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Surface gravity and deformation effects of water storage changes in China's Three Gorges Reservoir constrained by modeled results and in situ measurements

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ABSTRACT

The water impoundment of China's Three Gorges Reservoir (TGR), with the largest dam in the world, makes a large mass concentrated and thus influences the surface gravity field and crustal deformation field. In the TGR area, water impoundment began in 2003, and the Earth is responding to the ongoing changes of water storage. These responses can be investigated using the gravimeter and the GPS. In this paper, using a water load model derived from Digital Elevation Model (DEM) data and elastic loading Green's function, we modeled the surface gravity and displacement changes in the front area of TGR caused by water storage variations. Predictive results are compared with the measurements derived from absolute gravity by A10, continuous gravity by gPhone and GPS time series at the sites of front area in TGR. The observations agree well with the prediction spatially and temporally. The quantitative comparison and analysis indicate that the ground gravity and the vertical displacement are more sensitive to water storage changes than the horizontal displacement. The predictions from the water load model are consistent with the in situ measurements reported in this work and therefore can be utilized for water effect corrections for exacting the further signals related to lithospheric dynamics and geological hazards, such as abnormal deformation of active faults and landslides.

1. Introduction

The construction of artificial reservoirs behind dams impacts on global geodynamics because of reservoir water impoundment, which leads to variations of Earth's rotation, gravitational field and sea level (Chao et al., 2008; Fiedler and Conrad, 2010). This kind of water redistribution makes a large amount of mass concentrated. The resulted surface loading effects spread through a wide region, even the globe. China's Three Gorges Reservoir (TGR) is one of the largest hydropower generation reservoirs in the world. The Three Gorges Dam (TGD) is located in Sandouping, Yichang, Hubei Province (Fig. 1a), and has an elevation of 185 m above sea level. The reservoir holds 40 km^3 of water in 2009, which submerges a stretch of the Yangtze River channel approximately 600 km in length and 1–2 km in width (Wang et al., 2013). The water impoundment process has been implemented in phases starting in 2003 (Fig. 1b). The water level first rose from ~70 m to 135 m in June 2003 and then reached 156 m on October 27th, 2006. It should be noted that the obvious amplitude differences of seasonal excursions between the 2003–2006 stages and the 2007–2008 stages are due to the water impoundment of TGR in second stage (Fig. 1b). Through six consecutive years of experimental impoundment, the water level in the TGR reached 172.3 m for its first experimental maximum impoundment on November 4th, 2008, 171.4 m on November 24th, 2009, and 174.91 m on October 25th, 2010 (Wang et al., 2011). On October 30th, 2011, the water level reached 175 m, the highest water level projected by the engineering design. Controlling TGR's water level during yearly period is to serve various purposes. The reservoir's water level is retained at ~175 m to gain the best benefit of power generation during winter months (from November to February) and then gradually declines to 150–170 m to keep adequate water-allotment for downstream irrigation in the spring (from March to May) and remains at ~145 m to prepare for the flood control during most of the monsoon season (from June to August). Impoundment initiates again at the end of the flooding season in September each year (Wang et al., 2011, 2013).

Since the construction of TGR, scientists have been attempting to examine the effect of the reservoir impoundment and evaluate the resulted environment evolution giving rise to the occurrence of geological hazards. Previous studies have focused on the surface dynamical responses in the front area of TGR and earthquakes or landslides in

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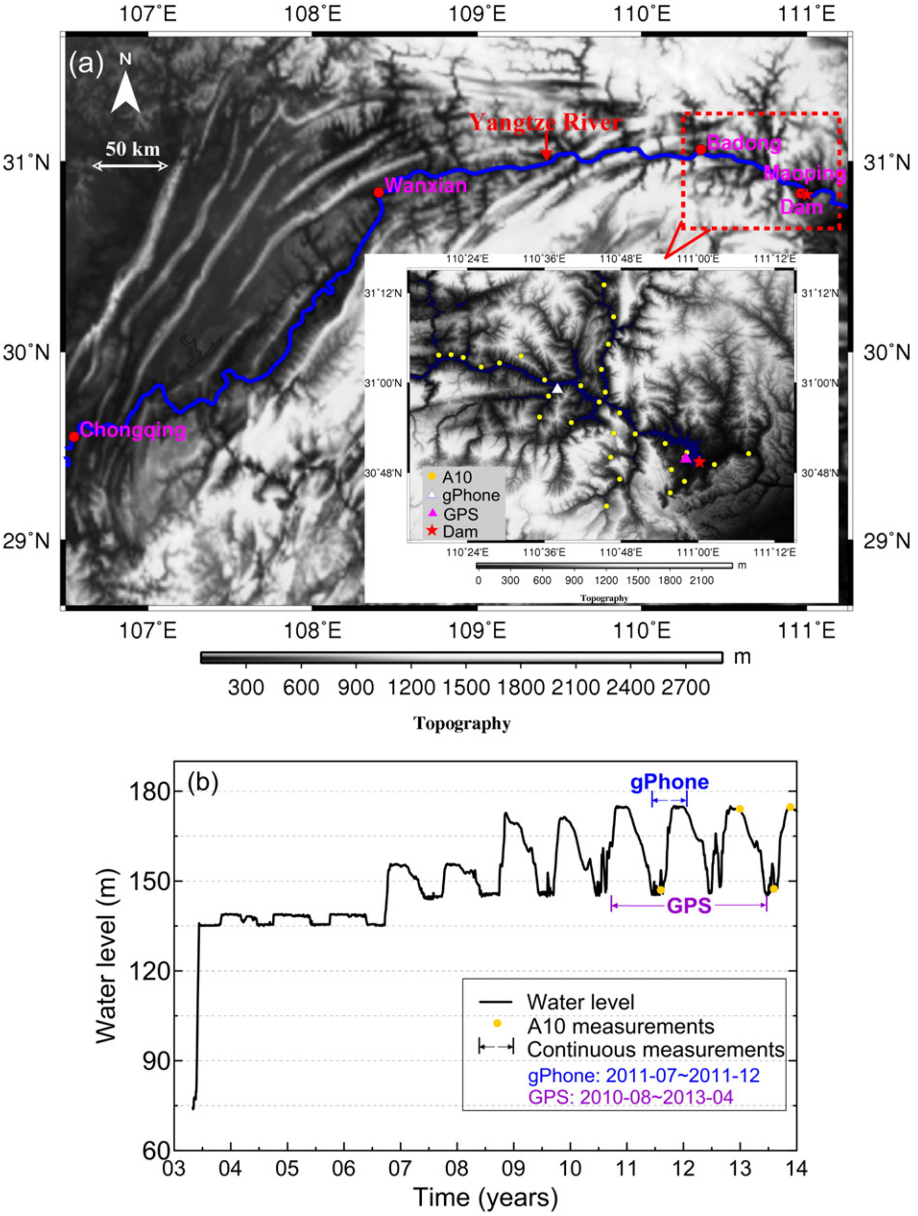

Fig. 1. Topography of the study area and water level of China's Three Gorges Reservoir (TGR). At the maximum level (i.e., 175 m), the impounded water stretches approximately 600 km along the Yangtze River from the TGD to Chongqing and covers approximately 976 km^2 (Wang et al., 2011) on the basis of the NASA Shuttle Radar Topography Mission (SRTM) global elevation data (90 m spatial resolution). The locations and observing time period of in situ measurements are shown in (a) and (b), respectively.

the weak portions of the structures in the same area during the filling period (e.g., Huang et al., 2013; Li and Han, 1987; Wang, 2000; Wang et al., 2002; Yao et al., 2013; Zeng and Gao, 1987). The impoundment of the TGR in China can be considered to be as a 'controlled experiment' that offers a unique opportunity for geophysical and geodetic studies (Boy and Chao, 2002). The gravity field near the TGR changes primarily because of the variations in the reservoir's water level. Those variations also give rise to the surface displacements, level plane changes, fluctuations of groundwater and possibly secondary geological hazards. Therefore, the numerical simulation results, for the gravity and deformation based on a classical forward modeling, can help us to understand the lithospheric loading response from observed data. Wang (2000) simulated the surface vertical displacements and level plane changes caused by filling the TGR, and Wang et al. (2002) first applied Green's function to predict the horizontal surface displacement, tilt changes and gravity field when the impounded water level reach 175 m via the PREM elastic Earth model. Boy and Chao (2002) used Green's function to predict the possible time-variable satellite gravity field changes caused by the impoundment at larger spatial scales.

Comparing with the earlier studies (Zeng and Gao, 1987), recent simulation results have significantly improved. Yet, there are still two issues which are worth to be discussed further. First, the previous studies used water load models that are too simple to meet the present needs for precise theoretical simulation, e.g., the US Geographical Survey (USGS) global Digital Elevation Model (DEM) GTOPO30 that has been available for the modeling of water load distribution since 1996 (Boy and Chao, 2002). Those coarse spatial resolution of 30 arc-seconds or approximately 900 m make the data not applicable because the width of most of the (original) river channel in the TGR is much less than 900 m (Wang et al., 2005). In contrast, the topography in the front area of TGR (a resolution of 50 m × 50 m) is used in the studies by Wang (2000) and Wang et al. (2002), but they did not consider the water load distributions from the Yangtze River branches, which are proved to be also important to the dynamic response of the TGR region. Second,