Quantifying water storage change and land subsidence induced by reservoir impoundment using GRACE, Landsat, and GPS data

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Abstract

The construction of hydropower dams is a common strategy to support a country’s increasing need for electricity and river water management for industry and agriculture. Although the hydrological and geophysical impacts of water relocation are usually assessed prior to impoundment, their accuracy is generally limited due to the lack of in situ observations, especially in a remote area. This study presents a workflow to quantify the terrestrial water storage change (ΔTWS) and land subsidence induced by a reservoir’s water impoundment using multiple satellite observations (GRACE, Landsat), land surface models (CABLE, GLDAS, NCEP, ECMWF), and GPS data. The study site is the Bakun Dam, located in Sarawak, Malaysia, which is the largest hydropower dam in Southeast Asia. Commencing operation in late 2010, the dam induced a change of water mass and lake surface area that was clearly observed by GRACE and Landsat observations, respectively. During the 17-month impounding period (from August 2010 to December 2011), GRACE observed a dramatic increase of approximately 200 mm equivalent water height, while Landsat detected an increased lake extent of around 600 km². In this paper, a forward model is developed to determine the increased water surface
level corresponding to GRACE observations, estimated to be about 120 m. In contrast to GRACE, the
TWS derived from land surface models cannot capture the increased ΔTWS, due to the lack of
reservoir routing algorithms in the models. In addition, the land subsidence was calculated using the
disk load model constructed based on the GRACE-derived lake level and Landsat-derived lake extent;
the result is validated with the GPS data from BIN1 station, located at the western coast of Borneo.
The commencement stage of the Bakun Dam induces the large-scale land subsidence, which causes
the GPS-BIN1 station to subside by ~9 mm, and move toward the Bakun Lake by ~4 mm.
Computation of the surface displacements directly from GRACE spherical harmonic coefficient data
fails to capture the subsidence feature, mainly due to the truncation error. Overall, this study
demonstrates that evaluating GRACE in conjunction with Landsat, LSMs, and GPS data allows the
exploitation of the gravity signal at a much smaller spatial scale than its intrinsic resolution.
Benefiting from global coverage, the newly developed satellite-based algorithm is a valuable tool for
assessing the impacts of reservoir operation on hydrological and geophysical changes from local to
regional scales.

Keywords: GRACE, Landsat, Bakun Dam, water storage change, land subsidence, disk load model

1. Introduction

Construction of fresh water reservoir is one of the potential solutions to secure the country
development under the risk of climate change and projected increases in population (Ehsani et al.,
2017; Ho et al., 2017). However, significant water relocation and impoundment affect the natural
hydrological cycle and also likely lead to land subsidence over an extended surrounding area (Graf,
1999; Boy & Chao, 2002). The assessment of the hydrological impact caused by the dam is a general
practice, but the accuracy is often limited by a lack of observations (Bierkens et al., 2015). Monitoring
the effect using a newly installed ground observation network (e.g., GPS receivers, river gauges)
around the construction site is not feasible due to its cost and intensive maintenance requirement.
Satellite remote sensing data provide a temporally global coverage measurement, making continuous
monitoring of reservoir water storage and land cover change possible (e.g., Gao et al., 2012; Wang et al., 2011; Zhou et al., 2018). For the land subsidence estimation, in particular, various remote sensing observations are combined to increase the accuracy of the estimate, demonstrated in various applications (e.g., groundwater depletion (e.g., Castellazzi et al. 2016; Hwang et al., 2016), snow accumulation (e.g., Heki, 2001), extreme rainfall (e.g., Bettinelli et al., 2008; Fu et al., 2013) (see Table 1). For the first time, this study utilizes multiple remote sensing data and numerical models to assess the terrestrial water storage (TWS) change and land subsidence caused by the reservoir operation.

[Table 1]

The TWS can be defined as the summation of several storage components, e.g., soil moisture, groundwater, snow, canopy, surface water (e.g., lake, river), and commonly expressed as Equivalent Water Height (EWH), describing an equivalent water thickness (e.g., in m) of a unit area. The TWS can be estimated both from land surface models (LSM) and satellite gravimetry observations (e.g., Syed et al., 2008). The LSMS, forced by precipitation and meteorology, estimate TWS using a sophisticated water and energy balance representation, and have been successfully used to assess the regional water resources in numerous applications (e.g., Koirala et al., 2013; Mo & Lettenmaier, 2013; Wu et al., 2014). The recent LSM development begins to include the representation of groundwater flow (e.g. Niu et al., 2007, Vergnes et al., 2012), anthropogenic water use, including dam operations (Felfelani et al., 2017, Döll et al., 2015), in a multi-physics framework (Yang et al., 2011).

However, while adequately representing the natural environment, a majority of LSMS often fail to represent the anthropogenic terms in a highly regulated or controlled environment (e.g., Tatsumi & Yamashiki, 2015; Wang et al., 2011). In such conditions, remotely sensed observation of the TWS derived from the satellite gravimetry observation is the far better alternative. The water (or mass) change produces an anomaly of the Earth’s gravity field and such a signal can be observed by the Gravity Recovery And Climate Experiment satellites (GRACE; Tapley et al., 2004). GRACE provides monthly Earth’s gravity field variations in terms of the spherical harmonic coefficient (SHC) and had been used to estimate the ΔTWS during its 2002 – 2016 lifetime (e.g., Han et al., 2017;
Lettenmaier & Famiglietti, 2006; Zhou et al., 2018). In contrast to LSM, GRACE observes the entire water column, including all natural and anthropogenic processes, leading to a more complete and accurate record of the estimated ∆TWS. Another advantage of GRACE is the sensitivity associated with mass concentration. A gravity signal of a concentrated mass over a small area can be recovered (Castellazzi et al. 2016), demonstrated by, e.g., Longuevergne et al. (2013), Castellazzi et al. (2018), making GRACE a potential measurement for monitoring the storage variability of the local reservoir.

A significant water impoundment during the dam commencement generally induces a displacement of the Earth’s surface (Boy & Chao, 2002). The displacement can be computed using the GRACE SHC data together with the load Love numbers (Bevis et al., 2016; Chanard et al., 2014; 2018; Karegar et al., 2018), which has shown a noticeable agreement with GPS records in broad geographical regions, e.g., Amazon River Basin (Davis et al., 2004), Europe (van Dam et al., 2007), Australia (Han, 2016).

Due to the limited spatial resolution (or limited maximum harmonic degree, $N_{\text{max}}$ in the spectral domain) of GRACE, the approach is only valid when the spatial extent of surface mass change is sufficiently large (e.g., >250 km resolution). However, the GRACE results may be not adequate for determining the mass change of a small spatial scale and the associated elastic surface deformation. Such a phenomenon can be understood as a GRACE truncation error, which commonly leads to a discrepancy between the GRACE and GPS’s vertical displacement estimate (e.g., Khan et al., 2010; Nahmani et al., 2012; Wang et al., 2017). The limitation of GRACE SHC motivates the use of the disk load model in the computation of the local land surface deformation over the region much smaller than GRACE’s spatial resolution (Wahr et al., 2013).

The disk load model adopts the Earth’s elastic and gravitational response concept to determine the effect of the local hydrological load placement (Bevis et al., 2016; Wahr et al., 2013). A point mass load (e.g., reservoir’s water) placed on the Earth’s surface would induce the surface of the nearby region to subside and move towards the load. The load model is suitable for a small mass extent as the response can be computed to a very high harmonic degree (e.g., 40,000; Bevis et al., 2016; Wang et al., 2012), representing a spatial resolution of several hundred times higher than what GRACE offers.
This paper focuses on assessing the hydrological and geophysical impacts of reservoir operation using Landsat (Irons et al., 2012), GRACE, LSMs, and GPS data. The study area is Sarawak, Malaysia, where the Bakun Dam (Sovacool & Bulan, 2011) was commenced in 2010, the period that Landsat, GRACE, and GPS data are all available for evaluation. The outline of this paper follows three main objectives:

1) Quantifying the change of water storage, lake level, and lake area caused by water impoundment,

2) Assessing the associated land subsidence, using a developed disk load model to increase the accuracy of the surface deformation estimate, and

3) Elaborating the importance of incorporating GRACE with multiple data for modeling regional ΔTWS and land subsidence that might be difficult to be accurately estimated by solely relying on the gravity data.

These objectives are presented accordingly in the following Methods, Results, and Discussions sections.

2. Study site and materials

2.1. Study area

The Bakun Dam, an embankment dam in Sarawak, Malaysia (Fig. 1), is the largest hydropower dam in Southeast Asia since 2015, supplying ~2,400 MW of electricity to the Malaysian household (Oh et al., 2010). The dam is located on the Balui River, a tributary of the Rajang River, about 37 km upstream from Belaga. The catchment of 14,750 km² receives a yearly average rainfall of ~300 – 400 cm, which makes it ideally suited for the hydroelectric development (Sovacool & Bulan, 2011). The 205m high dam began impoundment in late 2010 and has operated at its proposed capacity since August 2011. The dam created a vast freshwater reservoir, called Bakun Lake, of >600 km² (Shirley and Kammen, 2015), equivalent to the size of Singapore (Bujang et al., 2016). The substantial change in the geographical characteristic of Sarawak’s rainforest and altered the water quality and natural
flow of the Balui and Rajang river systems is well documented (e.g., Sovacool & Bulan, 2011).

However, impoundments of a significant amount of terrestrial water storage (TWS) not only affects the natural hydrological cycle (Guo et al., 2012; Lu & Siew, 2006), but also induces the land surface displacement, which likely presents as a large scale land subsidence over the area (Boy & Chao, 2002; Zerbini et al., 2007). To date, the impact of the Bakun Dam on the water storage change and land deformation has not been assessed. This study intends for the first time to quantify the TWS variation (ΔTWS) and land subsidence induced by the impoundment of the Bakun Lake.

[Fig. 1]

2.2. Landsat data and digital elevation models

The Landsat-7 (L7) and Landsat-8 (L8) Operational Land Imager (OLI) data are used to delineate the inundated area after the flood commencement. The OLI sensor observes the electromagnetic signals from visible to short-wave spectral bands reflected from the Earth’s surface. The combination of the observed surface reflectance can be used to evaluate the land cover change, particularly the surface water. The Landsat data are obtained from the Earth Explorer service (https://earthexplorer.usgs.gov), which provides the surface reflectance every 16 days with a spatial resolution of 30 m. The data are corrected for atmospheric effects using the Dark Object Subtraction (DOS1) method (Chavez, 1996).

The DOS1 is an image based algorithm, which applies the correction associated with atmospheric scattering, solar zenith angle, and irradiance. The scenes that have severe cloud cover over the Bakun Lake’s area are excluded. The surface water is then derived using the Normalized Difference Water Index (NDWI; McFeeters, 1996), which is computed as:

\[ NDWI = \frac{Green - NIR}{Green + NIR} \]  

where Green is a green band (band 2 for L7, band 3 for L8), and NIR is a near infrared band (band 4 for L7, band 5 for L8). The unitless NDWI ranges between -1 and 1. A positive value generally represents the open water, while a zero or negative value represents soil and terrestrial vegetation. The
L7 data are used in the NDWI computation prior to June 2013, and the L7 and L8 data are used together between June 2013 and March 2016 (when L8 data are available). Due to limited cloud-free scenes over Bakun Lake, the yearly-averaged NDWI is used for the analysis.

The lake volume can be approximated using a lake filling model associated with the derived NDWI and digital elevation model (DEM). Three DEMs are considered in the lake volume calculation, the Shuttle Radar Topography Mission (SRTM, Rabus et al., 2003), the Advanced Spaceborne Thermal Emission and Reflection Radiometer - Global Digital Elevation Model Version 2 (ASTER-GDEM2, Tachikawa et al., 2011), and the Advanced Land Observing Satellite World 3D - 30 m (AW3D30, Tadono et al., 2015). The 30 m spatial resolution data is obtained from all products.

2.3. GRACE data

The GRACE twin satellites measure variations of the Earth’s gravity field every month using a combination of several measurements onboard, e.g., K-band ranging, accelerometer, attitude, and orbital data (Bettadpur, 2012). As the gravity variation at the monthly time scale is dominated by the hydrological mass changes, the GRACE gravity data are often used to compute $\Delta$TWS (Wahr et al., 1998) and the associated (elastic) load deformation (van Dam et al., 2007), allowing the gravity information to be exploited in a wide range of hydrological and geophysical applications (e.g., Han et al., 2017; Liu et al., 2016; Simon et al., 2017). The GRACE monthly SHC data products are produced by different scientific centers (e.g., Bettadpur, 2012; Dahle et al., 2013; Watkins & Yuan, 2014).

Sakumura et al. (2014) demonstrated that averaging multiple gravity solutions may reduce the processing-dependent error in the derived gravity solutions and lead to improved $\Delta$TWS estimates. We compute the time series of $\Delta$TWS and load deformation by averaging four different GRACE solutions, the Centre National d'Etudes Spatiales/Groupe de Recherches de Géodésie Spatiale Release 3 Version 3 (CNES/GRGS; Lemoine et al., 2015), the Center for Space Research, The University of Texas at Austin Release 05 (CSR; Bettadpur, 2012), the Jet Propulsion Laboratory Release 05.1 (JPL, Watkins & Yuan, 2014), and the Deutsches GeoForschungsZentrum Release 05 (GFZ; Dahle et al., 2014).
The GRACE uncertainty is defined as the standard deviation across four solutions. The study period is between August 2002 and March 2016.

The CNES/GRGS solution provides the SHC up to the maximum degree and order \( N_{\text{max}} = 80 \). The solution has been regularized (using a truncated singular value decomposition), and no additional post-processing is needed to reduce the high-frequency noise (Lemoine et al., 2015). The low degree SHC (including degree 1 and C20 coefficients) are constrained using the Starlette and Stella Satellite Raser Ranging (SLR) data. The CNES/GRGS solution removes the short-term atmospheric and non-tidal oceanic variation from their gravity field solution, while such signals remain intact in the GPS measurement. The two data need to be made consistent in terms of signal contents when conducting the comparison between GRACE gravity and GPS displacement data. In this study, the atmospheric and oceanic variation obtained from the CNES/GRGS de-aliasing product is added to the CNES/GRGS GRACE SHC solutions. Furthermore, the CSR \( (N_{\text{max}} = 96) \), JPL \( (N_{\text{max}} = 90, \) and 60 for some months), and GFZ \( (N_{\text{max}} = 90) \) solutions are filtered using the non-isotropic filter DDK5 (Kusche et al., 2009). We obtain DDK5 solutions directly from the International Centre for Global Earth Models (ICGEM, http://icgem.gfz-potsdam.de/home). After retrieving the data, the degree 1 coefficients are restored using the value provided by Swenson et al. (2008) and the C20 coefficient is replaced by the SLR measurements (Cheng and Tapley, 2004). When comparing with the GPS measurement, the de-aliasing atmospheric and oceanic signals provided by the GRACE AOD1B product (Flechtner et al., 2015) are applied to these GRACE data. The monthly averaged SHC is computed by averaging four (CNES/GRGS, CSR, JPL, and GFZ) GRACE products. Then, its long-term mean (computed between 2002 and 2016) is removed from each monthly solution to obtain the monthly SHC variation.

### 2.4. LSMs-derived ∆TWS

The monthly ∆TWSs derived from different LSMs are also used to assess the effect of the dam. This study uses four publicly accessible LSM outputs, the Global Land Data Assimilation System, NOAH
(GLDAS; Rodell et al., 2004), the National Centers for Environmental Prediction and the Department of Energy Reanalysis-2 (NCEP; Kanamitsu et al., 2002), the European Centre for Medium-Range Weather Forecasts Re-Analysis Interim (ECMWF; Dee et al., 2011), and the Community Atmosphere Biosphere Land Exchange (CABLE; Decker, 2015). In all models, the ΔTWS is mainly composed of the soil moisture component from multiple soil layers (snow water equivalent is zero). GLDAS also includes canopy storage, while CABLE includes canopy and groundwater storages in the ΔTWS calculation. Water storage from neither natural nor artificial lakes like the Bakum Dam reservoir is available in the LSMs.

In this study, CABLE is forced by the forcing data from the GLDAS dataset and the precipitation from the Tropical Rainfall Measuring Mission (TRMM; Huffman et al., 2007) to increase the model accuracy, as described in Tangdamrongsub et al. (2018). The ensemble open-loop run is performed to obtain the LSM-derived TWS uncertainty. Selected forcing data and model parameters are perturbed by random white noises with 10% of their nominal values (see Tangdamrongsub et al., 2018). The number of ensemble is 100. The model is run independently for each ensemble, and the TWS standard deviation (across all ensemble) is used as the TWS error.

2.5. GPS measurements

The GPS records at station BIN1 (Fig. 1a) are obtained from two data processing centers, the University of Nevada, Reno (UNR), and the University of La Rochelle Analysis Center Consortium (ULR). The UNR solution between September 2007 and March 2016 is obtained from http://geodesy.unr.edu/index.php (Blewitt et al., 2018). The ULR version 6 (ULR6; Santamaría-Gómez et al., 2017) provided a shorter time series, between September 2007 and November 2013, and is downloaded from http://www.sonel.org/-GPS-.html. Other GPS stations located near the Bakun Dam (<150 km) are not used due to the significant data gap and short time span of the records. The monthly averaged value of all three components (up, north, east) is then computed from the daily time series. To reduce the plate tectonic effect (e.g., Fu and Freymueller (2012); Wang et al. (2017)), the
associated long-term trend of up, north, and east component is firstly fitted (using Eq. (A1)) and removed from its time series. Finally, the long-term mean is subtracted from the time series to obtain the variation of the GPS position.

3. Methods

The processing workflow is shown in Fig. 2. The satellite images obtained from Landsat 7 and 8 are used to delineate the Bakun Lake’s extent as well as to approximate the lake’s level. GRACE data and LSMs are used to estimate the ΔTWS, and the comparison between GRACE and LSMs results is conducted to evaluate a unique benefit of GRACE data in the controlled environment. A forward modeling of the GRACE-derived ΔTWS anomaly during the water impoundment period is also performed to approximate the water level. The lake’s outline obtained from Landsat and the lake’s level estimated from the GRACE forward modeling are then used to construct the disk load model. The land subsidence is assessed from the disk load model and the GRACE SHC estimate, and the comparison between both results together with the GPS records will confirm the effectiveness of the disk load model application over the Bakun Lake.

[Fig. 2]

3.1 Estimation of lake area and volume from Landsat data

The averaged water level in the Bakun dam after its full operation (e.g., after 2011) can be approximated using the flood simulated model associated with the Landsat-derived NDWI. The general approach is to impound a certain amount of water into the study area (characterized by DEM), and evaluate the water level that produces the same flood extent observed by Landsat (Musa et al., 2015; O’Grady et al., 2011). The GRASS GIS function r.lake (https://grass.osgeo.org/grass70/manuals/r.lake.html) is then used to simulate the flood extent associated with a given water level. A range of water levels is tested, and the optimal water level of
the Bakun Lake is chosen when it yields the maximum critical success index (CSI; Roebber, 2009).

The CSI is computed as:

\[ CSI = \frac{\sum_{i=1}^{K} A}{\sum_{i=1}^{K} (A + B + C)}, \]

where \( i \) is the Landsat pixel’s index, \( K \) is the number of total pixels, and

\[ A = \begin{cases} 1; & \text{simulated and observed pixels both identify water} \\ 0; & \text{otherwise} \end{cases}, \]

\[ B = \begin{cases} 1; & \text{simulated pixels detect water, but no water in observed pixels} \\ 0; & \text{otherwise} \end{cases}, \]

\[ C = \begin{cases} 1; & \text{simulated pixels fail to detect water} \\ 0; & \text{otherwise} \end{cases}. \]

The CSI values vary between 0 and 1 where 1 indicate that the simulated water level produces an identical flood extent as the observation.

The accuracy of derived NDWIs is assessed using a referenced image from the Earth Science Data Records of Global Forest Cover and Change (ESDR-GFCC, Feng et al., 2016). The ESDR-GFCC derives the percentage of forest cover change in ~5 year-window from the Global Land Survey (GLS) data, and provide the product at 30 m resolution. The 1990, 2000, 2005, 2010, and 2015 products are available, but only the 2015 scene captures the Bakun Lake, and it is used as a reference here. Over the Bakun Lake, the surface water pixel is defined as zero percent forest cover change. To resemble the 2015 ESDR-GFCC scene, we compute the percentage of water pixel change from the derived NDWIs between 2013 and 2016, and the pixel with a zero percent change is defined as surface water. The overall accuracy is computed as \((H + M)/N\), where \( H \) is 1 when the NDWI result and reference both detect water \((H = 0, \text{otherwise})\), \( M = 1 \) when both miss detecting water \((M = 0, \text{otherwise})\), and \( N \) is the number of considered pixels.

3.2 Estimation of \( \Delta \)TWS and surface deformation from GRACE data
The monthly GRACE product, together with load Love numbers (Bevis et al., 2016; Wang et al., 2012), is used to compute the ∆TWS (Wahr et al., 1998) and the 3D-displacement (van Dam et al., 2007; Wang et al., 2017) caused by the mass load variation as follows:

\[
\Delta TWS(\theta, \phi) = \frac{a \rho_{\text{ave}}}{3 \rho_w} \sum_{n=1}^{N_{\text{max}}} \sum_{m=0}^{n} \bar{P}_{nm}(\cos \theta)(\Delta \bar{C}_{nm} \cos(m\phi) + \Delta \bar{S}_{nm} \sin(m\phi)) \frac{2n + 1}{1 + k_n}
\]  \tag{3}

\[
\Delta r(\theta, \phi) = a \sum_{n=1}^{N_{\text{max}}} \sum_{m=0}^{n} \frac{\partial \bar{P}_{nm}(\cos \theta)(\Delta \bar{C}_{nm} \cos(m\phi) + \Delta \bar{S}_{nm} \sin(m\phi))}{1 + k_n} \frac{h_n}{1 + k_n}
\]  \tag{4}

\[
\Delta n(\theta, \phi) = -a \sum_{n=1}^{N_{\text{max}}} \sum_{m=0}^{n} \frac{\partial \bar{P}_{nm}(\cos \theta)(\Delta \bar{C}_{nm} \cos(m\phi) + \Delta \bar{S}_{nm} \sin(m\phi))}{1 + k_n} \frac{l_n}{1 + k_n}
\]  \tag{5}

\[
\Delta e(\theta, \phi) = \frac{a}{\sin \theta} \sum_{n=1}^{N_{\text{max}}} \sum_{m=0}^{n} \frac{\bar{P}_{nm}(\cos \theta)(-\Delta \bar{C}_{nm} \sin(m\phi) + \Delta \bar{S}_{nm} \cos(m\phi))}{1 + k_n} \frac{m l_n}{1 + k_n}
\]  \tag{6}

where \((\Delta r, \Delta n, \Delta e)\) are the displacement of the Earth’s surface (meter) in the radial (up), north, and east directions, \((\theta, \phi)\) are the colatitude and east longitude (radian), \((k_n, h_n, l_n)\) are the load Love numbers of degree \(n\) (unitless), \(\bar{P}_{nm}\) is the normalized associated Legendre function of the first kind of degree \(n\) and order \(m\) (unitless), \((\rho_{\text{ave}}, \rho_w)\) are the average density of the Earth and freshwater (kg/m³), \(a\) is the radius of the Earth (meter), and \((\Delta \bar{C}_{nm}, \Delta \bar{S}_{nm})\) are the monthly SHC variation (unitless). The load Love numbers associated with REF seismological model are used in this paper (Kustowski et al., 2007; Bevis et al., 2016).

3.3 Derivation of lake’s water level using TWS forward model

The forward model \((f)\) associated with the GRACE-derived ∆TWS can be used to determine a water level of the Bakun Lake. The lake basin function \((b_D)\) is firstly designed by setting a value of a uniform water level \((D)\) in the lake while setting outside value as zero. Then, the Gaussian smoothing \((G)\) is applied to the basin function \((f = G(b_D))\) to simulate the water storage at the GRACE spatial resolution. The variance ratio, \(\nu = \sum_{i}^{K} (d_i - f_i)^2 / d_i^2\) (\(i\) is the considered grid cell, and \(K\) is the...
number of grid cells), is used to find the optimal water level parameter $D$ from the GRACE observation ($d$). The spatial resolution of GRACE is obtained from the correlation length, estimated from the empirical covariance function $C(\psi)$ (see Eq. (3–5) of Tscherning and Rapp, 1974), where $\psi$ is the spherical distance. The correlation length is defined as the distance ($\psi$) where the $C(\psi = 0)$ decreases by half.

It should be noted that the GRACE-derived (equivalent) water level variation includes all hydrological components, e.g., surface water, soil moisture, groundwater, and the estimate might be different from the measured reservoir level (e.g., from gauge data) that reflects only the surface water component.

### 3.4 Development of disk load model

The disk load is designed as a cylinder with a given radius and thickness. A number of discrete loads are placed along the outline of the water body (e.g., delimited from the satellite imagery data), and the total displacement is computed by summing the contributed responses from all disk loads. Following this concept, the surface mass load ($\sigma$, kg/m$^2$) as a function of the angular distance ($\varphi$, radian) away from the load center can be formulated based on a series of Legendre polynomials as follows:

\[
\sigma(\varphi) = \sum_{n=0}^{N_{\text{max}}} \sigma_n P_n(\cos \varphi),
\]

and the disk load coefficient $\sigma_n$ (kg/m$^2$) is computed as (Bevis et al., 2016; Wahr et al., 2013):

\[
\sigma_n = \frac{\rho_\text{w}D}{2} \left\{ \begin{array}{ll}
(1 - \cos \alpha) & n = 0 \\
-P_{n+1}(\cos \alpha) + P_{n-1}(\cos \alpha) & n \geq 1
\end{array} \right.
\]

where $\alpha$ is the angular disk radius (radian), $P_n$ is the Legendre polynomial of degree $n$ (unitless), and $D$ is the disc thickness (meter), which is defined as a water depth in this study. The vertical ($V$) and horizontal ($H$) displacements (meter) caused by the disk load are formulated as:
\[
V(\varphi) = \frac{4\pi a^3}{M_e} \sum_{n=0}^{N_{\text{max}}} \frac{\sigma_n h_n}{2n+1} P_n(\cos \varphi),
\]

\[
H(\varphi) = \frac{4\pi a^3}{M_e} \sum_{n=0}^{N_{\text{max}}} \frac{\sigma_n l_n}{2n+1} \frac{\partial}{\partial \varphi} P_n(\cos \varphi),
\]

where \(M_e\) is the mass of the Earth (kg). \(V(\varphi)\) is measured upward, while \(H(\varphi)\) is measured in the direction of increasing angular distance. The uncertainties of \(V(\varphi)\) and \(H(\varphi)\) are calculated by using an error propagation (see, e.g., Eq. (15) of Tangdamrongsub et al. (2017)).

4. Results

4.1 Inundated area and lake volume from Landsat data

The yearly average NDWIs derived from the Landsat data between 2007 and 2016 are shown in Fig. 3. After a careful inspection, we found that the NDWI values greater than 0.2 represent the surface water, while the values <0.1 generally include clouds and vegetation. Therefore, we define a surface water pixel for NDWI > 0.2 as a safe threshold. The derived NDWI has an overall accuracy of ~95 % evaluating against the ESDR-GFCC data (Sect. 3.1). We found that the accuracy is reduced when the NDWI threshold is smaller than 0.2, which is likely caused by the contamination of cloud and vegetation pixels in the calculation. From Fig. 3, the distinct layouts of the Rajang and Balui Rivers are seen between 2007 and 2010 (and also before 2007, not shown), but no sign of the Bakun Lake is observed (Fig. 3a – d). The expansion of the inundated area is clearly visible in 2011 when the Bakun Dam began its operation (Fig. 3e), and the lake extent has no significant change from 2012 onward (Fig. 3f – j). The averaged NDWI between 2012 and 2016 is then used to delineate the lake boundary (polygon). The inundated area can be calculated by integrating the area of all water pixels inside the lake polygon, as shown in Fig. 3k. The inundated area is substantially increased by 12 times (from ~50 km\(^2\) before 2011 to ~600 km\(^2\) after 2012).

[Fig. 3]
The Landsat data and DEM are used to approximate lake volume. The water pixels derived from the averaged NDWI between 2012 and 2016 is defined as the observation (Fig. 4a). Figs. 4b – d demonstrate the simulated inundated area after filling the lake area with the averaged water levels of approximately 46 m, 60 m, and 73 m, respectively. With increasing water level, the flood firstly emerges around the downstream of the Balui River and progresses upstream through Rumah Baka and Rumah Kulit, respectively. The maximum CSI value is obtained when the simulated water level of ~ 75 m (corresponding to 48 Gt of total water mass) is used (Fig. 5), and it results in the best agreement with the observed flood extension (Fig. 4a). Comparing with SRTM, the average water level is reduced by ~ 2 m, and increased by ~1 m when AW3D30 and ASTER-GDEM2 are used, respectively. The difference is ~ 1.5 m or 1.8 % of the approximate water level.

[Fig. 4]

[Fig. 5]

4.2 GRACE-derived ∆TWS and water level changes

The GRACE-derived ∆TWS of the Bakun Dam (averaged ∆TWS inside the flood polygon) between 2002 and 2016 is shown in Fig. 6. The time series are fitted with six variables to estimate the long-term, annual amplitude, and phase (see Appendix A). The ∆TWS time series shows a slightly increasing trend of ~ 2 mm/year and a seasonal amplitude of ~ 16 mm (Table 2) before the flood commencement. On average, the ∆TWS’s standard deviation between 2002 and 2016 is ~52 mm. The water impoundment signature is clearly seen from August 2010, and the ∆TWS is significantly increased by approximately 200 mm (equivalent water height) between August 2010 and December 2011. Therefore, we define the period of August 2010 – December 2011 as the impoundment period in this study. The ∆TWS has been steady since 2012, with a similar trend (~2 mm/year) but with twice the seasonal amplitude, ~38 mm. This reflects the role of the Bakun Dam in transiently storing water during the wet season (and reducing runoff) to release during the dry season (e.g., Longuevergne et al. 2013). It is also observed that there is a change in the seasonal peak TWS occurrence from December to February, after the dam construction, which is likely caused by the
retention time of the reservoir. The reservoir fill and release regulation are made to spill excess capacity and to maintain some level of flow in the river downstream of the dam. In addition, the El Niño/Southern Oscillation (Wang et al., 2000) signature is seen in the ΔTWS before the flood commencement. The 2009 El Niño (less precipitation in South-East Asia) is the main cause of the low ΔTWS in summer 2009 (Han et al., 2017). The ENSO effect on the ΔTWS is less pronounced in the Bakun Dam area compared to the central and southern parts of Kalimantan (southern part of the island), where the peat fire also likely intensifies the water storage loss (Han et al., 2017).

[Fig. 6]

[Table 2]

The spatial pattern of GRACE ΔTWS change between the pre-dam (August 2002 – July 2010) and post-dam (January 2012 – March 2016) periods is computed and shown in Fig. 7a. The increased ΔTWS of ~200 mm is found around the Bakun Lake. The decreased ΔTWS in the southern part of the island is likely caused by the decreased rainfall after 2012 (Han et al., 2017). We apply the TWS forward model to approximate the water level of the Bakun Dam, by using the ΔTWS difference (Fig. 7a) as the observation and evaluate the forward model’s result associated with given uniform water levels ranging between ~100 m and ~140 m height with respect to the base of the dam. The smoothing radius of the forward model is obtained from the ΔTWS correlation length estimate. The averaged covariance functions computed using the GRACE-derived ΔTWS between August 2002 and March 2016 from all GRACE solutions (CSR, JPL, GFZ, CNES/GRGS, and average) presents a very similar feature, and the correlation length of ~275 km is found in all solutions (Fig. 7b). The forward model shows a similar spatial feature to the observation around the dam location (Fig. 7c), and its intensity is proportional to the parameter D. Considering only the averaged ΔTWS inside the Bakun Lake, the minimum variance ratio (v) is found when D ≈ 120 m (Fig. 7d). We assume that the error of GRACE-derived ΔTWS follows a normal distribution (described by zero mean and standard deviation of 52 mm), and the uncertainty of the approximate water level is estimated based on an error propagation method. This corresponds to the water level uncertainty of ~27 m. The TWS forward modeling approach is applied to all monthly GRACE-derived ΔTWS to approximate the water level variations.
of the Bakun Lake, and the water level time series is displayed in Fig. 2 (associated with the right axis).

[Fig. 7]

4.3 LSMs-derived ΔTWS

The ΔTWS estimates of the Bakun Dam simulated from four different LSMs are shown in Fig. 8a. All models show an increasing long-term trend in the pre-dam period (Table 2). The CABLE and GLDAS models show an increasing trend of approximately 3–4 mm/year, consistent with the value observed by the GRACE observation. The NCEP and ECMWF models show a significantly larger trend estimate of ~16 mm/year, mainly due to the significantly low ΔTWS between 2002 and 2005 influenced by the exceptionally low rainfall (Fig. 8b). In the post-dam period, in contrast to GRACE, the negative trends are observed from all models, which is mainly induced by the reduction of rainfall after 2008. None of the LSMS adequately captures the GRACE signals of ΔTWS increase associated with the Bakun Dam water storage. A seasonal variation during the post-dam period is observed in CABLE and GLDAS with the twice increased annual amplitude (compared to the pre-dam period). The increased precipitation is responsible for an increased wet condition, which is in favor of the water storing operation (see Sect. 4.2). By contrast, NCEP and ECMWF do not present any significant change in the seasonal variation over time. No significant change in the seasonal timing is observed from all models.

[Fig. 8]

The spatial patterns of the ΔTWS difference (post-dam minus pre-dam) are computed from LSMs (see Sect. 4.2) and shown in Figs. 8c – 8f. The precipitation differences corresponding to each LSM are also computed in the same manner and shown in Figs. 8g – 8j. It is found that the spatial patterns of the modeled ΔTWS are consistent with the associated precipitation data (Figs. 8g – 8j), not with GRACE observations (Fig. 7a).
The modeled $\Delta$TWS is evaluated in terms of temporal correlation against the GRACE observation, and the correlation coefficients associated with different LSMs (with 0.05 significant level) are shown in Table 3. The cross-correlation among four LSMs shows that only two out of six pairs are in agreement; for example, the correlation greater than 0.7 for the pairs of CABLE vs. GLDAS and NCEP vs. ECMWF. The correlation between CABLE (or GLDAS) and NCEP (or ECMWF) is as low as 0.22, indicating the high uncertainty of the LSM simulated $\Delta$TWS in this area. As expected, all models are poorly correlated with the GRACE observations. Absent to consider the Bakun Dam’s effect in the TWS calculation likely leads to an inaccurate $\Delta$TWS estimate, which makes the current LSM simulation less favorable for the water resource assessment or the hydrological reanalysis application in this region.

[Table 3]

During the reservoir impoundment, the impounded water is first distributed through the soil and groundwater zones, filling pore space until the maximum saturated TWS capacity is reached, and the exceeded capacity results in surface water. The required filling capacity (before the appearance of the lake) can be approximated by CABLE, whose land cover parameters are publicly accessible. We found that the CABLE-estimated TWS between January 2010 and July 2010 (period prior to impoundment) is stable at $\sim$10.40 ± 0.35 m, which is lower than the saturated capacity by $\sim$0.83 m. Note that the obtained value is at the model resolution. We compute the required filling capacity at the Bakun Lake by applying the TWS forward model in a similar manner as GRACE and obtained the water level of $\sim$34 ± 7 m that needs to be filled as a foundation of the Bakun Lake.

The summation between the Landsat-derived lake level (75 ± 1.5 m) and the required filling capacity (34 ± 7 m) shows a reasonable agreement with the water level approximated by GRACE (109 ± 7 m Vs. 119 ± 27 m).

4.4 Land subsidence
The solid Earth deforms elastically in response to surface water load (Farrell, 1972). An elastic Earth model is taken to compute the three-dimensional surface deformation induced by the Bakun Lake load using the GRACE (truncated) SHC data as well as the disk load model of the reservoir. The disk model is essentially determined with Landsat inundated area and constrained by GRACE-derived $\Delta$TWS for water level changes, as described previously. The Bakun Lake load is spatially localized demanding spherical harmonic expansion to the degree considerably higher than what GRACE data provide.

The Bakun Lake disk model is composed of multiple disks with variable radii covering the flooded area, as shown on the inset map in Fig. 9a. The total area of the disk loads is ~600 km$^2$, corresponding to the area derived from the Landsat data (Sect. 3.1). The averaged monthly water level derived from GRACE is used to constrain monthly changes of uniform thickness of the Lake disks (Sect. 3.3). The vertical displacement is calculated from the disk model using Eq. (9) with $N_{\text{max}} = 40,000$, and the result is shown in Fig. 9a. It is seen that significant subsidence (~200 mm) occurs beneath the lake as a result of the elastic deformation with the lake load and the amount of subsidence rapidly decreases with distance from the lake. The subsidence is computed to be around ~9 mm at GPS site BIN1. The vertical displacement is also computed using the GRACE SHC data using Eq. (4). The difference in the GRACE-derived vertical displacement between the pre-dam and post-dam period is shown in Fig. 9b. The subsidence derived from the GRACE SHC data is markedly smaller than the disk model (e.g., ~3 mm vs. ~200 mm around the lake) due to truncation of GRACE SHC data. The load deformation signal spreads (leaks) over a wider area around the lake resulting significantly smaller subsidence at the BIN1 site. Such leakage effect is considerable if the source load is spatially confined.

The displacement computed with the truncated GRACE SHC data is substantially underestimated due to the localized nature of the load (only over 600 km$^2$). The effect of the truncated GRACE data is demonstrated as follows. Two disk loads with the same mass (0.7 Gt) are assumed; one with 150 km radius and 1 cm depth (Disk 1), and the other with 15 km radius and 1 m depth (Disk 2). We compute the vertical displacements of Disk 1 and Disk 2 with different $N_{\text{max}}$ (90 and 40,000) using Eqs. (7 –
The vertical displacements of Disk 1 with different $N_{\text{max}}$ are similar, and the ratio ($\beta$) between the deformations associated with $N_{\text{max}} = 40,000$ and $N_{\text{max}} = 90$ at the disk’s center is 1.2. By contrast, the truncation degree plays a significant role for Disk 2. The vertical displacement at the center of the disk increases with $N_{\text{max}}$, and converges at $N_{\text{max}} \sim 3,000$ (not shown), which agrees with the rule of thumb given in Bevis et al. (2016). The $\beta$ value of Disk 2 is 17.9. It is also seen that the vertical load deformation by Disk 1 and Disk 2 are roughly similar at the GRACE resolution ($N_{\text{max}} \sim 90$). This example demonstrates that the ground displacements computed with GRACE (truncated) SHC data can be significantly underestimated for the case of spatially localized load (like Disk 2), while the GRACE computation of the load deformation is still acceptable for the broad scale load (like Disk 1).

Different choices of disk thickness and earth models have little impact on the estimated land subsidence at BIN1 station. To demonstrate this, we compute the deformation from the disk model constructed using 1) various disk thickness obtained from lake filling model (Sect. 4.3), and 2) uniform thickness obtained from the averaged lake level. The spatial pattern of two different load distributions is very similar (Fig. 11). Only a slight difference is seen near the upstream of the Bakun Lake (Fig. 11a, b). The deformation profile between the BIN1 station (point A) and the Bakun Dam (point B) shows a clear difference near the Bakun Dam, but hardly noticeable beyond 10 km away from the lake (Fig. 11c).

To assess the impact of the Earth’s model, various sets of Load Love Numbers (Bevis et al., 2016; Wang et al., 2012) are applied to the disk load model, and the estimated vertical deformation between the BIN1 station (point A in Fig. 11) and the Bakun Dam (point B in Fig. 11) are shown in Fig. 12. Similar to Fig. 10c, the difference is noticeable near the Bakun Lake, where PREMsoft model produces the greatest subsidence, and PREMhard produces the smallest. The estimated deformations
are converged after ~40 km away from the lake, and the effect of using different Earth’s model is trivial at BIN1 station. Wang et al. (2012) and Wahr et al. (2013), also report similar behavior. [Fig. 12]

The computed vertical displacements from the disk load model and the GRACE SHC data are compared with the GPS measurements at the BIN1 station after the long-term mean is removed (Fig. 13). The total subsidence is measured by two GPS solutions; GRACE, and the disk model, as shown in Table 4. The total change is calculated by multiplying the estimated linear trend between August 2010 and December 2011 (see the displayed slopes in Fig. 13) with the impoundment period (e.g., 17 months). The GPS data present that the BIN1 station indicates subsidence of approximately 10 – 11 mm (or about 7 – 8 mm/year) during the impoundment period. The GPS solutions show a significant agreement, with correlation value ($\rho$) of 0.9 (Fig. 14). The disk model is consistent with the GPS time series (~ 9 mm subsidence with $\rho = 0.77$). Due to SHC truncation, the GRACE-derived vertical displacement shows 6 – 7 times smaller deformation at BIN1, and the $\rho$ value is approximately 13 % lower than the disk model. [Fig. 13] [Table 4] [Fig. 14]

The horizontal displacements computed from the disk load model and the GRACE SHC data are compared with the GPS measurements (Fig. 15). The disk load model predicts the deformation southward by ~2.4 mm and eastward by ~3.3 mm (see Table 4), or 4.1 mm toward the Bakun Lake during the impoundment period (Fig. 16). The motion of the GPS-ULR solution shows a reasonable agreement with the disk load model or 3.8 mm toward the lake. The GPS-UNR solution only agrees with the disk load model (and the GPS-ULR solution) in the north component, while it moves away from the lake in the east-west direction (Fig. 15c). It is unclear why the east component of the GPS time series is less consistent between two solutions. The inconsistent use of reference frame, tropospheric model, and GPS orbit and clock could be responsible for such difference. The GRACE
SHC data fails to capture the elastic deformation by the lake load due to the omission error. Instead, the computed deformation from GRACE SHC data is likely the deformation caused by the seasonal migration of degree-1 load (geocenter motion), as also seen in Han (2016). The GPS horizontal measurements also present the coherent seasonal motions synchronized with the GRACE results.

5. Discussion

The satellite images obtained from Landsat 7 and 8 observe the flooded area expanded up to 600 km² between 2010 and 2011. The increased surface water area and water storage are caused by the artificial reservoir after the construction of the Bakun hydroelectric dam downstream of the Balui River. The increased water mass estimated from the Landsat image and DEM data analysis is approximately 48 Gt. The results obtained from remote sensing data are in line with the estimated lake area (594 – 695 km²) and gross storage capacity (~44 Gt) reported by the Sarawak integrated water resources management master plan (e.g., Sovacool & Bulan, 2011; Shirley & Kammen, 2015). In the same period, GRACE observes the increased mass change northwest (Malaysian part) of the Borneo island by ~200 mm in equivalent water height. This is 2-3 times larger than the seasonal water storage change predicted by the LSMs, which do not include the Bakun lake storage but are constrained principally by soil moisture and groundwater storages. We find the corresponding water level of ~120 m increasing during the impoundment, which is the composite of surface water (70 %) and underground water components (30 %). In total, GRACE observes ~71 Gt of fresh water that has been stored in the Bakun Lake since 2011. This is comparable to nearly twice the annual ice mass loss in Alaska glacier and more than the total annual loss of the western Antarctica ice sheet (Bamber, 2018).

Our developed disk load model of the Bakun Lake constrained by the GRACE and Landsat data predicts land subsidence about 200 mm at the lake and ~9 mm around the nearby coastal area. The
magnitude of the subsidence is around twice the global mean sea level rise trend (Chen et al., 2017). As such, the relative sea level rise near the west coastal Borneo is supposed to be tentatively 2-3 times faster during the impoundment period, and the impoundment effect should be considered in the estimation of the sea level variation in the coastal zones (Nicholls and Cazenave, 2010). Such load displacement estimate is in a good agreement with the actual GPS records at the coastal town Bintulu (BIN1). The reservoir impoundment causes the GPS site to move toward the lake by ~4 mm, observed from the disk load model and GPS-ULR solution. The magnitude of the horizontal displacement is approximately two to three times smaller than the vertical component, which is in line with the finding of Wahr et al. (2013). We emphasize here that the subsidence estimate of the Bakun Lake is the result of the elastic response. Subsidence process could link to an inelastic response of Earth material, e.g., a variation of aquifer system (Amelung et al. 1999; Erban et al., 2014), and our approach is unlikely suitable for such an application.

This study presents a framework for merging the strength of multiple remote sensing data and numerical modeling sources. The advantage and limitation of different data learned from this study are summarized in Table 5. GRACE possesses a clear strength of observing the total mass variation that cannot be captured by other observations. However, the direct use of GRACE data cannot provide a complete gravity signal due to the truncation of SHC. The effect is severe for a load associated with short wavelength, which can cause systematic misfits with the validated data (e.g., Fig. 11, see also Fu et al., 2013). A numerical model can be developed to utilize the strength of GRACE and Landsat data in an iterative manner and is used to recover the full spectral band of the gravity signal. As a result, GRACE is capable of detecting a variability of localized mass distribution over the area as small as 600 km$^2$. The size of this area is considered the smallest for which GRACE has been utilized for hydrological application, e.g., ~10 times smaller than Lake Nasser (Longuevergne et al., 2013), and Lake Urmia (Tourian et al., 2015). However, the mass variability of the Bakun Lake is as large as (or larger) than Lake Nasser and Lake Urmia, which explains the sensitivity of GRACE over the Bakun Lake. The size of mass variation (Gt) plays a major role in GRACE application, which is also
described in e.g., Longuevergne et al. (2013), Tourian et al. (2015), Yi et al. (2017), Castellazzi et al. (2018), Mu et al. (2019).

6. Conclusion

We developed and demonstrated a technique to quantify the total water storage change and land subsidence caused by the impoundment of the Bakun Lake. The lake area variability is derived from the high-resolution Landsat imagery data. The effective lake water level is determined using GRACE data through a developed forward model. The land subsidence is then estimated by incorporating Landsat and GRACE strengths into the developed disk load model, and the results are consistent with the GPS measurement.

Recovering the local water storage is difficult using the GRACE data alone. This study demonstrates how the low-resolution GRACE-derived ΔTWS data can be successfully used to determine and model the surface water load over an area considerably less than the GRACE’s intrinsic resolution, in conjunction with high-resolution Landsat image data. Our approach provides the opportunity to extract the local hydrological or geophysical signals that are still hidden in the GRACE observation, allowing the utilization of the GRACE data in broader applications. The impoundment of the Bakun Dam can be used as a large-scale natural experiment to test the current understanding of the water cycle under anthropogenic pressure, ability to capture mass changes with geodetic tools and propose how models could be improved.

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Appendix A: Estimation of annual amplitude and phase of time series

The time series is represented by

\[ L = f_0 + f_1 t + f_2 \sin(\omega t) + f_3 \cos(\omega t) + f_4 \sin(2\omega t) + f_5 \cos(2\omega t) \quad , \]

(A1)

where \( L \) is the vector containing observations, \( t \) is the observation time, and \( \omega = 2\pi/T \) with \( T \) the
annual period. The coefficients \( f_0, ..., f_5 \) are estimated using least-squares adjustment. The annual
amplitude \((A)\) is estimated as

\[ A = \sqrt{f_2^2 + f_3^2} \quad , \]

(A2)

and the phase \((\varphi)\) is estimated as

\[ \varphi = \arctan_2(f_2, f_3) . \]

(A3)

The \( \arctan_2 \) returns a value in the range \((-\pi, \pi]\), which can be represented using 12 calendar months
(from Jan to Dec).

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Fig. 1. (a) The overall geographical location of the study area and the location of the GPS station BIN1. The white rectangle identifies the location of Bakun Dam and Bakun Lake. The background presents the elevation. (b) Zoom-in locations of the Bakun Dam and Bakun Lake. (c) The Landsat’s natural color image of the Bakun Lake on August 12, 2010 (prior to filling). (d) The Landsat image of the Bakun Lake on August 4, 2013 (after the dam is online).

Fig. 2. Data processing diagram of this study. The section number (Sect) indicates the location where the explanation can be found.

Fig. 3. The yearly average NDWI (a – j) and the yearly estimated area (k) of the Bakun Lake derived from Landsat data between 2007 and 2016.

Fig. 4. (a) The Bakun Lake’s water pixel estimated based on the Landsat-derived NDWI between 2012 and 2016 (post-dam period). (b – d) The simulated flood extension using a different averaged water level, approximately 46 m, 60 m, and 73 m, respectively.

Fig. 5. The critical success index (CSI) associated with the different DEMs and averaged water level.

Fig. 6. The mean value (solid) and the standard deviation (envelop) of GRACE-derived monthly ΔTWS (in millimeter, left axis) over the Bakun Lake between August 2002 and March 2016. The time series associated with the right axis is the approximated Lake level (in meters) derived from the TWS forward model. The vertical dotted lines between August 2010 and December 2011 denote the impounding period.

Fig. 7. (a) The ΔTWS difference between the post- and pre-dam period. Warm colors indicate increased water. (b) Normalized empirical covariance function derived from GRACE solutions (CSR, JPL, GFZ, GRGS, and average) between 2003 and 2016. (c) The increased ΔTWS simulated from the TWS forward model. (d) The variance ratio associated with the different simulated water level.

Fig. 8. (a) The simulated ΔTWS over the Bakun Lake from four different LSM products (CABLE, GLDAS, NCEP, ECMWF) between August 2002 and March 2016 (see legends in (b)). The vertical
dotted lines between August 2010 and December 2011 denote the impounding period. (b) The model-associated yearly precipitation over the Bakun Lake. (c–f) The LSMS-simulated ΔTWS difference between the post- and pre-dam period. (g–j) The model-associated precipitation difference between the post- and pre-dam period.

Fig. 9. (a) The vertical displacement computed using the disk load model. The placement (location) of the disk loads is shown in the insert figure (zoom in of the white-dash boundary). (b) The vertical displacement computed using the GRACE SHC data. Note that (a) and (b) use different color scales.

Fig. 10. The vertical displacement induced by the placement of two different disk loads with the same mass (0.7 Gton) but different shape, Disk 1 (radius = 150 km, thickness = 1 cm, black), and Disk 2 (radius = 15 km, thickness = 1 m, blue) on the Earth’s surface. For a visualization purpose, the symbols of Disk 1 and Disk 2 are not scaled. The vertical displacement is computed to different maximum harmonic degrees ($N_{\text{max}} = 90$ (dash), and 40,000 (solid)). The insert figure is the zoom-in of the result around the disk’s center.

Fig. 11. The vertical displacement computed using the disk load model associated with (a) various disk thickness derived from lake filling model, and (b) uniform (average) disk thickness. The location of BIN1 station and the Bakun Dam is displayed as points A (green) and B (red). (c) The cross-section profile of vertical displacement between points A and B obtained from (a) and (b).

Fig. 12. The cross-section of vertical displacement between points A and B (Fig. 9), derived from different sets of Load Love Numbers. The insert figure is the zoom-in of the dashed rectangle.

Fig. 13. The vertical displacement at BIN1 station computed using (a) the disk load model, GRACE SHC data, and (b) GPS observations (UNR, ULR). The vertical dotted lines between August 2010 and December 2011 denote the impounding period. The thick solid lines are the estimated trend during the impoundment, and the dashed lines are the trend during pre- and post-dam period. The envelop represents the error of the displacement estimate.
Fig. 14. Scatter plots of the vertical deformation between (a) GPS-UNR and GPS-ULR, (b) GPS-UNR and GRACE SHC, and (c) GPS-UNR and disk load model. The correlation coefficient (ρ) associated to each scatter plot is also given.

Fig. 15. The horizontal displacement ((a, c) East, (b, d) North) at BIN1 station computed using the disk load model, GRACE SHC data, and GPS observations (UNR, ULR). The vertical dotted lines between August 2010 and December 2011 denotes the impounding period. The thick solid lines are the estimated (fitted) trend during the impoundment, and the envelop represents the error of the displacement estimate.

Fig. 16. The horizontal displacement ((a) East, (b) North) at BIN1 station computed using the disk load model, GRACE SHC data, and GPS observations (UNR, ULR). The vertical dotted lines between August 2010 and December 2011 denotes the impounding period. The thick solid lines are the estimated (fitted) trend during the impounding period.
| Loading sources       | Regions                  | Datasets          | Findings                                                                                     | References                  |
|----------------------|--------------------------|-------------------|----------------------------------------------------------------------------------------------|-----------------------------|
| Seasonal snow        | Japan                    | GPS               | Heavy snow build up contributes to annual surface displacement.                              | Heki (2001)                 |
| Monsoonal flooding   | Bangladesh               | GRACE, GPS        | Flood water of 100-150 Gt influences a vertical deformation up to 6 cm.                     | Steckler et al. (2010)      |
| Mountain snow and ice| Nepal Himalaya           | GRACE, GPS        | Detection of surface uplift causes by melting ice and snow.                                  | Fu and Freymueller (2012)   |
| Rainfall             | Amazon, Southeast Asia   | GRACE, GPS        | Heavy precipitation induces oscillation in the GPS horizontal components.                    | Bettinelli et al. (2008); Fu et al. (2013) |
|                      | India                    | GRACE, GPS, absolute gravity data | Hydrological effects are the major cause of periodic surface deformation.                  | Tiwari et al. (2014)        |
| Groundwater depletion| Central Mexico           | SAR, InSAR        |                                                                                              | Castellazzi et al. (2016)   |
|                      | North China Plain        | GRACE, GPS        |                                                                                              | Wang et al. (2017)          |
|                      | Iran                     | InSAR, Landsat    | Groundwater overexploitation causes significant land subsidence over the regions.          | Motagh et al. (2008)        |
|                      | Saudi Arabia             | GRACE, SAR, Landsat, GPS |                                                                                              | Othman et al. (2017)        |
|                      | California, Taiwan, North China | GRACE, altimetry, GPS |                                                                                              | Hwang et al. (2016)         |
| Reservoir impoundment| Malaysia                 | GRACE, Landsat, GPS | Impoundment period of the reservoir induces a large extent land subsidence.                 | This study                  |
Table 2  Trend, annual amplitude, and phase (calendar month) estimate computed from the GRACE-derived ΔTWS and four different LSM-simulated ΔTWS in the pre- and post-dam periods.

|          | Pre-dam       | Post-dam      |
|----------|---------------|---------------|
|          | trend (mm/year) | amplitude (mm) | phase (month) | trend (mm/year) | amplitude (mm) | phase (month) |
| GRACE    | 2.9 ± 1.0     | 16.1 ± 6.4    | Dec           | 2.3 ± 4.2       | 38.2 ± 14.7    | Feb           |
| CABLE    | 3.2 ± 0.8     | 34.5 ± 5.4    | Feb           | -8.2 ± 2.0      | 48.4 ± 6.9     | Jan           |
| GLDAS    | 3.9 ± 0.4     | 19.7 ± 2.5    | Jan           | -9.1 ± 1.5      | 34.4 ± 5.3     | Feb           |
| NCEP     | 16.0 ± 0.8    | 19.9 ± 5.6    | Feb           | -2.5 ± 1.2      | 11.5 ± 4.1     | Jan           |
| ECMWF    | 15.4 ± 1.0    | 42.1 ± 6.8    | Feb           | -1.5 ± 1.4      | 35.0 ± 5.0     | Jan           |

Table 3  The cross-correlation values (with 0.05 significant level) between GRACE and four different LSMs. The seasonal variation is removed (based on Least-squares fit, see Appendix A) before computing the correlation.

|          | GRACE | CABLE | GLDAS | NCEP | ECMWF |
|----------|-------|-------|-------|------|-------|
| GRACE    | 1.00  |       |       |      |       |
| CABLE    | -0.29 | 1.00  |       |      |       |
| GLDAS    | -0.21 | 0.73  | 1.00  |      |       |
| NCEP     | 0.20  | 0.22  | 0.29  | 1.00 |       |
| ECMWF    | 0.18  | 0.23  | 0.32  | 0.84 | 1.00  |
Table 4 Total change of the 3D displacement (mm) between August 2010 and December 2011 estimated using the disk load model, GRACE SHC data, and GPS observations (UNR, ULR).

|          | Up         | North      | East       |
|----------|------------|------------|------------|
| Disk load model | -8.77 ± 0.08 | -2.35 ± 0.02 | 3.32 ± 0.03 |
| GRACE    | -1.76 ± 0.06 | 0.04 ± 0.02 | 0.48 ± 0.02 |
| UNR      | -9.52 ± 0.23 | -3.28 ± 0.11 | -1.72 ± 0.13 |
| ULR      | -10.52 ± 0.26 | -1.60 ± 0.12 | 2.47 ± 0.14 |
Table 5 Strength and limitation of different remote sensing data and numerical models found from this study

| Observation, model | Strength                                                                 | Limitation                                                                                   |
|--------------------|---------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|
| GRACE              | Provide total water storage, including surface and underground water components. Concentrate mass over a small area is recoverable. | Spatial and temporal limited to a few hundred km and one month. Only provide the integrated water column, and cannot be disaggregated. |
| Landsat            | Capture high spatial resolution surface reflectance, which can be effectively used to delineate the surface water area. | Only provide surface water component. Limited number of “cloud free” scenes.                  |
| GPS                | Frequently observe the surface deformation at the local scale.            | Like GRACE, GPS senses an integrated deformation. Intensive care of data gaps, outliers, and noises are required. |
| LSM                | Simulate the individual hydrological component separately at any spatial and temporal scale. | The uncertainty is generally high due to the imperfect representation of model physics (e.g., lack of manmade reservoir component). |
| **Forward model**  | Simulate possible hydrological and geophysical signals based on the empirical relationship between the designed model and observation. The method is easy to implement. | Similar to LSM, the accuracy highly depends on the knowledge used to construct the model and the quality of the observation. |
| **Disk load model**| Utilize the strength of GRACE and Landsat data to estimate the local land deformation. |                                                                                               |
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Fig. 2. Data processing diagram of this study. The section number (Sect) indicates the location where the explanation can be found.
Fig. 3. The yearly average NDWI (a–j) and the yearly estimated area (k) of the Bakun Lake derived from Landsat data between 2007 and 2016.
Fig. 4. (a) The Bakun Lake’s water pixel estimated based on the Landsat-derived NDWI between 2012 and 2016 (post-dam period). (b – d) The simulated flood extension using a different averaged water level, approximately 46 m, 60 m, and 73 m, respectively.
Fig. 5. The critical success index (CSI) associated with the different DEMs and averaged water level.
Fig. 6. The mean value (solid) and the standard deviation (envelop) of GRACE-derived monthly $\Delta$TWS (in millimeter, left axis) over the Bakun Lake between August 2002 and March 2016. The time series associated with the right axis is the approximated Lake level (in meters) derived from the TWS forward model. The vertical dotted lines between August 2010 and December 2011 denote the impounding period.
Fig. 7. (a) The ΔTWS difference between the post- and pre-dam period. Warm colors indicate increased water. (b) Normalized empirical covariance function derived from GRACE solutions (CSR, JPL, GFZ, GRGS, and average) between 2003 and 2016. (c) The increased ΔTWS simulated from the TWS forward model. (d) The variance ratio associated with the different simulated water level.
Fig. 8. (a) The simulated ΔTWS over the Bakun Lake from four different LSM products (CABLE, GLDAS, NCEP, ECMWF) between August 2002 and March 2016 (see legends in (b)). The vertical dotted lines between August 2010 and December 2011 denote the impounding period. (b) The model-associated yearly precipitation over the Bakun Lake. (c – f) The LSMs-simulated ΔTWS difference between the post- and pre-dam period. (g – j) The model-associated precipitation difference between the post- and pre-dam period.
Fig. 9. (a) The vertical displacement computed using the disk load model. The placement (location) of the disk loads is shown in the insert figure (zoom in of the white-dash boundary). (b) The vertical displacement computed using the GRACE SHC data. Note that (a) and (b) use different color scales.
Fig. 10. The vertical displacement induced by the placement of two different disk loads with the same mass (0.7 Gton) but different shape, Disk 1 (radius = 150 km, thickness = 1 cm, black), and Disk 2 (radius = 15 km, thickness = 1 m, blue) on the Earth’s surface. For a visualization purpose, the symbols of Disk 1 and Disk 2 are not scaled. The vertical displacement is computed to different maximum harmonic degrees ($N_{\text{max}} = 90$ (dash), and 40,000 (solid)). The insert figure is the zoom-in of the result around the disk’s center.
Fig. 11. The vertical displacement computed using the disk load model associated with (a) various disk thickness derived from lake filling model, and (b) uniform (average) disk thickness. The location of BIN1 station and the Bakun Dam is displayed as points A (green) and B (red). (c) The cross-section profile of vertical displacement between points A and B obtained from (a) and (b).
Fig. 12. The cross-section of vertical displacement between points A and B (Fig. 9), derived from different sets of Load Love Numbers. The insert figure is the zoom-in of the dashed rectangle.
Fig. 13. The vertical displacement at BIN1 station computed using (a) the disk load model, GRACE SHC data, and (b) GPS observations (UNR, ULR). The vertical dotted lines between August 2010 and December 2011 denote the impounding period. The thick solid lines are the estimated trend during the impoundment, and the dashed lines are the trend during pre- and post-dam period. The envelop represents the error of the displacement estimate.
**Fig. 14.** Scatter plots of the vertical deformation between (a) GPS-UNR and GPS-ULR, (b) GPS-UNR and GRACE SHC, and (c) GPS-UNR and disk load model. The correlation coefficient ($\rho$) associated to each scatter plot is also given.
Fig. 15. The horizontal displacement ((a, c) East, (b, d) North) at BIN1 station computed using the disk load model, GRACE SHC data, and GPS observations (UNR, ULR). The vertical dotted lines between August 2010 and December 2011 denotes the impounding period. The thick solid lines are the estimated (fitted) trend during the impoundment, and the envelop represents the error of the displacement estimate.
Fig. 16. The horizontal displacement ((a) East, (b) North) at BIN1 station computed using the disk load model, GRACE SHC data, and GPS observations (UNR, ULR). The vertical dotted lines between August 2010 and December 2011 denotes the impounding period. The thick solid lines are the estimated (fitted) trend during the impounding period.