRACE) data and ground-based measurements, *Water Resour. Res.*, *49*, 2110–2118, doi:10.1002/wrcr.20192.

1. Introduction

[2] Groundwater is a vital source of fresh water for agriculture, industry, public supply, and ecosystems in many parts of the world. In the North China Plain (NCP), more than 60% of fresh water comes from groundwater [*Ministry of Water Resources of China (MWR)*, 2010a], and agricultural irrigation in this area relies heavily on groundwater [*Kendy et al*., 2003; *Yang et al*., 2010]. Globally, groundwater provides more than 50% of drinking water, 40% of industrial water, and 20% of irrigation water [*Zektser and Lorne*, 2004]. Overexploitation of groundwater has resulted in groundwater depletion and pollution as well as soil salinization and land subsidence, particularly in places where groundwater-based irrigation is intensive, such as in the NCP, northern India, and the central United States [*Shah et al*., 2000; *Scanlon et al*., 2007; *Wada et al*., 2010]. However, information regarding the spatial and temporal variability of groundwater storage (GWS) is extremely limited [*Shah et al*., 2000]. There are no extensive ground-based networks for monitoring large-scale GWS variations.

[3] Since its launch in 2002, the Gravity Recovery and Climate Experiment (GRACE) mission has been measuring variations in the Earth's gravity field that reveal mass redistributions [*Tapley et al*., 2004]. The GRACE mission presents a new opportunity to monitor large-scale GWS changes. Over land, temporal variations in the gravity field are mainly due to terrestrial water storage (TWS) change, which is the vertically integrated measure of groundwater, soil moisture (SM), snow, ice, and surface water. To isolate one component from total TWS (e.g., GWS), other components must be estimated from models or observations.

[4] In a prelaunch study, *Rodell and Famiglietti* [2002] evaluated the potential for isolating changes in the groundwater component of TWS in the High Plains aquifer of the central United States. Later, *Rodell et al*. [2007] isolated GWS anomalies from GRACE-derived total TWS and simulated SM data for the Mississippi River basin derived from the Global Land Data Assimilation System (GLDAS) models of the National Aeronautics and Space Administration (NASA). They found good correspondence between

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0043-1397/13/10.1002/wrcr.20192

GRACE-GLDAS estimates and those derived from monitoring well-based observations. Since then, numerous studies have shown that GRACE can be used to detect large-scale GWS changes in many parts of the world, especially where irrigation relies heavily on groundwater [*Yeh et al.*, 2006; *Strassberg et al.*, 2007, 2009; *Swenson et al.*, 2008a; *Rodell et al.*, 2009; *Tiwari et al.*, 2009; *Famiglietti et al.*, 2011; *Scanlon et al.*, 2012].

[5] Groundwater storage in the NCP, the largest wheat/maize production zone in China, is of great importance for water resources management, agricultural development, and ecosystem health in the region. The NCP includes one shallow unconfined aquifer and three deep confined aquifers of different depths (40–60 m, 120–170 m, 250–350 m, and 400–600 m) [*Sakura et al.*, 2003]. The aquifers consist of sand, gravel, clay, and silt. The region belongs to the littoral and semiarid climatic zone with nearly 70% of the rainfall occurring from June to September and 10% from March to May. Annual rainfall in this area ranges from approximately 400–600 mm/yr, whereas the evaporation rate is approximately 1000 mm/yr [*Liu et al.*, 2002]. Since the 1970s, rapid agricultural and industrial development has resulted in great demand for water resources, and nearly all of the major rivers in North China, including the Hai River, are dammed for hydroelectric power generation and urban water use. The Yellow River flows through the western and southern parts of the study region. However, only a small percentage of surface water here is used for agricultural irrigation [*Yang et al.*, 2010]. Instead, groundwater is pumped for use in agricultural irrigation. In the piedmont region of the Taihang Mountains where irrigation requirements are high, shallow groundwater level differences between 1958 and 1998 are as high as 50 m, whereas deep groundwater level differences over the same time period are as high as 90 m [*World Bank*, 2001]. By 2004, there were more than 7.6 million tube wells in North China, and 68% of irrigation here came from groundwater [*Wang et al.*, 2007]. In 2009, groundwater accounted for 61% of the total water supply in Beijing, 26% in Tianjin, 80% in the Hebei province, and 58% in the Shanxi province [*MWR*, 2010a]. With continued groundwater consumption, large depression cones have formed in the NCP [*Liu et al.*, 2001]. Based on the hydrogeological data set for North China, *Foster et al.* [2004] concluded that the excessive abstraction of groundwater has led to severe groundwater depletion in the piedmont and flood plain regions of the NCP. This groundwater depletion was further validated by two GRACE studies. *Zhong et al.* [2009] studied TWS trends in China using early GRACE data (level 2, Release 04) and found a TWS loss in Beijing, Hebei, and Tianjin at a rate of 2.4 cm/yr from 2003 to 2007. *Moiwo et al.* [2009] estimated TWS changes in the Hai River basin of North China based on gridded GRACE data (level 3, Release 04) collected more than 4 years and compared the results with in situ hydrological measurements. They found a TWS loss in the range of 1.3–2.4 cm/yr for the period from 2003 to 2006. However, the regional TWS time series based on level 3 GRACE data are potentially contaminated by leakage and amplitude-damping effects in GRACE data processing. In this study, we applied the latest level 2 (Release 05) GRACE data provided by the Center for Space Research (CSR) at the University of Texas at Austin and considered the leakage and amplitude-damping effects to make the estimate more reliable. We explored the potential of GRACE to monitor groundwater variations in North China, including the Beijing and Tianjin municipality, the Hebei and Shanxi province from 2003 to 2010. The area of our study region is large enough (~370,000 km^2) to be observed by GRACE satellites (Figure 1).

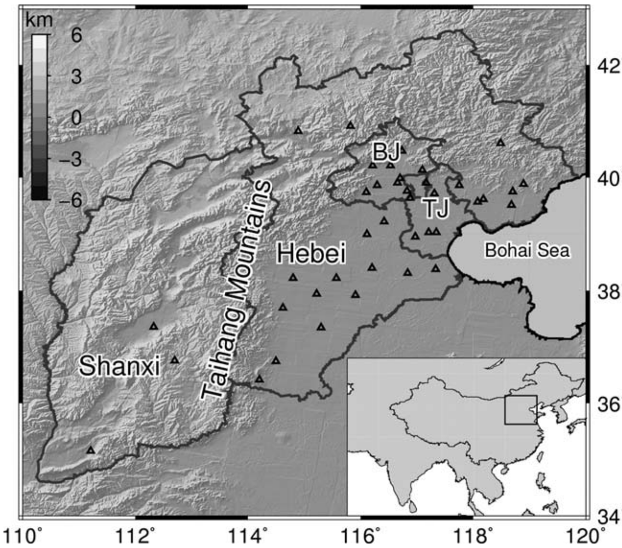

Figure 1. Map of North China showing locations of monitored well stations and shaded relief topography and boundaries of Beijing (BJ), Tianjin (TJ), the Hebei province, and the Shanxi province.

2. Data and Methods

2.1. GRACE Data and Processing

[6] We used the monthly Release 05 GRACE solutions provided by the CSR. The solutions were expressed in the form of spherical harmonic (SH) coefficients truncated to degree and order (d/o) 60. The degree 2 order 0 (C20) coefficients in the GRACE data were replaced by estimates obtained from satellite laser ranging [*Cheng and Tapley*, 2004]. Monthly geocenter estimates calculated by *Swenson et al.* [2008b] were used to account for the degree 1 coefficients of the gravity field, which GRACE does not observe. The GRACE data were corrected for glacial isostatic adjustment (GIA) based on the model of *Paulson et al.* [2007]. The SH coefficients were filtered to remove north-south stripes [*Swenson and Wahr*, 2006] and to reduce high-frequency noise (200 km Gaussian smoothing). Furthermore, we applied the following regional kernel function to these SH coefficients to obtain the TWS in the study area [*Swenson and Wahr*, 2002]:

$$\hat{\tilde{S}}_0 = \frac{4\pi a^3 \rho_E}{3R_0} \sum_{l=0}^{L_{\max}} \sum_{m=0}^{l} \frac{2l+1}{1+k_l^{'}} \left(\vartheta_{lm}^{c} \Delta C_{lm} + \vartheta_{lm}^{s} \Delta S_{lm} \right), \tag{1}$$

where R_0 is the area of the region, a and ρ_E are the mean radius and density of the Earth, $k_l^{'}$ is the lth load potential Love number, ΔC_{lm} and ΔS_{lm} are the SH coefficients anomalies with respect to the mean gravity field for the period ranging from 2003 to 2010, and ϑ_{lm}^{c} and ϑ_{lm}^{s} are the SH coefficients of the kernel function $\hat{h}$. We constructed the kernel function by decomposing the mask grid (1 at points inside the region and 0 at those outside) into SH coefficients, which were truncated to degree $L_{\max} = 60$.

[7] All of the processes mentioned earlier (i.e., truncation of SH coefficients to d/o 60, destriping, smoothing, and applying the kernel function) could make the TWS estimate biased within a given region. The signal in the target area might leak out to the surrounding areas, which would cause an amplitude damping in the area (bias). Meanwhile, the signal from the surrounding areas might leak into the target area (leakage). In theory, the regional water storage value $\overline{S_0}$ estimated by the above method can be presented in the following integral forms [*Klees et al.*, 2007]:

$$\overline{S_0} = \frac{1}{R_0}\int_{\Omega} S_0 \hat{h}\,\mathrm{d}\Omega = \frac{1}{R_0}\int_{R} S_{\mathrm{in}} \hat{h}\,\mathrm{d}\Omega + \frac{1}{R_0}\int_{\Omega-R} S_{\mathrm{out}} \hat{h}\,\mathrm{d}\Omega, \quad (2)$$

where S_0 is the true water storage variation field, S_{in} and S_{out} are the true variations inside and outside the basin, and $\overline{S_0}$ is the original regional estimate before bias and leakage corrections are applied. The first item on the right side of the equation is the biased estimate, and the second item is the leakage effect from outside of the basin. The true value in the basin is $1/R_0 \int_R S_{\mathrm{in}}\, h\mathrm{d}\Omega$, where h is the exact kernel (1 inside the basin, 0 outside). To recover this true value in the basin, we removed the leakage effect from the original estimate and corrected the biased estimate.

[8] The time series for leakage around the basin can only be estimated from mass change models, because there are no reliable observations of global large-scale mass variations except from GRACE. To estimate this "leakage in" signal, we constructed the synthetic global mass change from four hydrological models (see next section) and ocean bottom pressure data from a Jet Propulsion Laboratory (JPL) version of the Estimating Circulation and Climate of the Ocean general circulation model [*Lee et al.*, 2002]. We added a uniform layer to the global ocean to conserve the total land and ocean mass at every time step [*Velicogna and Wahr*, 2006a, 2006b]. The average values and standard deviations of the leakage time series from four models were calculated as our final leakage corrections and uncertainties.

[9] Furthermore, we used the scaling factor method to restore the amplitude-damped TWS time series. Many researchers have applied this method to study ice sheet mass loss in Greenland and Antarctica [*Velicogna and Wahr*, 2006a, 2006b], mass-induced sea level variations in the Mediterranean Sea and the Caspian Sea [*Fenoglio-Marc et al.*, 2006; *Swenson and Wahr*, 2007], and seasonal water storage variations in major drainage basins of the world [*Chen et al.*, 2007]. We used a scaling factor of 2.72 (corresponding to 200 km Gaussian smoothing) to restore the TWS time series (supporting information, section 1).

[10] In this study, we did not use the TWS and SM time series to estimate GWS anomalies directly. Instead, we used a new method proposed by *Scanlon et al.* [2012], in which SM data are filtered in the same way as GRACE data initially (i.e., projection of model grids to SH coefficients, truncation to d/o 60, application of a 200 km Gaussian smoothing). Next, we removed this filtered SM value from the GRACE-derived TWS value to obtain the filtered GWS value. Because we assumed that GWS changes are concentrated inside the area of interest, restoring the filtered GWS only requires bias correction (i.e., applying scaling factor), and no leakage correction (no external groundwater masses leaking into the area of interest) is needed. Therefore, errors of leakage corrections outside the area should be minimized. The scaling factor could be estimated using information on the spatial distribution of GWS changes, which is generally estimated from groundwater models or groundwater statistical data. Note that because the scaling factor is a parameter describing the relative change, the possible underestimates from groundwater models or statistical data will not affect the scaling factor estimate. We applied the groundwater statistical data issued by the Ministry of Water Resources of China (MWR) and the Department of Water Resources in the Hebei Province (DWRHP) to estimate the scaling factor for GWS changes (2.38) [*MWR*, 2010b; *Department of Water Resources of Hebei Province (DWRHP)*, 2010].

2.2. Hydrological Models

[11] We used four hydrological models: three versions (NOAH, VIC, and MOSAIC) of the GLDAS model from NASA [*Koster and Suarez*, 1992; *Liang et al.*, 1994; *Ek et al.*, 2003; *Rodell et al.*, 2004] and the Climate Prediction Center (CPC) model from the National Oceanic and Atmospheric Administration (NOAA) [*Fan and van den Dool*, 2004]. SM and snow water equivalents are simulated in the GLDAS models, whereas only SM data are included in the CPC model. The snow water component is typically small, and its contribution to the long-term TWS trend of North China is negligible (<0.01 km^3/yr). None of these models include the groundwater or surface water storage components. The average values and standard deviations of the four hydrological models were calculated as the best estimates and uncertainties of SM. To isolate the GWS changes from the TWS changes, we also needed to remove the contribution from the surface water reservoir storage. Nearly all of the major rivers in North China are dammed for municipal and industrial use. In fact, it is unlikely that surface water reservoir storage changes in North China contributed significantly to long-term TWS changes during the study time period [*Han et al.*, 2008]. Based on the hydrologic statistics [*MWR*, 2010a], the surface water reservoir storage change in the study region was approximately 0.04 km^3/yr from 2003 to 2010, which we considered in our final GWS estimate.

2.3. Ground-Based Measurements

[12] The ground-based measurements used in this study included 40 daily water table depth measurements collected from 2003 to 2010. The data were obtained from the National Earthquake Precursory Network of China. The locations of monitoring well stations are shown in Figure 1. We calculated monthly averages from the data to compare with GRACE results. To convert the water table depth change to the GWS change, the specific yield of each monitoring well had to be estimated. In the NCP, the specific yield of shallow aquifers increases westward from <0.05 in the coastal plain around the margin of the Bohai Sea to >0.2 in the piedmont region of the Taihang Mountains.

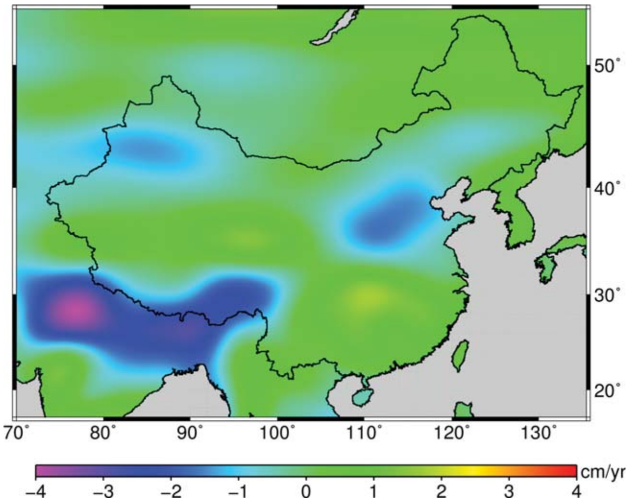

Figure 2. Trend map of terrestrial water storage (TWS) changes in China and surrounding regions derived from GRACE data collected from 2003 to 2010. Destriping and 200 km Gaussian smoothing were applied. In addition to the TWS loss in northern India and Pakistan, Figure 2 shows an obvious TWS loss in North China.

Based on the comparison between the isopleth map of specific yields in the NCP provided by *Zhang and Fei* [2009] and the locations of wells, we concluded that a reasonable range of average values for specific yields was 0.05–0.07, which we used to estimate GWS changes [*Geological Memoirs*, 1992; *Moiwo et al*., 2009; *Zhang and Fei*, 2009]. In addition, we used the 2003–2010 GWS statistics of shallow aquifers from the *Groundwater Bulletin of China Northern Plains* (*GBCNP*), which is issued annually by the MWR, and the *Groundwater Bulletin of Hebei Plain* (*GBHP*), which is issued quarterly by the DWRHP [*MWR*, 2010b; *DWRHP*, 2010].

3. Results

[13] The spatial pattern of TWS trends estimated from GRACE data for China and its surrounding regions from 2003 to 2010 is shown in Figure 2. The most obvious negative trend is located in northern India and Pakistan, which is believed to be due to groundwater depletion [*Rodell et al*., 2009; *Tiwari et al*., 2009]. GRACE-derived glacial mass loss in the Himalayas and Tian Shan, shown in Figure 2, was discussed by *Matsuo and Heki* [2010]. Figure 2 shows the obvious TWS loss in North China, specifically in Beijing, Tianjin, the Hebei province, and the Shanxi province.

[14] Figure 3 shows the percentage of each 5 arc min grid cell equipped for irrigation with groundwater globally [*Siebert et al*., 2010]. Numerous studies have demonstrated that GRACE can detect GWS changes in many heavily groundwater-based irrigated areas, shown in Figure 3, such as in northern India and Pakistan [*Rodell et al*., 2009; *Tiwari et al*., 2009], the High Plains aquifer [*Strassberg et al*., 2007, 2009], the Central Valley [*Famiglietti et al*., 2011; *Scanlon et al*., 2012], and the alluvial aquifer along the Mississippi River in the United States [*Rodell et al*., 2007]. Groundwater-based irrigation is also used extensively in the NCP (Figure 3). We further investigated how much of the GRACE-derived TWS loss in North China is the result of groundwater depletion.

3.1. GRACE Estimates of GWS Changes and Comparison With Ground-Based Measurements

[15] Figure 4a illustrates the time series of GRACE-derived changes in TWS in North China, which showed a persistent decrease since 2004. The averaged SM changes from the four hydrological models (NOAH, VIC, MOSAIC, and CPC) showed a smaller amplitude than the GRACE-derived TWS changes (Figure 4b). The phases of the TWS and SM time series agree relatively well, both peaking around October/November and reaching a minimum near April/May. Changes in GWS were estimated as the difference between GRACE-derived TWS and simulated SM, which decreased continuously since 2005 (Figure 4c). The rate of groundwater depletion obtained by subtracting simulated SM from GRACE-derived TWS was 2.2 cm/yr from 2003 to 2010. Average groundwater depth changes from the monitoring well stations over the same period also showed a continuously decreasing tendency, at a rate of 1.4 m/yr (Figure 4d). Assuming that no groundwater depletion occurred in the mountain areas and that the average specific yield is in the range of 0.05–0.07, the groundwater depletion rate estimated from well measurements is within the range of 2.0–2.8 cm/yr.

[16] The GRACE-based GWS trend from the CSR showed the largest groundwater depletion in the piedmont region of the Taihang Mountains (Figure 5a), where irrigation relies heavily on groundwater (Figure 3) [*Kendy et al*., 2003; *Yang et al*., 2010; *Siebert et al*., 2010]. The spatial pattern of the GWS trend was further estimated using a forward-modeling method. In the forward-modeling scheme, we used the spatial information of groundwater depletion trends from the *GBCNP* and the *GBHP* [*MWR*, 2010b; *DWRHP*, 2010] (see Figure 6) and rescaled the GWS estimate to make it consistent with the GRACE-based GWS

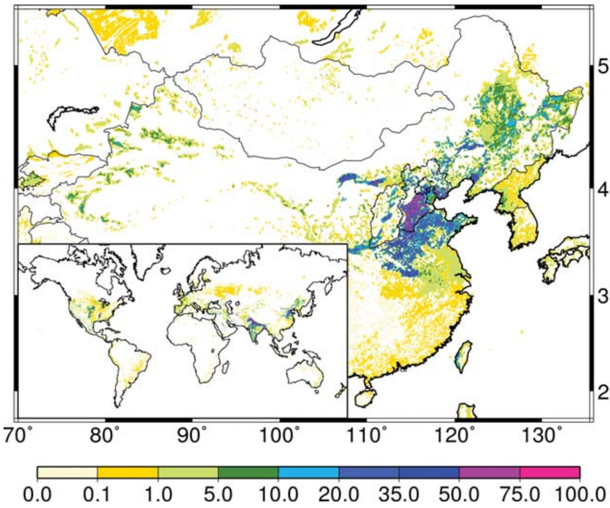

Figure 3. The area equipped for irrigation with groundwater, given as a percentage of cell area, for $5' \times 5'$ cells [*Siebert et al*., 2010]. The high percentage of area equipped for irrigation with groundwater is mapped for the North China Plain.

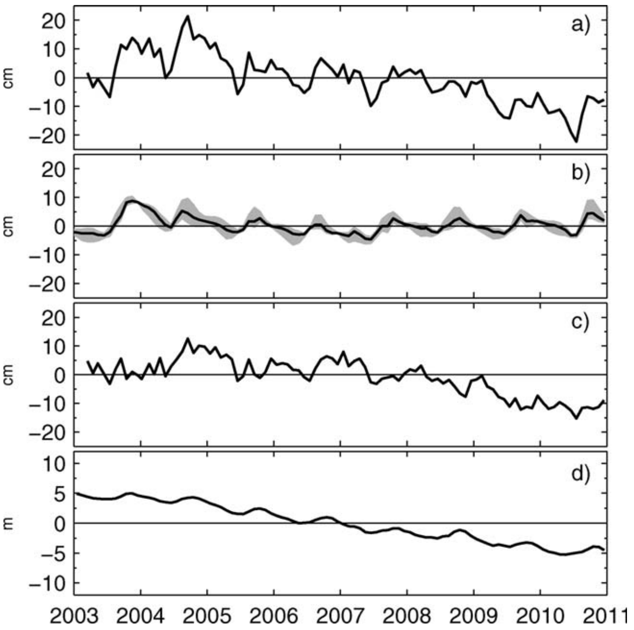

Figure 4. (a) Total terrestrial water storage (TWS) changes estimated from GRACE data. (b) Average soil moisture (SM) changes estimated by four hydrological models (GLDAS_NOAH, GLDAS_VIC, GLDAS_MOSAIC, and CPC). The gray shaded area depicts the range of the simulated SM values. (c) Groundwater storage (GWS) changes estimated from GRACE-SM data. (d) Average groundwater depth changes measured by monitoring well stations.

estimate. We then transformed the rescaled gridded data to the SH domain, truncated to d/o 60, destriped, and smoothed with a 200 km Gaussian filter. The spatial pattern of groundwater depletion derived from forward modeling agrees rather well with the GRACE-SM results (Figure 5). The groundwater depression cones in shallow aquifers were mainly located in the piedmont region of the Taihang Mountains, whereas most of the groundwater depression cones in deep aquifers were located in the central plain region of the Hebei province (Figure 5d) [*Ministry of Land and Resources of China (MLR)*, 2009]. Although the spatial resolution of groundwater depletion from GRACE data is limited to approximately 300 km, there is a good correlation between the location of GRACE-observed groundwater depletion and that of groundwater depression cones, which confirms that GRACE does observe the groundwater depletion occurring in North China.

[17] Figure 6 depicts the spatial pattern of GWS trends in shallow aquifers in the plain and piedmont regions of North China based on the *GBCNP* issued annually by MWR and the *GBHP* issued quarterly by DWRHP [*MWR*, 2010b; *DWRHP*, 2010]. More details can be found in section 4 of the supporting information. The most obvious depletion of shallow groundwater occurred in the piedmont region of the Taihang Mountains (Figure 6). The shallow groundwater table here declined more than in the eastern plain areas (supporting information, section 5, Figure S2). The depletion of shallow groundwater in Beijing was also extremely severe. Note that the possible GWS changes in deep aquifers are not included in Figure 6. Nevertheless, the spatial pattern of the GWS depletion rate in Figure 6 is in good agreement with the GRACE-SM results (Figures 5a–5c). As stated earlier, the results of forward modeling based on the data in Figure 6 also show good agreement with the spatial pattern from GRACE-SM results at GRACE resolution (i.e., filtered) (Figure 5d), which increases the confidence in GRACE results.

3.2. Error Estimation of GRACE-Based GWS Changes

[18] We further considered the uncertainty of GWS changes derived from GRACE data and hydrological models. As summarized by *Longuevergne et al.* [2010], the errors induced by the GRACE data processing include the scaled GRACE measurement error ($k\Delta\hat{\overline{S_0}}$), the error due to leakage correction ($k\Delta S_{\mathrm{leakage}}$), and the uncertainty of the scaling factor ($\Delta k\hat{\overline{S_0}}$ and $\Delta kS_{\mathrm{leakage}}$). The error from hydrological models, processing error from applying Gaussian smoothing with different radii and different destriping methods, and the error from GIA were also considered here.

[19] To estimate GRACE measurement error, we used the method proposed by *Chen et al.* [2009]. The measurement error was determined from root-mean-square variability over the Pacific Ocean at the same latitude as North China, in which true mass variation should be small, as barotropic ocean mass variations have been removed by the dealiasing process. A potential limitation of the scaling method is how mass change is distributed inside the basin. We applied the mass distribution within the study area determined from four hydrological models to estimate the uncertainty of the scaling method (supporting information, section 1). Based on our simulation, we conclude that the uncertainty of the scaling factor estimation (Δk) is less than 5%, which we included in our final error budget. The uncertainty of applying Gaussian smoothing with different radii and applying different destriping methods was estimated to be 0.12 cm/yr, which is also included in our final error budget as the GRACE data processing error (supporting information, section 2). The GIA effect in our study area is approximately 0.13 cm/yr. We pessimistically assumed that the uncertainty of the GIA correction was ±50% and thus 0.06 cm/yr.

[20] Table 1 lists the different error components in the final error budget of monthly GWS estimates and the trend. As shown in Table 1, the errors primarily result from the hydrological model error, GRACE measurement error, processing error, and leakage error. The hydrological models used in this study only simulate SM above 2 m. There might be significant variations in unsaturated water storage below 2 m, which would not be included in the hydrological models. This is especially true for the western part of the Hebei province, where the mean water table depth is usually tens of meters [*Foster et al.*, 2004]. Therefore, the unmodeled SM could lead to errors in our final groundwater estimate. The error from leakage corrections estimated from hydrological models might be underestimated as well. The final error estimate of the GWS trend based on GRACE data and hydrological models was 0.3 cm/yr, based on the assumption that no correlations exist between the individual trend errors.

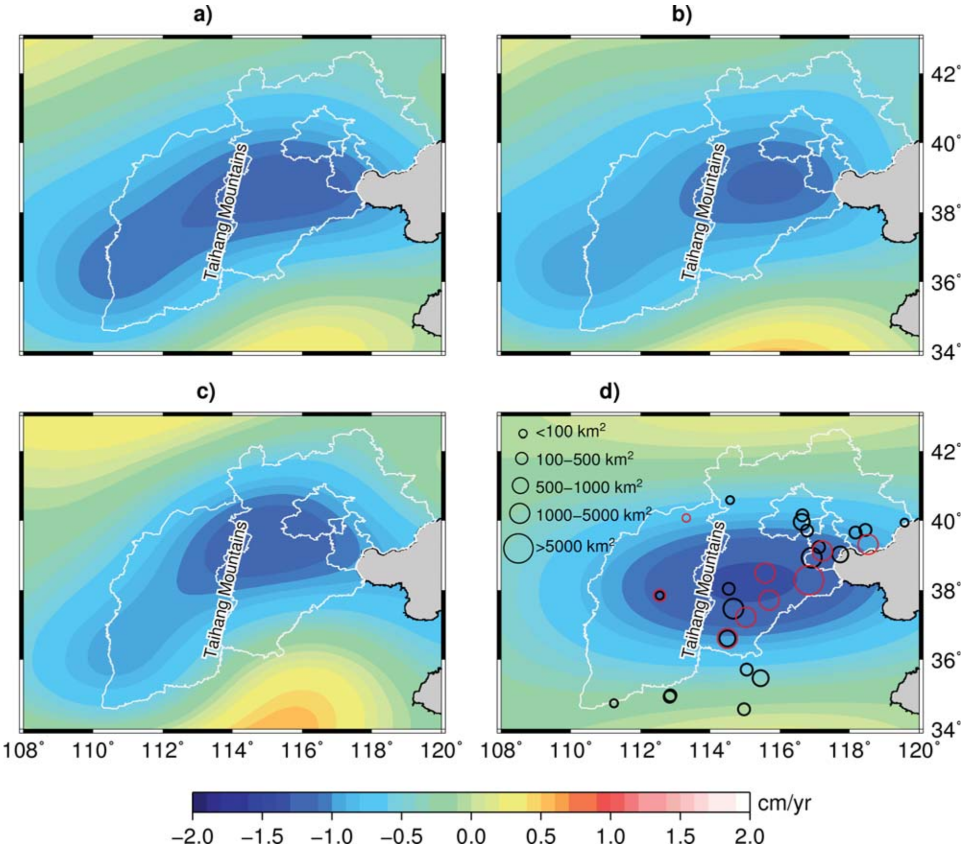

Figure 5. Spatial patterns of groundwater storage (GWS) trends estimated from GRACE-SM data (a) CSR, (b) GFZ, and (c) JPL and (d) forward modeling over the time period of 2003–2010. The location and size of groundwater depression cones in shallow aquifers (black circles) and deep aquifers (red circles) are also shown in Figure 5d [*MLR*, 2009].

4. Discussion

[21] Our final estimate of the groundwater depletion rate in North China based on GRACE data and hydrological models was 2.2 ± 0.3 cm/yr for 2003–2010, which is equivalent to a volume rate of 8.3 ± 1.1 km^3/yr. For the same time period, the estimated groundwater depletion rate in shallow aquifers according to the *GBCNP* was approximately 2.5 km^3/yr [*MWR*, 2010b], which is about one third of our estimate. One of the main reasons for this difference is that the *GBCNP*-based estimate includes only groundwater information in shallow aquifers of China northern plains, whereas the GRACE observes all GWS changes from all aquifers. Some studies have shown that the deep groundwater table is also decreased greatly in the piedmont region of the Taihang Mountains and the central plain region of the Hebei province [*World Bank*, 2001; *Foster et al*., 2004; *Tamanyu et al*., 2009]. The high-groundwater depletion rate estimated using GRACE data indicates the important contribution of groundwater depletion in deep aquifers of North China. In addition, the contribution of possible groundwater depletion in the mountain areas of North China is not included in the *GBCNP*. The mountain areas of the Shanxi province are among the largest coal-producing regions in China. Large-scale coal mining processes could destroy the aquifers and result in the observed groundwater depletion. However, determining the effect of coal mining processes on groundwater depletion is beyond the scope of the current study. Recently, *Konikow* [2011] estimated the contribution of global groundwater depletion since 1900 to sea level rise. Based on groundwater level measurements and groundwater flow models, cumulative net groundwater depletion in the NCP was found to be 130.3 km^3 and 170.3 km^3 for the 1900–2000 and 1900–2008 periods, respectively, which indicates that the groundwater depletion rate was 5 km^3/yr from 2001 to 2008. Our estimate based on GRACE data was 3.9 ± 1.6 km^3/yr for 2003–2008. Although the two time periods are not the same, our GRACE-based estimate is generally consistent with that reported by *Konikow* [2011]. Note that GRACE-based GWS time series are stable during 2003–2004, which leads to the difference in GRACE-based groundwater depletion rates between 2003–2008 and 2003–2010. Based on the earlier analysis, we conclude that the current depletion of groundwater resources in North China is more serious than previously reported in official groundwater bulletins.

[22] The spatial pattern of groundwater depletion based on GRACE data shows significant groundwater loss in the piedmont and central plain regions of North China. In these regions, numerous studies have reported the consequences of groundwater depletion, such as groundwater depression, land subsidence, soil salinization, groundwater pollution,

and seawater intrusion [*Wang et al*., 2007; *Liu et al*., 2001; *Shah et al*., 2000; *Foster and Chilton*, 2003; *Foster et al*., 2004], and demonstrated that extensive groundwater-based irrigation is the main cause of groundwater depletion in North China [*Foster et al*., 2004; *Kendy et al*., 2004].

[23] GRACE satellite gravimetry offers an important approach to estimating GWS changes in North China. However, some limitations to this method exist. First, only simulated SM data were used. The effect of extensive groundwater-based irrigation on SM in North China is not considered in the hydrological models. Although the four hydrological models we used agreed well with each other, a ground-based network of SM sensors would provide more reliable SM data and improve the GRACE-derived estimate of GWS changes. In addition, a uniform spatial distribution of more monitoring well stations in North China is needed. Expanding the monitoring well network would provide more reliable groundwater information and validate our GRACE-based estimate further. Specific yield, i.e., the storage coefficient for converting the water table depth to water storage, is also important. In the future, estimating the specific yield of each well would enhance the certainty of GWS estimates calculated from monitored well data. Moreover, uncertainty still exists in the GRACE data. We further calculated the groundwater depletion rate and its spatial pattern in North China using the GeoForschungsZentrum Potsdam (GFZ), JPL, and Groupe de Recherche de Géodésie Spatiale (GRGS) GRACE products. A regularization process was applied in the GRGS GRACE products [*Bruinsma et al*., 2010]. Groundwater depletion rates in North China estimated from the GFZ, JPL, and GRGS data were 7.6 ± 1.4 km^3/yr, 7.9 ± 1.3 km^3/yr, and 9.2 ± 0.8 km^3/yr, respectively, for 2003–2010. The spatial patterns of GWS trends obtained from CSR, GFZ, and JPL GRACE data agree well with each other (Figures 5a–5c). However, the largest groundwater depletion rate according to GRGS data is located in the northern region of the Shanxi province, approximately 250 km away from the location predicted by CSR, GFZ, and JPL data (supporting information, section 3, Figure S1). This difference indicates that uncertainty still remains within GRACE products derived using different gravity field inversion strategies.

Table 1. Different Error Components in the Final Error Budget of Monthly GWS Estimates and the Trend[a]

	Monthly (cm)	Trend (cm/yr)
TWS (GRACE)		
Measurement error ($k\Delta\hat{\overline{S_0}}$)	3.54	0.16
Leakage ($k\Delta S_{\text{leakage}}$)	2.61	0.12
$\Delta\hat{k}\overline{S_0}$	<0.58	0.03
$\Delta kS_{\text{leakage}}$	<0.22	0.01
Processing error		0.12
GIA		0.06
Total	4.87	0.24
SM		
Hydrological model	3.98	0.18
GWS		
GRACE-SM	5.96	0.30

[a] Processing error represents the uncertainty of applying Gaussian smoothing with different radii and applying different destriping methods. Uncertainties in the trends were estimated by applying a least squares fit through the error propagation from the monthly data using a covariance matrix. The final error estimate of the GWS trend based on GRACE data and hydrological models was 0.3 cm/yr, under the assumption that no correlations exist between the individual trend errors.

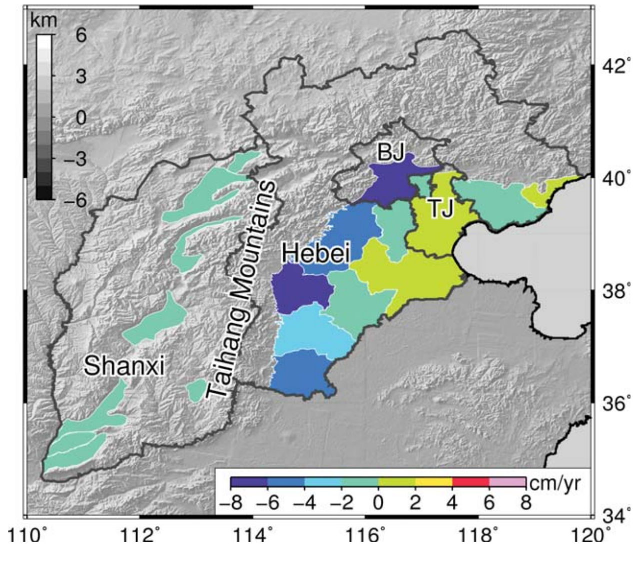

Figure 6. Spatial pattern of shallow groundwater storage (GWS) trends in the plain regions of North China from 2003 to 2010, based on the statistical data sets from the *GBCNP* and the *GBHP* [*MWR*, 2010b; *DWRHP*, 2010]. In the Shanxi province, statistical data for eight basins were collected. The statistical data for the Hebei province were collected based on the administrative divisions. More details can be found in section 4 of the supporting information.

5. Summary

[24] In this study, regional groundwater depletion in North China was estimated from GRACE-derived TWS and simulated SM data from 2003 to 2010. The estimate was compared with in situ water table observations and the results from groundwater bulletins. Based on the GRACE-derived TWS and simulated SM estimates, the groundwater depletion rate in North China was 8.3 ± 1.1 km^3/yr from 2003 to 2010, which is about three times higher than the official estimate of the groundwater depletion rate in shallow plain aquifers from the *GBCNP* (2.5 km^3/yr). The difference between our estimate and the *GBCNP* result indicates the potential deep groundwater depletion in the plain and piedmont regions of North China. Even if we apply the low bound of our estimate conservatively, the study region lost approximately 50 km^3 of groundwater between January 2003 and December 2010, which is greater than the capacity of China's Three Gorges Dam, the largest power station in the world.

[25] Given the continuous groundwater depletion estimated by GRACE in North China, more effective measures should be taken to curb groundwater loss, such as artificial recharge of water into aquifers [*Han*, 2003], crop structure adjustment [*Yang and Zehnder*, 2001], and reintroducing fallow periods [*Kendy et al*., 2004]. China's South-North Water Transfer Project, which takes water from the Yangtze River and the Han River in the south to the arid region

of North China, could partially ease the water shortage in North China and also reduce the dependence on groundwater.

[26] **Acknowledgments.** The authors are grateful to the two anonymous reviewers and the Associate Editor whose comments and suggestions have significantly improved the manuscript. This work was initiated during the stay of the first author at CNES/GRGS, thanks to the Sino-French Joint Ph.D. Scholarship Program. This work was supported by the National Key Basic Research Program of China (973 program, grant 2012CB957703), the National Natural Science Foundation of China (grants 40974045 and 41021003), and the CAS/SAFEA International Partnership Program for Creative Research Teams (grant KZZD-EW-TZ-05). W. F. thanks Haoming Yan, C. K. Shum, and Laurent Longuevergne for their constructive comments on an earlier version of the manuscript.

References

Bruinsma, S., J. M. Lemoine, R. Biancale, and N. Vales (2010), CNES/GRGS 10-day gravity field models (release 2) and their evaluation, *Adv. Space Res.*, *45*(4), 587–601.

Chen, J. L., C. R. Wilson, J. S. Famiglietti, and M. Rodell (2007), Attenuation effect on seasonal basin-scale water storage changes from GRACE time-variable gravity, *J. Geod.*, *81*, 237–245, doi:10.1007/S00190-006-0104-2.

Chen, J. L., C. R. Wilson, B. D. Tapley, Z. L. Yang, and G. Y. Niu (2009), 2005 drought event in the Amazon River basin as measured by GRACE and estimated by climate models, *J. Geophys. Res.*, *114*, B05404, doi:10.1029/2008JB006056.

Cheng, M., and B. D. Tapley (2004), Variations in the Earth's oblateness during the past 28 years, *J. Geophys. Res.*, *109*, B09402, doi:10.1029/2004JB003028.

Department of Water Resources of Hebei Province (DWRHP) (2010), *Groundwater Bull. Hebei Plain*, Dep. Water Resour. of Hebei Province, Gov. of China, Beijing.

Ek, M., K. Mitchell, Y. Lin, E. Rogers, P. Grunmann, V. Koren, G. Gayno, and J. Tarpley (2003), Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model, *J. Geophys. Res.*, *108*(D22), 8851, doi:10.1029/2002JD003296.

Famiglietti, J., M. Lo, S. Ho, J. Bethune, K. Anderson, T. Syed, S. Swenson, C. de Linage, and M. Rodell (2011), Satellites measure recent rates of groundwater depletion in California's Central Valley, *Geophys. Res. Lett.*, *38*, L03403, doi:10.1029/2010GL046442.

Fan, Y., and H. van den Dool (2004), Climate Prediction Center global monthly soil moisture data set at 0.5 resolution for 1948 to present, *J. Geophys. Res.*, *109*, D10102, doi:10.1029/2003JD004345.

Fenoglio-Marc, L., J. Kusche, and M. Becker (2006), Mass variation in the Mediterranean Sea from GRACE and its validation by altimetry, steric and hydrologic fields, *Geophys. Res. Lett.*, *33*, L19606, doi:10.1029/2006GL026851.

Foster, S., and P. Chilton (2003), Groundwater: The processes and global significance of aquifer degradation, *Philos. Trans. R. Soc. London B*, *358*(1440), 1957–1972.

Foster, S., H. Garduno, R. Evans, D. Olson, Y. Tian, W. Zhang, and Z. Han (2004), Quaternary aquifer of the North China Plain—Assessing and achieving groundwater resource sustainability, *Hydrogeol. J.*, *12*, 81–93.

Geological Memoirs (1992), *Comprehensive Hydrogeologic Evaluation of the Huang-Huai-Hai Plain, Ministry of Geology and Mineral Resources, pp. 277, People's Republic of China*, Geol. Publishing House, Beijing.

Han, S., Y. Yang, Y. Lei, C. Tang, and J. P. Moiwo (2008), Seasonal groundwater storage anomaly and vadose zone soil moisture as indicators for precipitation recharge in the piedmont region of Taihang Mountain, North China Plain, *Hydrol. Res.*, *39*(5–6), 479–495.

Han, Z. (2003), Groundwater resources protection and aquifer recovery in China, *Environ. Geol.*, *44*, 106–111.

Kendy, E., D. J. Molden,T. S. Steenhuis, C. Liu, and J. Wang (2003), *Policies drain the North China Plain: Agricultural policy and groundwater depletion in Luancheng County, 1949–2000,* IWMI Res. Rep. 71, Int. Water Manage. Inst., Colombo, Sri Lanka.

Kendy, E., Y. Zhang, C. Liu, J. Wang, and T. S. Steenhuis (2004), Groundwater recharge from irrigated cropland in the North China Plain: Case study of Luancheng County, Hebei Province, 1949–2000, *Hydrol. Process.*, *18*(12), 2289–2302.

Klees, R., E. A. Zapreeva, H. C. Winsemius, and H. H. G. Savenije (2007), The bias in GRACE estimates of continental water storage variations, *Hydrol. Earth Syst. Sci.*, *11*, 1227–1241.

Konikow, L. (2011), Contribution of global groundwater depletion since 1900 to sea-level rise, *Geophys. Res. Lett.*, *38*, L17401, doi:10.1029/2011GL048604.

Koster, R. D., and M. J. Suarez (1992), Modeling the land surface boundary in climate models as a composite of independent vegetation stands, *J. Geophys. Res.*, *97*(D3), 2697–2715, doi:10.1029/91JD01696.

Lee, T., I. Fukumori, D. Menemenlis, Z. F. Xing, and L. L. Fu (2002), Effects of the Indonesian throughflow on the Pacific and Indian oceans, *J. Phys. Oceanogr.*, *32*, 1404–1429.

Liang, X., D. Lettenmaier, E. Wood, and S. Burges (1994), A simple hydrologically based model of land surface water and energy fluxes for general circulation models, *J. Geophys. Res*, *99*(D7), 14,415–14,428.

Liu, C., X. Zhang, and Y. Zhang (2002), Determination of daily evaporation and evapotranspiration of winter wheat and maize by large-scale weighing lysimeter and micro-lysimeter, *Agr. Forest Meteorol.*, *111*, 109–120.

Liu, C., J. Yu, and E. Kendy (2001), Groundwater exploitation and its impact on the environment in the North China Plain, *Water Int.*, *26*(2), 265–272.

Longuevergne, L., B. R. Scanlon, and C. Wilson (2010), GRACE Hydrological estimates for small basins: Evaluating processing approaches on the High Plains Aquifer, USA, *Water Resour. Res.*, *46*, W11517, doi:10.1029/2009WR008564.

Matsuo, K., and K. Heki (2010), Time-variable ice loss in Asian high mountains from satellite gravimetry, *Earth Planet. Sci. Lett.*, *290*, 30–36.

Moiwo, J. P., Y. H. Yang, H. L. Li, S. M. Han, and Y. K. Hu (2009), Comparison of GRACE with in situ hydrological measurement data shows storage depletion in Hai River basin, Northern China, *Water SA*, *35*, 663–670.

Ministry of Land and Resources of China (MLR) (2009), *Groundwater regime in major cities of China*, Ministry of Land and Res. of China, Beijing. [Available at http://www.mlr.gov.cn/.].

Ministry of Water Resources of China (MWR) (2010a), *China water resources bulletin*, Ministry of Water Res. of China, Beijing. [Available at http://www.mwr.gov.cn/.].

Ministry of Water Resources of China (MWR) (2010b), *Groundwater Bull. China Northern Plains*, Ministry of Water Res. of China, Beijing. [Available at http://www.mwr.gov.cn/.].

Paulson, A., S. J. Zhong, and J. Wahr (2007), Inference of mantle viscosity from GRACE and relative sea level data, *Geophys. J. Int.*, *171*, 497–508.

Rodell, M., and J. Famiglietti (2002), The potential for satellite-based monitoring of groundwater storage changes using GRACE: The High Plains aquifer, Central US, *J. Hydrol.*, *263*, 245–256.

Rodell, M., et al. (2004), The Global Land Data Assimilation System, *Bull. Am. Meteorol. Soc.*, *85*(3), 381–394.

Rodell, M., J. L. Chen, H. Kato, J. S. Famiglietti, J. Nigro, and C. R. Wilson (2007), Estimating groundwater storage changes in the Mississippi River basin (USA) using GRACE, *Hydrogeol. J.*, *15*(1), 159–166.

Rodell, M., I. Velicogna, and J. S. Famiglietti (2009), Satellite-based estimates of groundwater depletion in India, *Nature*, *460*, 999–1002.

Sakura, Y., C. Tang, R. Yoshioka, and H. Ishibashi (2003), Intensive use of groundwater in some areas of China and Japan, in *Intensive Use of Groundwater: Challenges and Opportunities*, edited by M. R. Llamas and E. Custodio, Balkma, Rotterdam, Netherlands.

Scanlon, B. R., I. Jolly, M. Sophocleous, and L. Zhang (2007), Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality, *Water Resour. Res.*, *43*, W03437, doi:10.1029/2006WR005486.

Scanlon, B. R., L. Longuevergne, and D. Long (2012), Ground referencing GRACE satellite estimates of groundwater storage changes in the California Central Valley, USA, *Water Resour. Res.*, *48*, W04520, doi:10.1029/2011WR011312.

Shah, T., D. Molden, R. Sakthivadivel, and D. Seckler (2000), *The Global Groundwater Situation: Overview of Opportunities and Challenges*, Int. Water Manage. Inst., Colombo, Sri Lanka.

Siebert, S., J. Burke, J. M. Faures, K. Frenken, J. Hoogeveen, P. Doll, and F. T. Portmann (2010), Groundwater use for irrigation—A global inventory, *Hydrol. Earth Syst. Sci.*, *14*, 1863–1880.

Strassberg, G., B. R. Scanlon, and M. Rodell (2007), Comparison of seasonal terrestrial water storage variations from GRACE with groundwater-level measurements from the High Plains Aquifer (USA), *Geophys. Res. Lett.*, *34*, L14402, doi:10.1029/2007GL030139.

Strassberg, G., B. R. Scanlon, and D. Chambers (2009), Evaluation of groundwater storage monitoring with the GRACE satellite: Case study of the High Plains aquifer, central United States, *Water Resour. Res.*, *45*, W05410, doi:10.1029/2008WR006892.

Swenson, S., and J. Wahr (2002), Methods for inferring regional surface-mass anomalies from Gravity Recovery and Climate Experiment (GRACE) measurements of time-variable gravity, *J. Geophys. Res.*, *107*(B9), 2193, doi:10.1029/2001JB000576.

Swenson, S., and J. Wahr (2006), Post-processing removal of correlated errors in GRACE data, *Geophys. Res. Lett.*, *33*, L08402, doi:10.1029/2005GL025285.

Swenson, S., and J. Wahr (2007), Multi-sensor analysis of water storage variations of the Caspian Sea, *Geophys. Res. Lett.*, *34*(16), L16401, doi:10.1029/2007GL030733.

Swenson, S., J. Famiglietti, J. Basara, and J. Wahr (2008a), Estimating profile soil moisture and groundwater variations using GRACE and Oklahoma Mesonet soil moisture data, *Water Resour. Res.*, *44*, W01413, doi:10.1029/2007WR006057.

Swenson, S., D. Chambers, and J. Wahr (2008b), Estimating geocenter variations from a combination of GRACE and ocean model output, *J. Geophys. Res.*, *113*, B08410, doi:10.1029/2007JB005338.

Tamanyu, S., H. Muraoka, and T. Ishii (2009), Geological interpretation of groundwater level lowering in the North China Plain, *Bull. Geol. Surv. Jpn.*, *60*(1/2), 105–115.

Tapley, B. D., S. Bettadpur, J. C. Ries, P. F. Thompson, and M. M. Watkins (2004), GRACE measurements of mass variability in the Earth system, *Science*, *305*, 503–505, doi:10.1126/science.1099192.

Tiwari, V. M., J. Wahr, and S. Swenson (2009), Dwindling groundwater resources in northern India, from satellite gravity observations, *Geophys. Res. Lett.*, *36*, L18401, doi:10.1029/2009GL039401.

Velicogna, I., and J. Wahr (2006a), Acceleration of Greenland ice mass loss in spring 2004, *Nature*, *443*, 329–331.

Velicogna, I., and J. Wahr (2006b), Measurements of time-variable gravity show mass loss in Antarctica, *Science*, *311*, 1754–1756.

Wada, Y., L. P. H. van Beek, C. M. van Kempen, J. W. T. M. Reckman, S. Vasak, and M. F. P. Bierkens (2010), Global depletion of groundwater resources, *Geophys. Res. Lett.*, *37*, L20402, doi:10.1029/2010GL044571.

Wang, J., J. Huang, A. Blanke, Q. Huang, and S. Rozelle (2007), The development, challenges and management of groundwater in rural China, in *Groundwater in Developing World Agriculture: Past, Present and Options for a Sustainable Future*, edited by M. Giordano and T. Shah, Int. Water Manage. Inst., Colombo, Sri Lanka.

World Bank (2001), China: Agenda for Water Sector Strategy for North China, vol. 1: Summary Report, pp. 1–141, Washington, D. C.

Yang, H., and A. Zehnder (2001), China's regional water scarcity and implications for grain supply and trade, *Environ. Plann. A*, *33*(1), 79–95, doi:10.1068/a3352.

Yang, Y., Y. Yang, J. Moiwo, and Y. Hu (2010), Estimation of irrigation requirement for sustainable water resources reallocation in North China, *Agr. Water Manage.*, *97*(11), 1711–1721.

Yeh, P., S. Swenson, J. Famiglietti, and M. Rodell (2006), Remote sensing of groundwater storage changes in Illinois using the Gravity Recovery and Climate Experiment (GRACE), *Water Resour. Res.*, *42*, W12203, doi:10.1029/2006WR005374.

Zektser, I., and G. E. Lorne (2004), *Groundwater Resources of the World and Their Use, UNESCO IHP-VI Ser. on Groundwater 6*, UNESCO, Paris.

Zhang, Z. J., and Y. H. Fei (2009), *Atlas of groundwater sustainable utilization in North China Plain*, 185 pp., China Cartographic Publishing House, Beijing.

Zhong, M., J. B. Duan, H. Z. Xu, P. Peng, H. M. Yan, and Y. Z. Zhu (2009), Trend of China land water storage redistribution at medi- and large-spatial scales in recent five years by satellite gravity observations, *Chin. Sci. Bull.*, *54*(5), 816–821.