Missing water from the Qianqtang Basin on the Tibetan Plateau

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ABSTRACT

The Qiangtang Basin is a large endorheic basin in the inner part of the Tibetan Plateau and has been thought to be a dry region in contrast with its wet surrounding outer region that feeds all the major Asian rivers. Combining surface hydrological data with modelling and satellite data between 2002 and 2016, our study reveals that an enormous amount of water, approximately 54 ± 4 km^3, is unaccounted for annually in the Qiangtang Basin. The amount of missing water is comparable to the total annual discharge of the Yellow River. Data from the Gravity Recovery and Climate Experiment (GRACE) show little increase of local terrestrial water storage. Thus, the missing water must have flowed out of the basin through underground passages. Interpreting this result in the context of recent seismic and geological studies of Tibet, we suggest that a significant amount of meteoric water in the Qiangtang Basin leaks out by way of groundwater flow through deep normal faults and tensional fractures along the nearly *N-S* rift valleys that are oriented sub-normal to and cross the surficial hydrological divide on the southern margin of the basin. Cross-basin groundwater outflow of such a magnitude defies the traditional view of basin-scale water cycle and leads to a very different picture from the previous hydrological view of the Qiangtang Basin. The finding calls for major rethinking of the regional water balance.

1. INTRODUCTION

The Tibetan Plateau is considered to be our planet's 'third pole' and the water tower of Asia (Immerzeel et al., 2010). It is fed by water vapour from the Indian monsoon, and composed of outer and inner regimes with distinct hydrological characteristics (Yao et al., 2013; Zhang et al., 2017; Gao et al., 2019). All major rivers on the Asian continent, including the Indus, Ganges, Yarlung-Zangbo, Irrawaddy, Salween, Mekong, Yangtze and Yellow rivers, originate from the water-rich outer region (~1.24×10^6 km^2; Fig. 1A), with a total discharge over 518 km^3 yr^{-1} supplying freshwater for more than 1.4 billion people (Immerzeel et al., 2010; Immerzeel and Bierkens, 2012). In contrast, the inner, endorheic Qiangtang Basin (~7.08×10^5 km^2) has no outflow or inflow rivers and features only short-course ephemeral rivers (Zhang et al., 2017; Ding et al., 2018; Wang et al., 2018). This has led to the view that the Qiangtang Basin is a dry region despite the presence of widely spread glaciers, snowy mountains and freshwater lakes inside the basin, and being surrounded by a very wet outer ring (Immerzeel et al., 2013; Lutz et al., 2014; Fig. 1A). Here we present a new water balance study of the Qiangtang Basin, which leads to a very different picture of view about the water cycle in Tibet and its surrounding areas.

The basic principle of water balance in a hydrologic unit may be illustrated by the conceptual diagram in Figure 1B. The net groundwater flow (G) is typically assumed small and often neglected. Thus, the classical water balance equation (Davie, 2018) for a hydrologic unit is given by

$$P - E - R = \Delta S \qquad (1)$$

where P, E and R are the total amounts of precipitation, evapotranspiration and net stream discharge over a period of time, respectively; and ΔS is the change in the terrestrial water storage. Given that the landlocked Qiangtang Basin has no river flowing in or out, $R = 0$;

furthermore, as shown below, the long-term water storage of the basin has little change, i.e. ΔS = 0, and hence one would expect $P = E$ within the Qiangtang Basin.

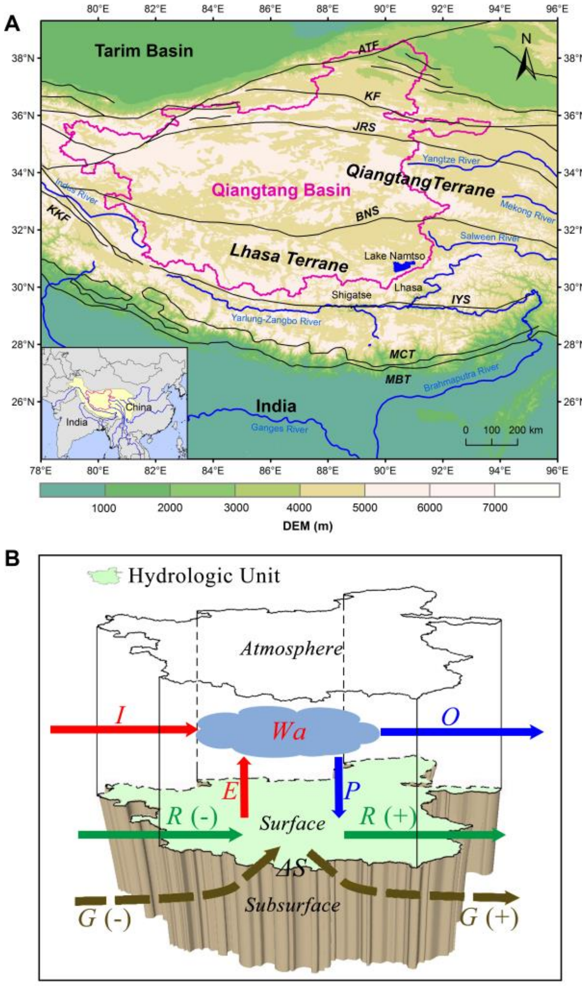

Figure 1. (**A**) **Topographic map showing the geographic locations of Tibet, the Qiangtang Basin, the major rivers originating from the outer rim of the basin, and the sutures that bound the major tectonic blocks in Tibet.** KF, the Kunlun fault; JRS, the Jinsha River Suture; BNS, the Bangong-Nujiang Suture; IYS, the Indus-Yarlung Suture; STD, the South Tibet Detachment System; MCT, the Main Central Thrust; and MBT, the Main Boundary Thrust. Notice that the Qiangtang Basin, defined by its water divide (maroon), overlies several tectonic blocks, while the Qiangtang Terrane, bounded by the BNS and JRS sutures, is much smaller in size. (**B**) **Conceptual diagram of atmospheric and terrestrial water balance in the Qiangtang Basin.** The atmospheric elements in the water balance include water vapour content in atmosphere (W_a), precipitation (P), evapotranspiration (E), and water vapour fluxes into (I) and out of (O) the atmosphere above the basin. The terrestrial components in the water balance include the change in water storage (ΔS), the total amount of river discharge (R = 0 for Qiangtang, an endorheic basin) and net groundwater flow (G); G is typically assumed small and often neglected, but here found to be an important component in Qiangtang's water balance.

2. METHODS

At elevations above 5000 m (Fig. 1A), the Qiangtang Basin is inaccessible and mostly ungauged. There is limited surface data on precipitation, evapotranspiration, surface water, soil moisture or groundwater. Thus, our study makes use of optimal modelling and satellite data from Global Land Data Assimilation System (GLDAS; Rodell et al., 2004), European Centre for Medium-Range Weather Forecasts Interim Reanalysis (ERA-Interim; Dee et al., 2011), Japanese 55-year Reanalysis (JRA-55; Kabayashi et al., 2015) and GRACE satellites

(Tapley et al., 2004), in combination with available surface hydrological data (refer to dataset S1 in the Supplementary Material).

We first employed the latest GLDAS to compute precipitation (P) and evapotranspiration (E) for the Qiangtang Basin on grids of 0.25°×0.25°. To assess and validate the accuracy of precipitation estimated by GLDAS, we used five sets of TRMM-based mainstream multisatellite precipitation products for comparison with GLDAS results at a monthly time scale (see the Supplementary Material and Fig. S1). The estimated P values are verified by the ground-measured data from nine rainfall gauges distributed around Namtso Lake in the southeast part of the basin (Zhou et al., 2013).

It is difficult to directly validate the actual evapotranspiration (E) in the water balance equation, due to lack of measuring data over the poorly gauged plateau basin. Thus, we adopted an alternative approach to further validate the GLDAS results based on comparison between the net atmosphere-land exchange (given by $P – E$) and the net water vapour flux to the atmosphere. In theory, the net water vapour flux ($I – O$) to the atmosphere above a hydrological unit (Fig. 1B) equals the net atmosphere-land exchange given by $P – E$ under the quasi-steady state condition over the monthly or yearly time scale (see the Supplementary Material for a detailed explanation), i.e.,

$$I - O = P - E \tag{2}$$

where I and O are the vapour fluxes into and out of the atmospheric control volume (Fig. 1B), respectively.

3. RESULTS AND DISCUSSION

The estimate of yearly terrestrial water storage change (ΔS) in the Qiangtang Basin based on three GRACE datasets (refer to the Supplementary Material) from May 2002 to December 2016 shows little long-term accumulation of water storage in Qiangtang (Fig. 2A), consistent with the finding of a recent study (Wang et al., 2018). However, the results from all three different models (GLDAS, ERA-Interim and JRA-55) show consistently an overall dominance of precipitation over evapotranspiration, yielding a large positive value of total $P - E$ (or $I - O$) each year (Figs. 2B and 2C). Combined with the GRACE data, these results led to an estimate of the long-term averaged value of $P - E - \Delta S$ (or $I - O - \Delta S$) being 76 ± 5 mm yr^{-1}, giving a total excess of 54 ± 4 km^3 yr^{-1} (uncertainties indicated by the 95% confidence intervals) in the water budget over the Qiangtang Basin (Figs. 2D, S2 and S3; Details of data processing and uncertainty analysis are given in the Supplementary Material). The result implies that Eq.1 does not hold for the basin. This large amount of unaccounted water is approximately equivalent to the total annual discharge of the Yellow River (a major river on the Asian continent) and represents an important outflow from the basin. Given that no rivers flow out of the basin, this outflow can only take place through underground passages.

Surface water leakage to underground has been found by Zhou et al. (2013) at Namtso Lake (2,017 km^2; Fig. 1A) within the Qiangtang basin. Their hydrological observations including precipitation (9 stations), runoff (4 gauges), evaporation (1 gauge) and lake level (1 site) in the Namtso basin from 2007 to 2011 indicate a large water imbalance, which can only be explained by water leakage, corresponding to an average outflow of 3.8 ~ 6.0 km^3 yr^{-1} through the subsurface fault system. To explore the potential spatial distribution of underground leakage (L) of the entire Qiangtang Basin, we combine the grid-based GLDAS and GRACE data to map $L = P - E - \Delta S$. The calculated leakage represents the local excess water that could eventually leave the Qiangtang Basin through underground passages. The result shows that leakage is always positive and that the greatest leakage occurs in the southern part of the basin where six major rift valleys exist (Fig. 3). These rift valleys, up to 20 km wide and 300 km long, are bordered by steep range-front normal faults with large shear displacements (Cogan et al., 1998) and were formed by Cenozoic *E-W* extension that occurred concurrently with the *N-S* convergence between India and Asia (Molnar and Tapponnier, 1975; Styron et al., 2013). They extend from inside the Qiangtang Basin in the north, cut across its southern water divide and terminate near the Himalayas. We hypothesize that these rift valleys facilitate escape of the missing water from the Qiangtang Basin.

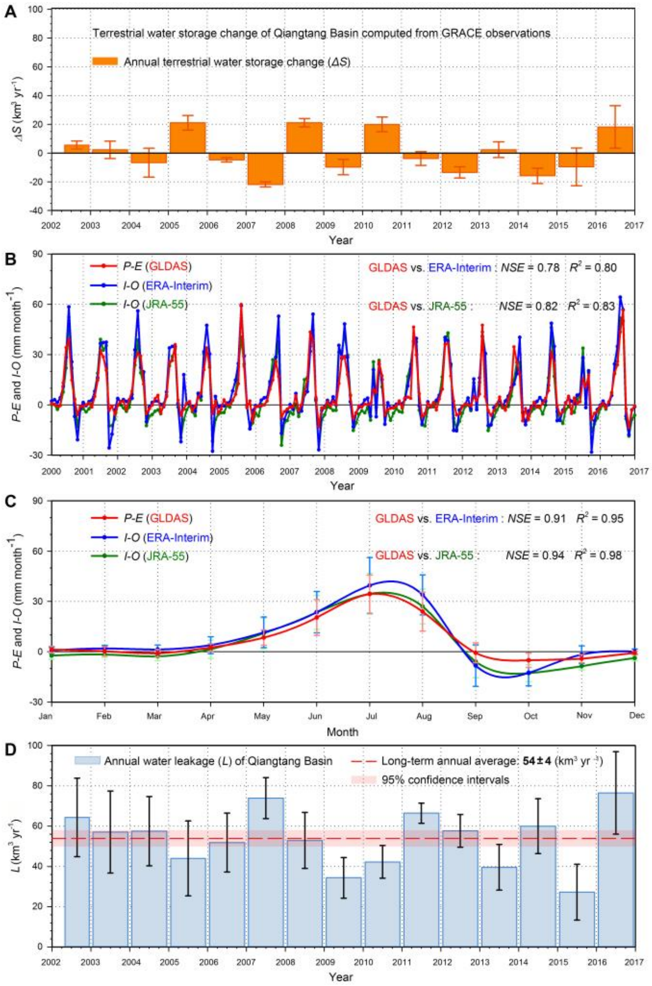

Figure 2. Water budget of the Qiangtang Basin. (**A**) Time series from May 2002 to December 2016 of the annual terrestrial water storage change (ΔS) of the Qiangtang Basin, estimated from three GRACE satellite retrieval solutions including CSR, JPL and GFZ (refer to the Supplemental Material). (**B**) Time series from 2000 to 2016 of the difference between precipitation (*P*) and evapotranspiration (*E*) and between water vapour input (*I*) and output (*O*) in the Qiangtang Basin, calculated from three different models including GLDAS, ERA-Interim and JRA-55. *NSE* is the Nash-Sutcliffe efficiency coefficient. (**C**) Same as (B) but for the averaged monthly values of the net atmospheric water vapour budget. (**D**) Time series of the annual water leakage (*L*; i.e., $P - E - \Delta S$ or $I - O - \Delta S$) of the entire Qiangtang Basin, estimated from three models (GLDAS, ERA-Interim and JRA-55) and GRACE data by nine groups of modelling experiments (refer to Fig. S3). Dash line shows the long-term average of the water leakage in the studied period. Pink, partially transparent shade illustrates the 95% confidence interval. Error bars in (A), (C) and (D) represent standard derivations. See the Supplemental Material for details of the uncertainty analysis.

Suggestive evidence for downward leakage from the rift valleys is the vastly different hydrological characteristics between tributaries that join the Yarlung-Zangbo River near the rift valleys and those located away from the rifts (Fig. S4). The runoff coefficient (*RC*; ratio of the total runoff to the total precipitation) is 0.7 for the Lhasa River (Wen et al., 2002) located away from the rifts, but is 0.248 for the Nyang Qu River (Dunzhu, 2015) that intersects the Yadong-Gulu Rift and is 0.39 for the Lazi Basin (see the Supplementary Material and Fig. S5) located just downstream of the intersection of the Nyima-Tingri Rift and the Yarlung-Zangbo River (Figs. 3 and S4). The latter values are both unusually low, suggesting that significant leakages may be ongoing beneath the rift valleys.

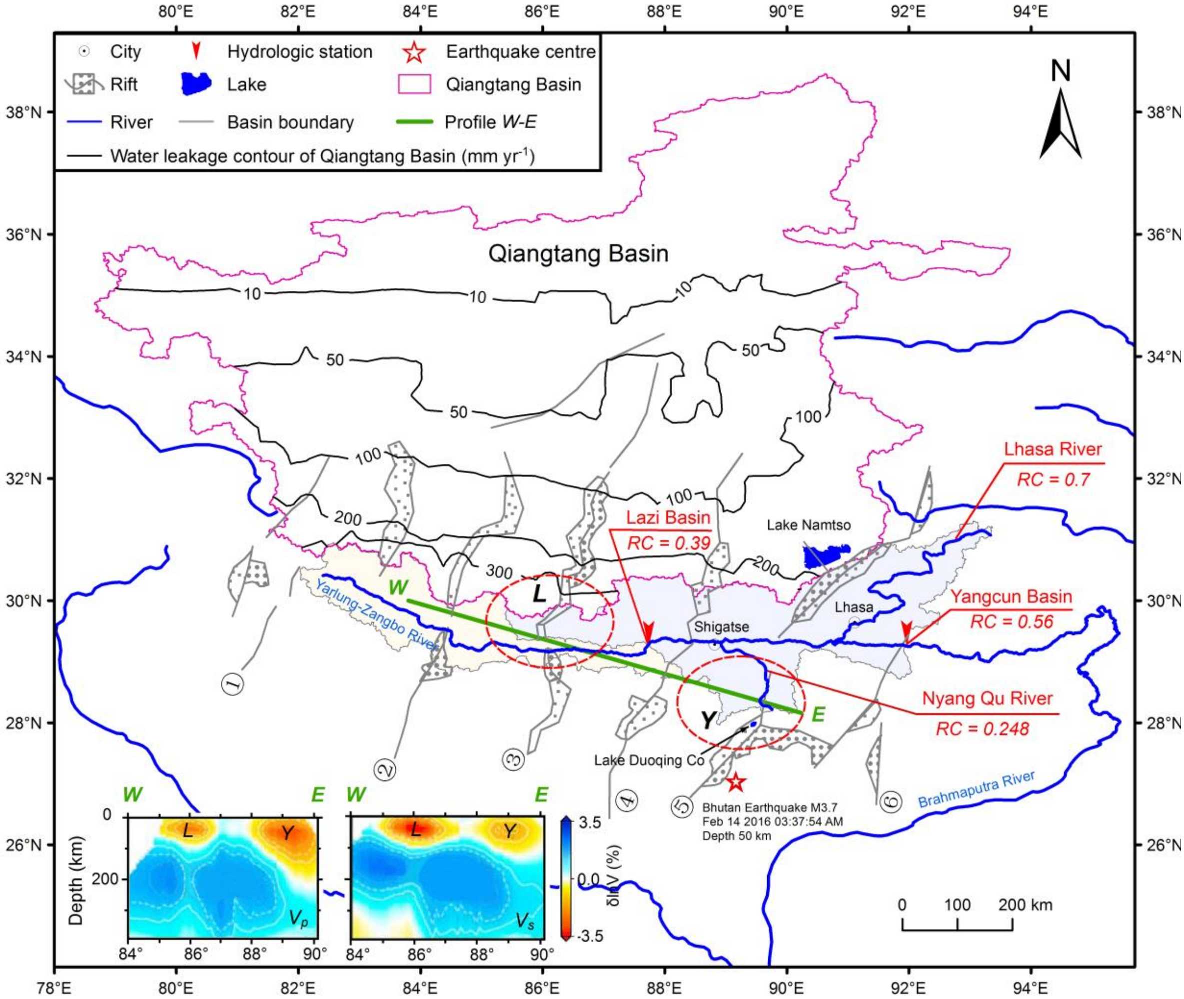

Figure 3. Hydrogeological analysis of underground leakage. Estimated water leakage contours and locations of six major rifts across the Southern Qiangtang Basin and the Yarlung-Zangbo River: ①Burang Rift, ②Lunggar Rift, ③Nyima-Tingri Rift, ④Xainza-Dinggye Rift, ⑤Yadong-Gulu Rift, and ⑥Lhozhag Rift. Red arrow heads show locations of the runoff gauges. Oblate circles *L* and *Y* show the locations of two regions of low seismic velocities that extend from near the surface to depths of ~100 km (inserts of the seismic velocity anomaly cross-sections along the line *WE* are modified from Hung et al. [2011]). The runoff coefficients of Lazi Basin, Yangcun Basin, Lhasa River and Nyang Qu River are shown for comparison.

Other evidence of water leakage from the rift valleys is the sudden disappearance of a lake (Duoqing Co) in the Yadong-Gulu Rift south of the Yarlung-Zangbo River (refer to satellite images in Fig. 4), which had an average surface area of 57 km^2 but dried up (Wu et al., 2018) following a nearby M3.7 earthquake (USGS: 14 February 2016, 03:37:54 a.m. local time; epicentre: N27.0333, E89.1686, epicentre marked by a red star in Fig. 3). Geologic examination of the dry lake floor showed numerous tensional fractures oriented subparallel to the general direction of the rift (Wu et al., 2018). Due to the remoteness of the area and the lack of nearby seismographic stations, the focal mechanism of this earthquake is difficult to determine. But the fact it locates beneath a rift valley suggests that it may have a normal faulting mechanism, like many earthquakes in similar tensional tectonic settings (Yin, 2000).

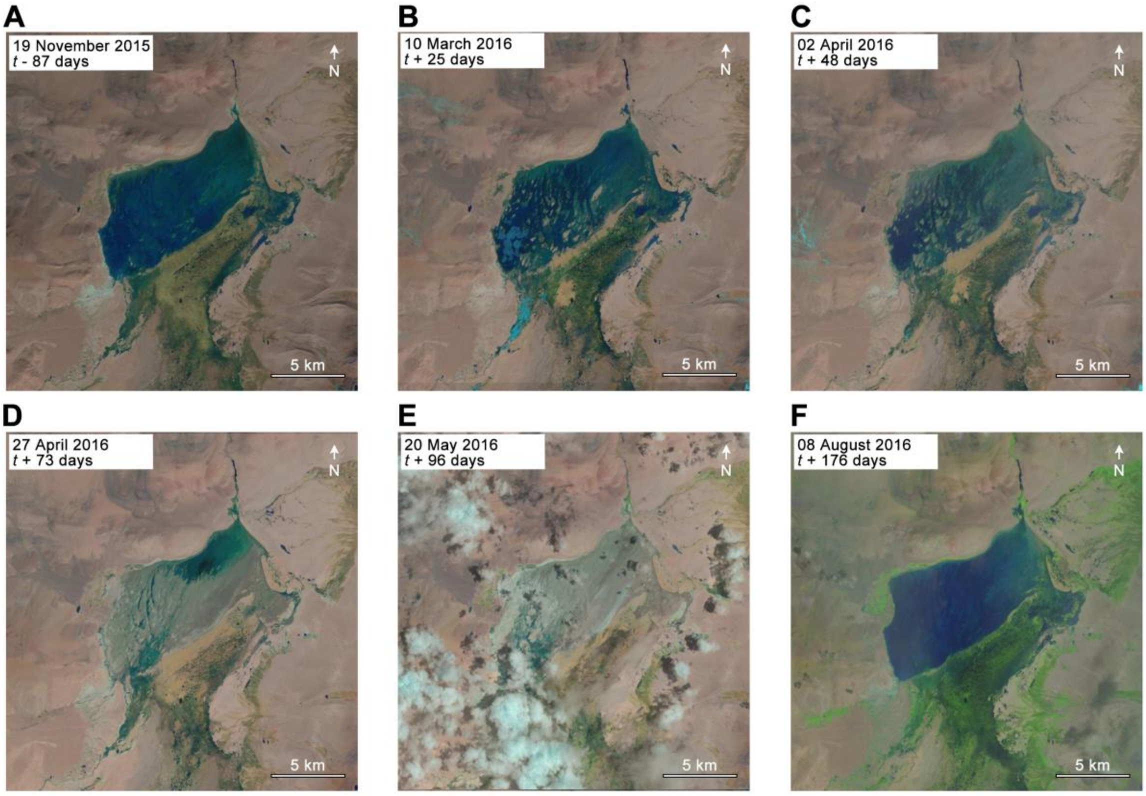

Figure 4. Satellite images covering the Duoqing Co Lake before and after the nearby M3.7 earthquake. (**A**) 87 days before earthquake, Time *t* days refers to the earthquake date (14 February 2016). (**B**) 25 days after earthquake. (**C**) 48 days after earthquake, the lake started drying. (**D**) 73 days after earthquake, the lake dried up except for a small part to the north. (**E**) 96 days after earthquake, the lake dried up completely. (**F**) 176 days after earthquake, the lake reverted to its earlier type. Note that the Duoqing Co Lake with an area of 57 km^2 never dried up before this earthquake.

Significant coseismic drawdown of groundwater seems to be not uncommon in areas of tensional earthquakes, as suggested by the disappearance of another lake and groundwater drawdown over a large area (160 km^2) affected by tensional faults after the 2016 M_w7.0 Kumamoto earthquake in Japan (Hosono et al., 2019). Given that the rift valleys in southern Tibet have been tectonically active since Miocene (Styron et al., 2013) and continuously affected by extension (Yin, 2000), we suggest that the missing water from the Qiangtang Basin may have escaped through the cross-basin *N-S* rift valleys in southern Tibet (Fig. 3).

Subsurface evidence for the missing water is difficult to find. Using seismic tomography, Hung et al. (2010, 2011) imaged two isolated regions of anomalously low seismic velocities (V_p and V_s) that coincide with the axes of the Nyima-Tingri and the Yadong-Gulu rifts (circled areas marked by *L* and *Y*, respectively, in Fig. 3) and extend from the surface down to depths of 50-100 km (see inserts in Fig. 3). Interpretation of the low seismic velocities at depth is uncertain. Partial melting of rocks was suggested to explain abnormally low seismic velocities in the upper mantle beneath Tibet (e.g., Nelson et al., 1996), but cannot explain the low-velocity zones beneath the rift valleys, which extend to the surface. Cai et al. (2018) suggested mineral hydration to explain the low seismic velocities that extend to depths > 50 km beneath the Marianna Trench. We test whether this hypothesis may explain the missing water from the Qiangtang Basin by estimating the upper bound of water required for mineral hydration (two tenth of one weight percent of rock [Christensen et al., 2004]). From the total volume of the low seismic velocity zones beneath the rift valley (Figs. 7a and 7b in Hung et al. [2011]) and assuming an average density of ~3,000 kg km^{-3} for the crust and upper mantle, we estimate that an upper bound of ~6×10^3 km^3 of water is required for the assumed mineral hydration. This is far from enough to explain the missing water from the Qiangtang Basin unless the leakage occurred only in the last 100 years – an unlikely supposition. Also, the mineral hydration would lead to increase of terrestrial water storage, which is not evident in the GRACE data. Hence none of the existing hypotheses can explain the low velocities beneath the rift valleys. Since tensile fractures have been experimentally measured under high pressures and high temperatures (e.g., Kumari et al., 2018; Xing et al., 2019), our hypothesis that tensile fractures beneath the rift valleys may allow groundwater to escape from the Qiangtang Basin is not inconsistent with the available geophysical and experimental data.

4. CONCLUDING REMARKS

Our findings have two important implications. First, the water budget of Tibet and its surrounding areas needs to be re-visited in consideration of the large amount of missing water from the Qiangtang Basin. As the ‘water tower’ of Asia, Tibet’s water directly and indirectly affects the water resources of a large area and population. Second and more generally, leaked groundwater crossing basin boundaries is expected to upwell and resurface in other basins. Thus cross-basin groundwater flow may be an important, and sometimes dominant, component in water budgets; not only for the basin where leakage occurs, but also for basins where groundwater upwells.

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