Hydrology and Earth System Sciences Discussions

GRACE water storage estimates for the Middle East and other regions with significant reservoir and lake storage

L. Longuevergne[1], C. R. Wilson[2], B. R. Scanlon[3], and J. F. Crétaux[4]

[1]Géosciences Rennes, UMR6118, CNRS – Université de Rennes 1, Rennes, France
[2]Department of Geological Sciences, Jackson School of Geosciences,
The University of Texas at Austin, Austin, TX, USA
[3]Bureau of Economic Geology, Jackson School of Geosciences,
The University of Texas at Austin, Austin, TX, USA
[4]LEGOS, UMR5566, CNES/CNRS/IRD – Université Paul Sabatier, Toulouse, France

Correspondence to: L. Longuevergne (laurent.longuevergne@univ-rennes1.fr)

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

L. Longuevergne et al.

Abstract

While GRACE (Gravity Recovery and Climate Experiment) satellites are increasingly being used to monitor water storage changes globally, the impact of spatial distribution of water storage within a basin is generally ignored but may be substantial. In many basins, water may be stored in reservoirs, lakes, flooded areas, small aquifer systems, and other localized regions with sizes typically below GRACE resolution. The objective of this study was to assess the impact of non-uniform water storage distribution on GRACE estimates as basin-wide averages, focusing on surface water reservoirs. Analysis included numerical experiments testing the effect of mass size and position within a basin, and application to the Lower Nile (Lake Nasser) and Tigri–Euphrates (TE) basins as examples. Numerical experiments show that by assuming uniform mass distribution, GRACE estimates may under- or over-estimate basin-average water storage by up to a factor of two, depending on reservoir location and extent. Although their spatial extent may be unresolved by GRACE, reservoir storage may dominate in some basins. For example, it accounts for 95 % of seasonal variations in the Lower Nile and 10 % in the TE basins. Because reservoirs are used to mitigate droughts and buffer against climate extremes, their influence on interannual time scales can be large, for example accounting for 50 % of total water storage decline during the 2007–2009 drought in the TE basin. Effects on GRACE estimates are not easily accounted for via simple multiplicative scaling, but in many cases independent information may be available to improve estimates. Accurate estimation of the reservoir contribution is critical, especially when separating groundwater from GRACE total water storage changes. Because the influence of spatially concentrated water storage – and more generally water distribution – is significant, GRACE estimates will be improved when it is possible to combine independent spatial distribution information with GRACE observations, even when reservoir storage is not a major factor. In this regard, data from the upcoming Surface Water Ocean Topography (SWOT) satellite mission should be an especially important companion to GRACE-FO observations.

1 Introduction

Large rivers cross the Middle East and bring life to these dry regions, where throughout human history reservoirs have served to ensure an adequate water supply by storing water in times of surplus and releasing it in times of scarcity (Altinbilek, 2002), provid-
5 ing a buffer to mitigate seasonal and interannual variability of precipitation. Regulation to ensure water supply and control floods may become even more critical in the future with increasing intensity of the hydrologic cycle (Easterling et al., 2000). Initially, only small dams were built for water supply and for irrigation, but today half the world's large dams were built exclusively or primarily for irrigation and an estimated 30–40 %
10 of irrigated lands rely on reservoirs (WCD, 2000). The last century experienced a rapid increase in large-dam building, from ~ 5000 large dams by 1950 globally, mostly in industrialized countries, to $\sim 45\,000$ by the end of the 20th century in ~ 150 countries. About 50 % of the dams were built mainly for irrigation purposes, mostly in India (World Bank, 1998). Water inflows to reservoirs are mostly controlled mainly by pre-
15 cipitation and water convergence from contributing basins, while outflows are subject to laws and policies serving agricultural, industrial, and urban needs, in addition to physical processes of seepage and evaporation. Most reservoirs are above ground; but below-ground reservoirs (groundwater banks), with up to $\sim 1\,km^3$ storage are now being developed in the Central Valley of California, and are in service elsewhere.
20 Reservoirs can also have large scale impacts on water sharing among countries. For example, in the Tigris–Euphrates basin, population growth and associated higher reliance on irrigated agriculture highlights water sharing issues among upstream (Turkey) and downstream (Syria and Iraq) users and is causing strong rivalries in this transboundary watershed. Continued development of hydraulic resources in upstream
25 Tigris–Euphrates also leads to higher sensitivity to droughts and lower water quality downstream, seriously aggravating the geopolitical environment (Mutin, 2009). While dam building was the path of progress a few decades ago, it is now appearing as one example of deepening water inequalities among riparian countries. Because of limited

ground-based data, GRACE satellite data may be very valuable for monitoring water storage changes. Accurate GRACE water storage estimates have importance beyond practical hydrology, given the politics and conflicts associated with drought and transboundary water allocation and management among Turkey, Syria, and Iraq. Accurate assessment of total water storage and its variations within a basin thus requires careful attention to the reservoir component.

GRACE satellites are unique in their ability to monitor changes in total water storage (ΔTWS), a combination of changes in ice + snow water equivalent (ΔSWES), surface water (ΔSWS), soil moisture (ΔSMS) and groundwater storage (ΔGWS) (Tapley et al., 2004; Güntner, 2008; Schmidt et al., 2008). Extracting individual contributions from individual storage compartments requires solving the disaggregation equation, and often the objective is an estimate of groundwater storage changes ΔGWS = ΔTWS – ΔSWES – ΔSWS – ΔSMS. In this process, surface water is often neglected (e.g. Frappart et al., 2011; Shamsudduha et al., 2012), but should be estimated properly to avoid accumulating errors. One difficulty is that surface water storage variations are often concentrated in small areas, such as lakes, rivers, and flooded areas. A related problem is that storage is often within artificial reservoirs (ΔRES) under anthropic control, and is therefore frequently omitted from physically-based Land Surface Models (LSM's).

The spatial resolution of GRACE data is typically given as a few hundred km, but GRACE is actually sensitive to total water storage variation, including storage within regions with small spatial scales if water level variations are sufficiently large. In agricultural regions, for example, where groundwater systems are exploited in conjunction with surface water (e.g. Scanlon et al., 2012b), a separate estimate of groundwater storage variations requires estimation of the surface water contribution, especially reservoirs. As a result, anthropic management of reservoirs, and anthropic contributions to the water cycle have recently been incorporated in global modeling studies (Liu and Yang, 2010; Döll et al., 2012; Pokhrel et al., 2012; Wada et al., 2012) and

there is now a database available to separate groundwater and surface water uses (Siebert et al., 2010).

Virtually all artificial reservoirs are point masses at the spatial resolution of GRACE. For example, a large reservoir has a surface area of $\sim 1000\,\mathrm{km}^2$ which is smaller by about two orders of magnitude than the smallest basin ($\sim 200\,000\,\mathrm{km}^2$) that can be usefully resolved by GRACE. However, GRACE is able to detect a 1 cm water storage change with a $200\,000\,\mathrm{km}^2$ basin, which is comparable in mass (hence observability) to a few meters of water level change within a $1000\,\mathrm{km}^2$ reservoir. The capability of GRACE to monitor reservoirs was documented in a pre-launch study by Boy and Chao (2002) for the Three-Gorges reservoir, and examined subsequently by Wang et al. (2011). Other GRACE studies have examined storage in the great African lakes (Swenson and Wahr, 2009; Becker et al., 2010), and the Aral Sea (Singh et al., 2012). In these, GRACE observations were supplemented with satellite radar altimetry observations of water level changes.

While the contributions of surface water and reservoirs have been recognized, their quantitative influence has been unclear. More precisely, it has not been clear how small scale and/or discontinuous distribution of water sources affect basin-scale average water storage variations that are typically computed from GRACE data. For example, Rodell et al. (2008) estimated groundwater depletion in Rajasthan, but applied different multiplicative factors for rescaling seasonal variations and trends in GRACE. Seasonal variations were attributed to soil moisture, distributed over an area larger than the aquifer, while trends were attributed to the groundwater system. More recently, Scanlon et al. (2012a) noted that the effective multiplicative (scaling) factor required to correct for spatial distribution may vary by $\sim 15\,\%$ among storage components, due to varied spatial distribution. For example, snow is usually concentrated within mountains on a basin perimeter, while soil moisture tends to be more evenly distributed over a basin. The fundamental problem is that variations in spatially-limited regions are to be estimated from spectrally-limited (GRACE) data (Simons et al., 2006).

The objective of this study is to evaluate how the spatial distribution of water affects GRACE basin-scale estimates of ΔTWS. Point masses are taken as the model for the distribution of typical reservoirs. Simple parametric numerical experiments are used first to estimate the impact of reservoir location and areal extent on basin-scale average water storage variations, from GRACE. Then, examples from basins with large reservoir components are used to show the effect by combining independent satellite data on reservoir storage with GRACE data. The examples demonstrate the importance of adding spatial distribution information to obtain accurate TWS estimates, and to disaggregate soil moisture and groundwater components.

2 Material and methods

2.1 Synthetic numerical experiment

The influence of spatially concentrated water storage variations on GRACE is illustrated via two simple synthetic numerical experiments. Results apply to any spatially concentrated storage component (glaciers, rivers, small-scale groundwater system) estimated from GRACE observations, whether in Spherical Harmonic (SH), gridded (Landerer and Swenson, 2012) or "mascon" (e.g. Tiwari et al., 2009; Rowland et al., 2010) form, given that spatial resolution is constrained by potential field physics to be comparable to GRACE satellites' altitude of ~ 400 km. In these experiments, a simple circular basin contains a point mass representing a 1 km^3 reservoir and its impact on GRACE is forward modeled from a 1/8th degree grid. In the first experiment, location of the point mass is varied relative to the basin center. In the second experiment, the mass is fixed at the basin center, but its spatial extent increases from a concentrated point up to a uniform distribution over the entire basin.

2.2 Tigris–Euphrates and Lower Nile basins

Results from the numerical experiments, and other data, are used to interpret GRACE water storage estimates within two basins in arid/semi-arid Middle East regions: the lower Nile and the Tigris–Euphrates basins, both with significant anthropic reservoir management. Additional examples are provided in the Supplement, including Guri Lake (Orinoco Basin) Amu and Syr Darya (Aral Sea) and the East African lakes (Xie et al., 2012). Lake and reservoir volume variations were first estimated using independent radar altimetry data, in order to predict the GRACE signal. Predicted and observed water storage variations at GRACE resolutions were then compared with LSM estimates.

Lake Nasser (6216 km^2 area) is located in the lower Nile basin at the border between Egypt and Sudan (Fig. 2). The lake was filled in the 1960s to 1970s with the construction of the Aswan high dam upstream of the old Aswan dam. The total capacity of the reservoir is 162 km^3 at the level 182 m a.m.s.l. (Sadek et al., 1997). Lake levels may vary by up to 7 m between summer and winter, with evaporation accounting for 2.35 m (15 % of river inflow) and seepage to nearby aquifers accounting for 230 mm (1.2 % of river inflow), see (Aly et al., 1993).

The Tigris–Euphrates (TE) basin has seen anthropic management for over six millennia. The regional climate shows predominantly winter precipitation, with snow in surrounding mountain ranges (Jones et al., 2008). Therefore, summer crop production relies heavily on irrigation. For example, Mesopotamia (from the Greek "land between two rivers"), as the cradle of modern civilization, was built upon the wealth of irrigated agriculture, and remains now as one of the most engineered basins in the world. Irrigation greatly expanded at the beginning of the 20th century. Both rivers originate in Turkey and construction of several dams in Turkey and Syria has greatly reduced flow into downstream Iraq. Jones et al. (2008) showed a large streamflow reduction in TE basin related to dam impoundment and operations on the 1989–1998 period, as compared to predevelopment (1965–1973), reaching 26 to 48 % at annual time scales. Streamflow decrease reached 75 % in January 1990 when Turkey began to fill

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

the Ataturk reservoir, leading to crop loss of 15 % (Mutin, 2009). Beyond dam storage, water loss by evapotranspiration (lake surface, crop irrigation) and seepage, also decreases streamflow and increases sensitivity of downstream reservoirs to droughts.

2.3 Reservoir data

In a few regions of the world, such as the state of California in the US, reservoir storage information is publicly available, but more commonly such data are difficult to obtain. However, satellite radar altimetry estimates of reservoir water level and/or volume variations are available for many large reservoirs. Several missions have been launched since the early 1990s: ERS-1 (1991–1996), T/P (1992–2005), ERS-2 (1995–2002), GFO (2000–2008), JASON-1 (2001–cont.), JASON-2 (2008–cont.) and ENVISAT (2002–2012). The combined global altimetry historical data set now covers approximately two decades and will be continuously updated in the coming decade. Merging altimetry data from several in-orbit altimetry missions also increase the spatio-temporal resolution of the remotely-sensed hydrological variables.

We used lake and reservoir level/volume variations obtained from the Hydroweb database (Crétaux et al., 2005, 2011) for regions shown in Table 1. Time series of water stage, computed from satellite altimetry for 165 natural lakes and artificial reservoirs, are available on http://www.legos.obs-mip.fr/en/soa/hydrologie/hydroweb/. Estimates incorporate specific biases of each satellite (Crétaux et al., 2009). The accuracy of radar altimetry over lakes is for 2–3 cm for large lakes, and up to 70–80 cm for small and narrow lakes. Lake areas and volume are also provided in Hydroweb for a selection of 30 lakes worldwide. Satellite remote sensing optical imagery (mainly Landsat satellites) has been used for these purposes. At a resolution of about 30 m these data can be successfully used to detect the presence of water on the Earth and estimate lake surface area at different levels. A water area-level relationship is therefore derived from the synergy of satellite radar altimetry and imagery to calculate lake area and water volume variations over time. For the cases where lake volumes are unavailable, a constant lake surface area is

assumed. Two other data centers release lake and rivers level variations: US Dept. of Agriculture (http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir) and European Space Agency (http://tethys.eaprs.cse.dmu.ac.uk/RiverLake/shared/main).

2.4 Land surface models

For comparison with GRACE and reservoir data, we examine water storage estimates from LSMs, which mainly describe changes in snow storage (ΔSWES) and soil moisture storage (ΔSMS) due to natural physical processes. Water storage changes in managed reservoirs are generally not included in LSMs because regulation rules are not well known. However, one LSM, WGHM (Water Gap Hydrological Model) incorporates these variations in some basins (Döll et al., 2003; Hunger and Döll, 2008). A version of WGHM has been calibrated jointly with GRACE and river discharge data (Werth and Güntner, 2010), but the version used here is independent of GRACE. Storage estimates are also taken from another widely used LSM, GLDAS (Global Land Data Assimilation System) (Rodell et al., 2004) which omits reservoir water storage changes. GLDAS results include four different LSMs, CLM, MOSAIC, NOAH and VIC. In the following, GLDAS ΔSMS is computed as the mean water storage variations among MOSAIC, NOAH and VIC model (soil moisture + snow water equivalent). The relative importance of reservoir storage changes on TWS can be evaluated by comparing GLDAS ΔSMS results with WGHM (which includes reservoirs). Results are compared with GRACE by integrating LSM grid values over Oki and Sud (1998) basins available at 0.5° resolution.

2.5 GRACE data

Two different GRACE solutions are examined. The first is based upon monthly release 04 Spherical Harmonic (SH) data from CSR (Center for Space Research), truncated at degree and order 60 (Bettadpur, 2007) including a destriping filter (Swenson and Wahr, 2006) and additional 300-km Gaussian smoothing. The second uses 10-day RL02 data

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

from GRGS (Groupe de Recherche en Géodésie Spatiale), stabilized and truncated at 50° (Lemoine et al., 2007; Bruinsma et al., 2010). No additional filtering is required for GRGS solutions. In each example, basin-scale water storage variations and associated errors are calculated following procedures outlined by Longuevergne et al. (2010). The

5 GRACE SH expansion of apparent mass change is integrated over the basin, and then bias and leakage corrections are computed assuming GLDAS-NOAH correctly represents water mass variations and distribution both within and outside the basin. Bias and leakage corrections are determined separately, then added to the GRACE apparent mass change. Because GLDAS excludes reservoir storage, bias and leakage

10 corrections are likely less accurate when reservoir is a major component of the water balance.

3   Synthetic numerical experiment–analysis

We use SH representations of surface mass change (Wahr et al., 1998), limiting degree and order to 50 (to simulate GRGS), and to 60 (to simulate CSR RL04, including

15 a Gaussian 300 km filter). A hard truncation (no filtering) at 50° does not exactly duplicate stabilization of GRGS solutions at higher degrees (Lemoine et al., 2007). We evaluate SH expansions of mass change over circular basins of varying size, and calculate apparent basin-wide average mass when the true mass is spatially concentrated within the basin. Apparent Basin Storage (ABS) equals the SH expansion of mass in-

20 tegrated over the entire basin, divided by basin area. True Basin Storage (TBS) equals the actual mass located within the basin divided by basin area.

The overall impact of point mass on GRACE is the sum of the effects of its location, area and GRACE processing. In the first experiment (Figs. 1, S1), the location of a point mass representing 1 km^3 of water (in practice assigned to a 1/8th degree cell) was

25 varied relative to the basin center, for basins of various sizes (Figs. 1, S1). Three main results are evident:

1. The position of a point mass strongly affects ABS. For example, a 0.4 M km^2 basin has TBS = 2.5 mm (1 km^3/0.4 M km^2), but ABS (50°) is 24 % larger (3.1 mm) when the point mass is at the center. When located near the edge, ABS is 50 % lower (1.2 mm) than TBS. ABS diminishes quickly as the mass moves off-center due to leakage to regions outside the basin.

2. Basin area influences the magnitude of the point mass effect. A 0.2 M km^2 basin where TBS = 5 mm but ABS is always less than this (for 50°), with ABS = 4.1 mm when at the basin center and 2.5 mm at the basin edge. Masses outside the basin yield a similar ABS to point masses inside the basin, when the basin is small (area < 300 000 km^2).

3. ABS is strongly affected by smoothing. The degree 60 case yields ABS that is biased as smoothing spreads the signal over a large area, decreasing ABS relative to the 50° case.

In the second experiment (Figs. 1, S2), the mass is centered within the basin but its radius is varied from a point (in practice 1/8 degree) up to the basin radius. The results are described by Relative ABS, the ratio of ABS divided by its value when mass radius equals basin radius (equivalent to assuming a uniform distribution for storage). More concentrated masses increase relative ABS, as much as 60 % (multiplicative factor of 1.6) because leakage to regions outside the basin is diminished with greater concentration. Hard-truncation negative sidelobes in the 50° case cause diminished Relative ABS for larger basins.

These two experiments can be used to interpret GRACE estimates for any basin with a spatially irregular water storage distribution. A first point is that ABS from GRACE is rarely equal to TBS and may be smaller or larger, depending upon the position of the mass and its areal extent. Masses outside a basin may contribute significantly as well by leakage into the basin. Second, the signal produced by a concentrated mass tends to increase with concentration. Simple GRACE estimates will over-estimate average basin storage if the distribution is incorrectly assumed to be uniform (and point mass

GRACE water storage estimates for the Middle East

L. Longuevergne et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

close to the center). When no smoothing is applied, ABS will be close to TBS when the reservoir is located half way to basin edge and has a small area. When smoothing is applied, ABS is always smaller than TBS. As the reservoir moves towards the basin margin, the effects of location and spatial extent partially cancel one another.

4 Application to GRACE and RES observations

4.1 Lower Nile and Lake Nasser

The impact of anthropic water management is evident from differences between GLDAS ΔSMS (which does not include Lake Nasser storage changes) and WGHM (incorporating Lake Nasser regulation rules) over the Lower Nile basin (Fig. 2). The difference is ∼ 40 mm for seasonal variations. GRACE estimates clearly capture changes in Lake Nasser, though some differences in phase are evident during Fall of 2007 and 2008. Estimates of Lake Nasser storage changes from GRACE shown in Fig. 2 can be understood using experiment 1. If the mass is assumed uniformly distributed over the Lower Nile basin then estimated storage is twice that actually determined from GRACE, as expected from experiment 1. A consequence is that long-term variations will be greatly overestimated. While the area of Lake Nasser constitutes only 1.5 % of the Lower Nile basin, it accounts for ∼ 95 % of the water storage changes.

The Lower Nile basin is also important because the region evaluated in this study covers ∼ 30 % of the Nubian Aquifer System (NAS). There is interest in applying GRACE to evaluate groundwater storage changes in the NAS. The NAS extends over more than 2 M km^2 and is one of the largest groundwater system in the world shared by Egypt, Lybia, Sudan and Chad (Sultan et al., 1997; Gossel et al., 2008). It is the only major fresh water resource in the Eastern Sahara besides the River Nile. In this arid area, recharge from rainfall is limited to a couple of mm a year. Water stored within this aquifer is mostly fossil nonrenewable groundwater accumulated during the Quaternary (Sultan et al., 1997). Groundwater extraction has been rapidly increasing, and the NAS

L. Longuevergne et al.

Title Page

Abstract	Introduction
Conclusions	References
Tables	Figures

| ◄◄ | ►► |
| ◄ | ► |

| Back | Close |

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

is now being mined in several areas, mainly in oases spread over Egypt and Libya, west of the Nile valley, with pumping rates reaching 10 times natural discharge (Gossel et al., 2008).

Application of GRACE data in this region to estimate groundwater storage variations is subject to careful consideration of: (1) the impact of surface water, from reservoirs, but also long-term storage variations from temporary lakes located further west in the Tushka depression. These lakes are created by unusual water rise in Lake Nasser induced by high precipitation in the Ethiopian Highlands (Abdelsalam et al., 2008). During the last wet period, these lakes covered an area of 1586 km^2. Recharge of the Nubian aquifer by these intermittent lakes is insignificant as they are underlain by impermeable shale and chalk formations; (2) the complex nature of the aquifer system. NAS is confined over most of the northern half of the aquifer, where most of pumping stations are located, but also overlain by the unconfined post-Nubian aquifer system; (3) GRACE itself. While signal amplitude is limited in this region (note high noise amplitude on Fig. 2b), there might be potential leakage from high amplitude water storage variations farther south in the recharge area.

4.2 Tigris–Euphrates basin

In the TE basin, the nine largest reservoirs have been taken into account (Table 1; Fig. 3a). As suggested by experiment 1, reservoirs outside TE basin are also included to estimate spatial leakage into the Tigris–Euphrates basin. Tharthar lake (2500 km^2) constitutes ∼ 35 % of the overall mass variability in the basin, with ∼ 7 m level decrease (∼ 17 km^3) during the recent three year drought observed between 2007 and 2010. As it is located near the center of the basin (experiment 1) with a reduced area (experiment 2), it is expected to contribute significantly to the GRACE signal. Predicted impact of reservoir storage to CSR is twice as large as the sum of reservoir storage variations uniformly distributed over the basin (Fig. 3d). In addition, the effect for GRGS is larger than for CSR (not shown), giving GRGS larger seasonal maxima and minima on time series (Fig. 3d).

While artificial reservoirs cover only 0.8 % of the 790 000 km^2 basin, they account for about 10 % of seasonal water storage variations on GRACE (Fig. 3, Table 2). As a result the cycle of water storage variations differ from natural storage variations simulated by GLDAS ΔSMS – which does not include reservoirs – causing a 15-day phase shift in the seasonal signal (Table 2). Indeed, the role of irrigation is to store water from times of excess for use during dry periods, which shifts the phase towards the summer season. Summing predicted reservoir storage with GLDAS shows improved agreement with GRACE in both amplitude and phase, RMS differences are also reduced (Table 2, Table S1). The improved agreement with GRACE obtained by addition of reservoir storage to GLDAS is likely greater for interannual variations (Fig. 3, Tables 1, 2), because reservoir management tends to become more important at longer time scales to mitigate drought.

Reservoir storage management appears to explain about ∼ 50 % of mass variations on GRACE within the Tigris–Euphrates basin over the recent drought from 2007–2009, and not groundwater variations. That is, ΔSMS from GLDAS in combination with reservoir storage (estimated from altimetry) explain most of the GRACE signal, at both seasonal and interannual time scales. Long term groundwater changes appear limited, or possibly closely related to surface water via infiltration. This conjecture is supported by the sources of irrigation water (Siebert et al., 2010). Indeed, while 1755 ha are equipped for irrigation within the basin, only 20 % of the water is derived from groundwater. Recent modeling studies also indicate that return flow from irrigation with surface water replenishes groundwater in this region (Döll et al., 2012).

The computed impact of reservoir on GRACE explains most of the apparent mass variability along with ΔSMS, however, several sources of error should be highlighted. First, all surface water bodies have not been taken into account in this analysis. For example, surface mass variations from the Mesopotamia Marshes, south of Iraq, are not included in this study and their size has increased from 750 to 4000 km^2 between 2002 and 2005 (Jones et al., 2008), which may account for unmodeled interannual variations (Fig. 2d). Second, we considered a constant area hypothesis to compute

lake volume variations from level variations for 7 out of the 9 lakes. Both errors would lead to overestimating the actual long-term depletion from surface water, but do not change the main analysis.

Total water depletion in this region may be caused by two main factors. The first is impoundment and operation of upstream dams, accumulating available water (Jones et al., 2008; Jongerden, 2010). The second is of climatic origin, a drought related to lower than average rainfall and snowfall in the upstream mountains (approximately 60 mm or 47.5 km^3 over three years with respect to the 250 mm annual mean, Fig. 3e). Half the total depletion in GRACE is linked to soil moisture over the entire region; the other half mainly to depleting Iraqi reservoirs (Fig. 3b). Reservoirs are the first hydrological storage elements impacted by decreasing inflows from the contributing area. Droughts are especially critical for downstream reservoirs, which are more dependent on upstream river discharge, and more affected by droughts.

4.3 Surface Water Ocean Topography (SWOT) mission perspective

Accurate GRACE estimates with substantial reservoir and/or lake storage changes depend upon information regarding both location and amount of water masses. Surface water will have a large impact on TWS for large lakes with large volume variations (e.g. Nasser, Guri, and others in the the Supplement). A similar effect is expected in regions with large numbers of small lakes varying coherently (e.g. the Canadian Prairie, Yirdaw et al., 2008).

The value of supplementary information from satellite altimetry to monitor lake levels is evident, but is limited by ground track spacing and fixed nadir pointing of recent and current missions. To improve sampling of surface water storage, Papa et al. (2010) proposed a multi-satellite product to monitor surface water extent at monthly time scales with 25-km spatial resolution, and construction of resulting hypsometry curves from lake level and area data to constrain lake volume variations (Cretaux et al., 2011).

In the coming decade several new satellite altimetry missions are planned that will provide long-term continuous time series of water levels over large lakes and

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

⏮ | ⏭

◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

CC BY

reservoirs. New remote sensing imagery missions enabling land surface classification (including water extent) will also be launched. For example, several new satellites have been planned within the European Union framework of the Global Monitoring for Environment and Security (CMES). However, none of the missions will be dedicated to continental hydrology, in contrast to the Surface Water and Ocean Topography (SWOT) satellite, a joint NASA-CNES mission planned for a 2019 launch. It will be the first satellite designed to the measurement of continental surface water. SWOT will provide a global inventory of all terrestrial water bodies whose surface area exceeds ($250\,\mathrm{m}^2$) with sub-monthly sampling (Biancamaria et al., 2010). It should yield global sampling of many water bodies too small to be measured with current satellites. The principal SWOT instrument will be a Ka-band Radar Interferometer (KaRIN), which will provide heights and co-registered all weather imagery of water over 2 swaths, each 60 km wide, with an expected absolute height precision over lakes of $100\,\mathrm{mm\,km}^{-2}$. The potential of SWOT measurements will be enhanced when coupled with other remote sensing data, and the GRACE follow-on mission especially. SWOT should considerably improve our understanding of lakes and reservoirs water balance and their impact on continental total water storage.

5 Conclusions

We have investigated how spatial concentration and distribution of water masses affect GRACE water storage estimates. Glaciers, lakes, small-scale groundwater systems, with spatial scales well below the GRACE nominal resolution will act as point masses that contribute to the GRACE signal significantly if water level variations are sufficiently large.

Two parametric synthetic experiments illustrate a number of points relevant to interpreting GRACE estimates as basin-wide average water storage changes. Conclusions apply to any basin with an irregular water storage distribution, whether due to human activity or not. The quantitative effect of water mass concentration on GRACE estimates

is not obvious, especially for small basins. GRACE estimates are unlikely to be equal to a simple sum of reservoir storage variations. Estimates will generally be smaller, but may be larger, depending on the position of the mass within the basin. In addition, mass changes outside a basin of interest may contribute significantly. In most cases, the effect of a concentrated mass will be over-estimated by up to 60 % if the mass is assumed incorrectly to be uniformly distributed.

We have applied these results to several basins which contain significant anthropic reservoir management, in the Middle East, and additional basins from different climate zones in the Supplement. The impact of reservoir on GRACE is generally different from the simple sum of reservoir volume variations distributed over the basin of interest. In the Lower Nile basin, combining information on the position and extent of water bodies and level variations from independent observations (radar altimetry), allows us to quantify the impact of reservoir storage on GRACE estimates and to verify that large reservoirs contribute substantially to the hydrological cycle, at both seasonal and interannual time scales. For example, lake Nasser constitutes only 1.5 % of the Lower Nile basin, but accounts for ∼ 95 % of the water storage changes. In the Tigris–Euphrates basin, the simple sum of reservoir storage underestimates their actual impact on GRACE by nearly 50 %. Both soil moisture (∼ 50 %) and predicted impact of reservoir (∼ 50 %) account for most of the TWS decline during the 2007–2010 droughts.

Inland lakes provide important sources of fresh water for agricultural and industrial uses in most of the world, and are an important element in the hydrological budget. In dry regions in particular, agriculture relies heavily on surface water and dams are instruments of economic policy. With significant storage volumes and relatively short time response (compared to groundwater), lakes and reservoirs are important targets for monitoring by GRACE (e.g. Milzow et al., 2011; Velpuri et al., 2012). Because the influence of irregular water storage distribution is significant, GRACE estimates require careful interpretation in these cases, especially when attempting to separate ΔGWS in agricultural regions where both surface and groundwater are used together. The GRACE mission, supported by other satellite instruments, appears to be a useful observational

tool in these arid and semi-arid regions where water resources are scarce, irregularly distributed and ground-based programs to monitor water resources limited. It is also clear that GRACE estimates will be improved when it is possible to combine independent information on spatial distribution of water with GRACE observations, even when
5 concentrated reservoir storage is not a major factor within a basin.

Supplementary material related to this article is available online at: http://www.hydrol-earth-syst-sci-discuss.net/9/11131/2012/ hessd-9-11131-2012-supplement.pdf.

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Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◀ | ▶

◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◀ | ▶

◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

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Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◀◀ | ▶▶

◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

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GRACE water storage estimates for the Middle East

L. Longuevergne et al.

Title Page

Abstract	Introduction
Conclusions	References
Tables	Figures

⏮   ⏭

◀   ▶

Back   Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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GRACE water storage estimates for the Middle East

L. Longuevergne et al.

Title Page

Abstract	Introduction
Conclusions	References
Tables	Figures

|◀ | ▶|

◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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GRACE water storage estimates for the Middle East

L. Longuevergne et al.

Title Page

Abstract	Introduction
Conclusions	References
Tables	Figures

|◀ ▶|

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Table 1. Lake and reservoir data summary.

Region	Lake name	Lake Area (km^2)	Variability (km^3)	Volume/Level data
Lower Nile (410 000 km^2)	*Nasser*	*6216 km^2*	*16 km^3*	*Level*
Tigris–Euphrates (790 000 km^2)	*TOTAL*	*15 268 km^2*	*24 km^3*	
	Asad	447	0.30	Level
	Ataturk	707	1.6	Level
	Daryace (outside)	5200	3.1	Level
	Mossoul	285	1.7	Level
	Qadisiyah	415	2.8	Volume
	Razazah	1501	1.3	Level
	Saksak	458	1.6	Volume
	Tharthar	2500	8.5	Level
	Van (outside)	3755	1.0	Level

Table 2. Comparison between GRACE, ΔSMS and reservoir (ΔRES) for Tigris–Euphrates basin. Please refer to supplementary material Table S1 for comparison with more LSM models.

	GRACE CSR	ΔSMS	ΔRES Contribution to GRACE	ΔSMS + ΔRES
Seasonal amplitude (mm)	63.1	48.5	6.81 (10 %) (True contribution from altimetry: 3.92, 6 %)	50.1
Phase (seasonal) (days)	Ref.	−22	+15	−12
Correlation	Ref.	0.89		0.95
Rms with GRACE (mm)	Ref.	31		23
Trend (Oct 2002–Sep 2009) (mm year^{-1})	−11	−5.8	−4.2 (40 %) (True contribution from altimetry: −2.25, 20 %)	−9.9
Trend (Oct 2002–Sep 2009) (km^3 year^{-1})	−8.6	−4.6	−3.3 (40 %)	−7.8
Trend (Oct 2006–Sep 2009) (mm year^{-1})	−39	−15.7	−19 (49 %) (True contribution from altimetry: −11, 28 %)	−34
Trend (Oct 2006–Sep 2009) (km^3 year^{-1})	−31	12	−15 (49 %) (True contribution from altimetry: −9.1, 28 %)	−27
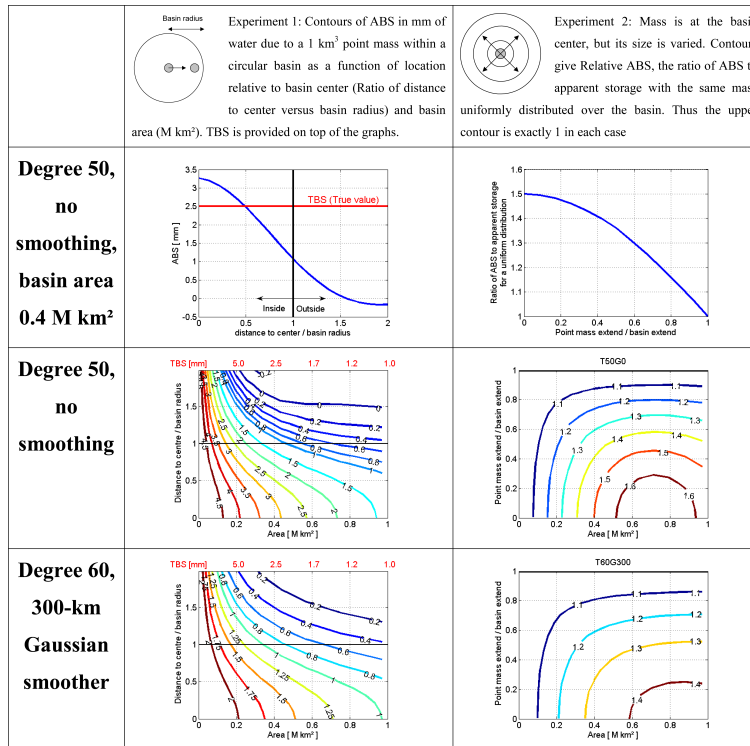
Fig. 1. Numerical experiment of the impact of a point mass to basin-wide estimates Sect. 1 (left) shows contours of ABS for varying basin sizes (horizontal axis) and increasing distance of the mass from the basin center (vertical axis). Section 2 (right) shows contours of ABS divided by the same impact (apparent storage) when the mass is distributed uniformly for varying basin size (horizontal axis) and decreasing concentration (vertical axis). Refer to Fig. S1 and S2 in the Supplement for more case studies and additional figures.
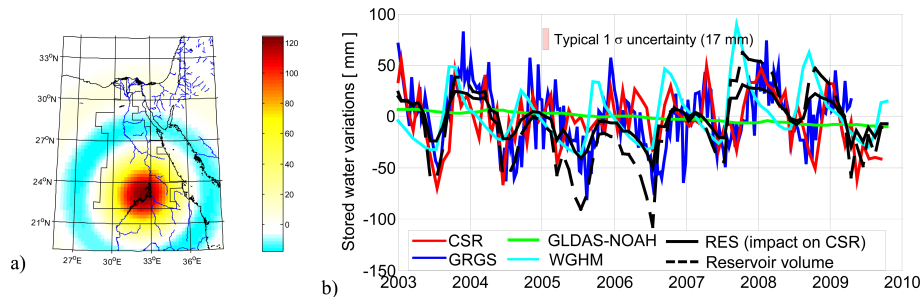
Fig. 2. (a) Apparent water storage change for a uniform 2.7 m water layer distributed over Lake Nasser after hard SH truncation at degree 50 (similar to GRGS), superimposed on an outline of the Lower Nile basin ($410\,000\,km^2$). Note the negative sidelobes associated with hard truncation. The outline of the area of interest is artificially set at the Egypt–Sudan border to compute the impact of a single point mass located at the border of the area of interest. **(b)** The colored lines show Nile basin TWS from GRACE CSR and GRGS estimates, GLDAS-SMS, WGHM (which includes Lake Nasser). The black lines show predicted impact of Lake Nasser on CSR (ΔRES – solid line) and the simple reservoir volume from altimetry uniformly distributed over the basin (dashed line). Lake Nasser accounts for 95 % of the mass variability within the basin.
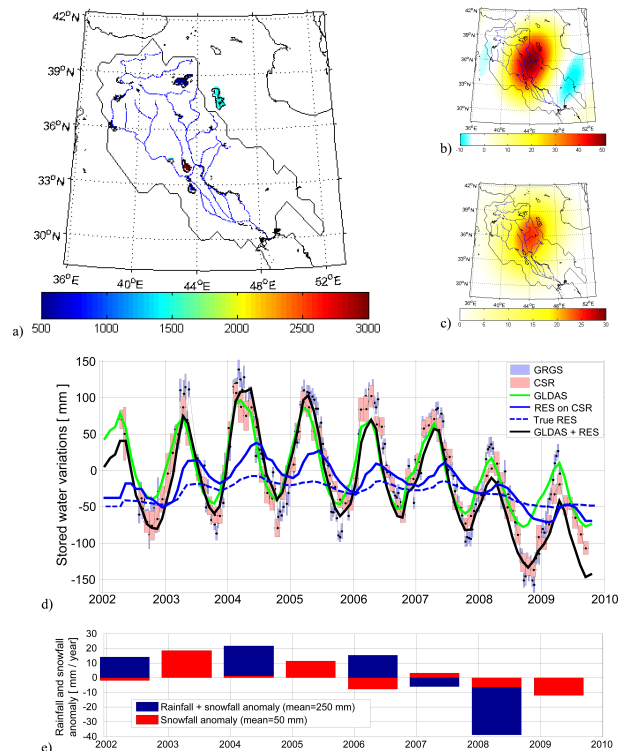
Fig. 3. (a) Reservoir distribution and standard deviation of lake level variations in mm for each of the nine Tigris–Euphrates reservoirs and lakes; **(b)** spatial distribution of estimated water storage variations after hard truncation at degree 50 (similar to GRGS); **(c)** same as **(b)** but after truncation at degree 60 and 300-km Gaussian smoothing (similar to CSR) **(d)** Water storage variations for the Tigris–Euphrates basin from GRACE, GLDAS SM, predicted reservoir storage (RES) impact on CSR and the simple sum of reservoir storage simple distributed over the basin. **(e)** rainfall and snowfall anomaly over the Tigris–Euphrates basin.