How much water is seeping off the Three Gorges Reservoir?

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Satellite gravity observations, hydrologic modeling, elevation data, and in situ measurements help to clarify uncertainties in water volume changes for a major water-control scheme.

The Three Gorges Reservoir (TGR) and dam in central China constitutes one of the largest hydropower-generation projects in the world. The reservoir stretches upstream to Chongqing and has an official length of 660 km, a surface area of 1040 km$^2$, and a static storage capacity (water volume) of 39.3 km$^3$ at its highest constraining water level of 175 m above sea level, which is ~110 m above its downstream water level (see Figure 1). The water impoundment (i.e., filling) and operation of the TGR serve as controlled experiments amenable to a range of ecological and other studies.

Water impoundment in the TGR initially occurred in three main stages. The water level first rose from ~70 m to 135 m in June 2003, then reached 156 m on 27 October 2006, and finally increased to 172.3 m on 4 November 2008 and 174.9 m on 25 October 2010 (see Figure 2). Since then, the water level in the reservoir has followed an annual cycle, peaking at 175 m for power generation and navigation during winter months (from November to February), then gradually declining to 150–170 m for downstream irrigation and navigation in spring (March–May), and finally reaching its lowest constraining level of ~145 m for flood control during most of the monsoon season (June, July, and August). Impoundment starts again at the end of the flooding season in September each year.

One question we are investigating is how much water is seeping into the neighboring areas of the TGR and recharging groundwater during impoundment. Deliberate recharging of groundwater is a widely used method of preserving a supply of drinking water. However, over-recharging due to seepage carries the risk of problems such as diminished levee security, landslides, land subsidence, and earthquakes. Field well (in situ) monitoring provides reliable data about changes in groundwater levels, but only at a limited number of sites. Consequently, the overall picture of total water storage changes in the TGR area is incomplete. Currently, the best way to estimate changes in the total water mass, and thus groundwater changes, is through data from the Gravity Recovery and Climate Experiment (GRACE), a dedicated dual-satellite mission launched in March 2002 as a joint partnership between NASA and the German Space Agency. GRACE delivers monthly observations of the total mass changes across the earth at ~400 km resolution.

According to basic principles of hydrology and water balance, changes in total mass/water storage ($\Delta TWS$) in the TGR area could be expected to be caused mainly by water impoundment ($\Delta TGR$), groundwater storage change due to TGR seepage ($\Delta GW$), and natural variations in soil moisture ($\Delta SM$). That is, $\Delta TWS = \Delta TGR + \Delta GW + \Delta SM$. In an initial study, we obtained changes in total mass/water storage ($\Delta TWS$) in the TGR area from GRACE observations. We also simulated $\Delta SM$ using the WaterGAP Global Hydrology Model (WGHM). If negligible water was being lost by seepage into groundwater ($\Delta GW = 0$), the residual (i.e., difference) between the GRACE estimate and the WGHM simulation would be equal to the water impounded in the reservoir: $\Delta TGR = \Delta TWS - \Delta SM$. Our results showed that before 2008, GRACE-WGHM estimates ($\Delta TWS - \Delta SM$) agreed
Figure 2. Time evolution of the impoundment of the TGR according to official reports of water elevation and volume.

Figure 3. Water volume changes obtained from TGR in situ observations and from Gravity Recovery and Climate Experiment (GRACE) and WaterGAP Global Hydrology Model (WGHM) estimates. The volume change values in the inset table represent the difference of mean volumes computed for two consecutive periods from both sources. The averaging periods of June 2002–May 2003, June 2003–May 2006, June 2006–May 2008, and June 2008–May 2010 represent the pre-filling, first, second, and third stages of TGR impoundment, respectively. Ano: Anomalies. (Adapted from Wang et al.,2 Figure 4B.)

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with TGR in situ water volume measurements during the first
two impoundment phases, but were much greater (11.51 vs.
6.47 km$^3$) following the third impoundment phase after 2008 (see
Figure 3). This substantial increase might indicate a large qua-
tity of water lost ($\Delta GW \gg 0$) from the TGR in the recharge of the
underlying aquifer, especially when water levels increased from
156 to 175 m in October of that year.\textsuperscript{2}

The total impounded water volume of the TGR consists of
static volume and wedge storage (created during a flood wave
when inflow exceeds outflow). Our most recent study\textsuperscript{1}
showed that in situ stored water volumes were reported by the China
Three Gorges Corporation,\textsuperscript{4} which operates the TGR, as near
static. In other words, the measurements only took into account
the water level at the dam and neglected the actual water sur-
face profile along the reservoir’s 660 km length. For example,
on 24 July 2012 the water level at the dam was 156 m, yet the
volume was reported as 24.0 km$^3$. That is equivalent to assum-
ing a flat surface along the reservoir at 156 m. This assumption
holds up during times of steady flow, but it underestimates real
volume during the flooding season. In fact, on 24 July 2012 the
water level in Chongqing at the upstream tip of the reservoir was
187 m, forming a wedge of storage of $\sim$5 km$^3$ within the reser-
voir. Such an omission could cancel out about 5% of the water
mass difference between the GRACE-WGHM estimates and the
TGR-reported volume changes. Nonetheless, the groundwater
increase due to TGR impoundment is still significant.

In summary, the combination of GRACE observations, global
hydrological modeling, and in situ observations taken together
provide an indirect estimate of groundwater storage increase
due to reservoir seepage and associated groundwater recharge
increase in the TGR area. After correcting for wedge storage
(particularly large during peak flooding), the groundwater in-
crease due to the TGR impoundment is still substantial. The find-
ing of an error in reporting the total water volume in the TGR
reduces the uncertainty of groundwater recharge estimates. As
a next step, we plan to employ a range of data, such as well-
monitoring data, Landsat images, and other information per-
taining to the neighboring lake and reservoir to quantify the total
water mass changes beyond the TGR. So doing will enable us to
refine the estimate of total seepage and groundwater recharge
resulting from operation of the reservoir.

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