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News & Views

New methods designed to estimate the daily discharges of rivers in the Tibetan Plateau

Lei Wang [a,b,c,*], Arthur W. Sichangi [a,d], Tian Zeng [a], Xiuping Li [a], Zhidan Hu [e], Mulugeta Genanu [a,b]

[a] Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] Center for Excellence in Tibetan Plateau Earth Sciences, Chinese Academy of Sciences, Beijing 100101, China
[d] Dedan Kimathi University of Technology, Nyeri 657-10100, Kenya
[e] Information Center, Ministry of Water Resources, Beijing 100053, China

River discharge is a significant hydrological variable, as it represents the basin-scale integrated output of the hydrological cycle. At present, river discharge observations are usually measured at ground-based gauges across rivers worldwide. In some areas, however, measurements used in the practice of flood prediction and disaster prevention are either fully inaccessible or difficult to obtain in a timely and functional fashion [1]. It has also been reported that the scarcity of global river discharge observations may have undermined the efforts to calculate a globally meaningful estimate of the adjusted biodiversity threat [2]. The Tibetan Plateau (TP), also known as the "Asian Water Tower", is the headwater of more than 10 large rivers that provide water for billions of people and numerous ecosystems (Fig. 1). The TP has an average elevation greater than 4,000 m and an approximate area of 2.5×10^6 km^2. It is largely covered by cryospheric components (glaciers, snow, and frozen soil), and is highly sensitive to climate change [3,4]. Due to the TP's rapid warming in recent decades, prominent glacial recession, snowmelt, and permafrost degradation have occurred, resulting in water cycle modifications, as well as variations in streamflow both over the plateau and in its downstream regions [5].

The streamflows over the TP are mainly regulated by climatic change, while human interference is usually limited and negligible, especially for the headwater catchments [6]. During summer, monsoon precipitation is generally the overwhelming contributor to streamflow over the eastern and southeastern TP [7]. In the western TP, meltwater from glaciers and snow is the major contributor to streamflow; this meltwater may increase with rising temperatures. In the central TP, dominated by westerly winds, both meltwater and groundwater significantly contribute to streamflow during summer [8]. In general, glacial contributions are crucial primarily in watersheds having a large proportion of glacier coverage. In order to assess climate change in the TP and its downstream regions, it is of particular importance to quantify the impacts of regional warming and its accelerated cryospheric melts on river discharges (i.e., surface water resources). To achieve this goal, long-term, continuous, and spatially consistent gauge records are prerequisites. However, river discharge gauges are very deficient and far below the required spatial density over most high-mountain regions, such as the TP. In addition, constructing new in-situ discharge gauges on the TP can be rather costly, and maintenance can be difficult due to the remote and harsh environment.

Remote sensing, whose applications over inland water bodies have been enhanced in past decades, has become a promising alternative for estimating river discharge given its ability to accurately measure hydraulic variables, such as river width, slope, stage, and velocity. Recently, there has been a growing interest in estimating global river discharges from remote sensing via altimeters [9] and spectral bands [10]. A review of the literature reveals that satellite-based methods primarily consist of discharge estimations using altimetry-derived river stages, spectral remote sensing-derived river width and velocity, and multi-variant (multi-satellite) approaches. However, the majority of the existing techniques were developed for global continental rivers and are thus not applicable to high-mountain TP rivers, which feature complex topography and relatively narrow channels.

Therefore, based on the various river features of the TP (e.g., spatial scale and glacier coverage), we propose 2 different approaches to estimate the daily discharges of TP rivers, as described below (Fig. 1).

For river discharge measurements or calculations/estimations, channel cross-section is the most commonly used feature. For a given river cross-section, hydraulic features including velocity v (m s^{-1}), width w (m), and depth d (m) can be measured directly via ground-based observations. The total instantaneous water flux Q (m^3 s^{-1}) flowing through a cross-section with an area A (m^2) should be

$$Q = A \cdot v, \tag{1}$$

The mean velocity (v) of the river cross-section can be calculated using the Manning formula [11]:

$$v = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}}, \tag{2}$$

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* Corresponding author.
E-mail address: wanglei@itpcas.ac.cn (L. Wang).

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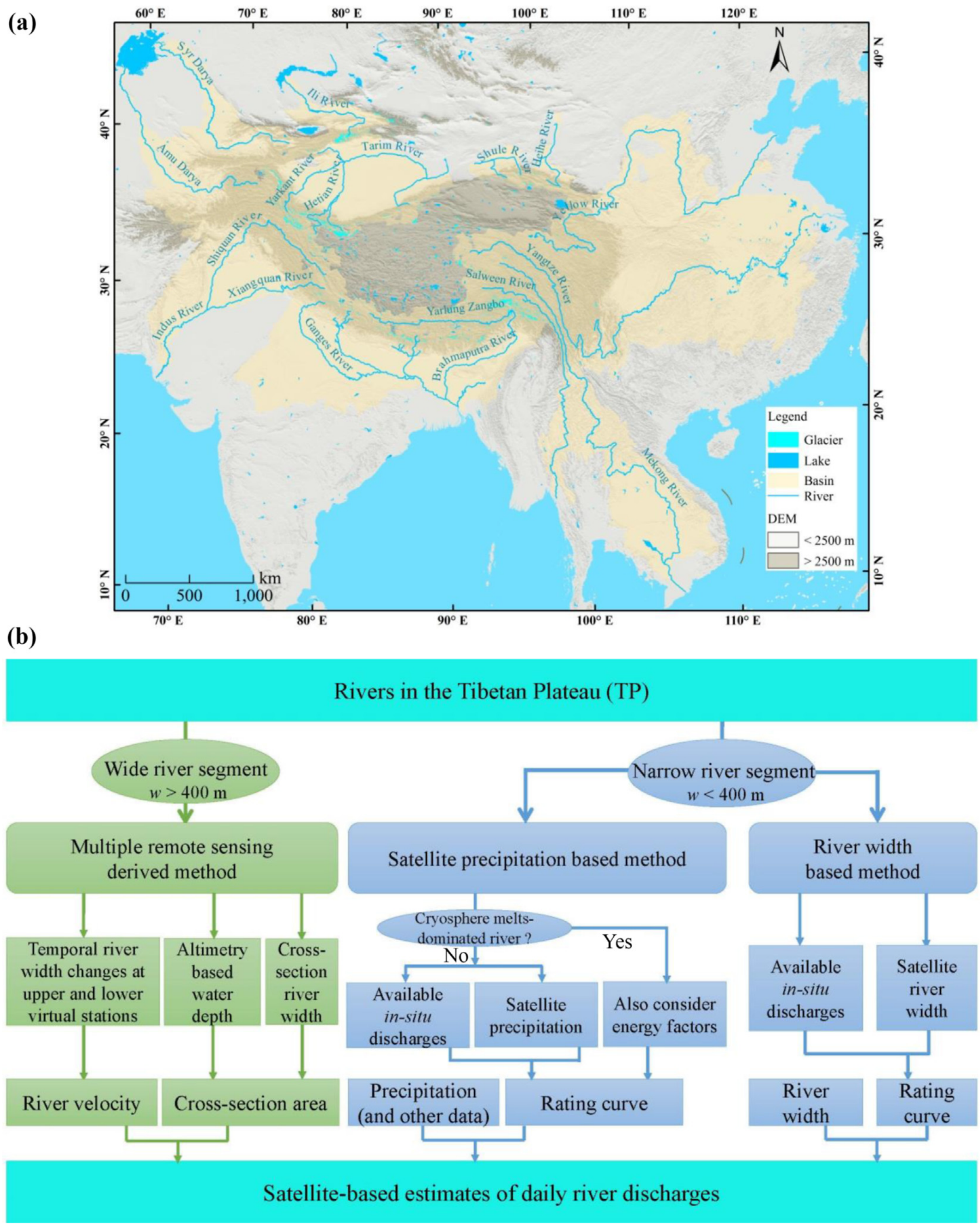

Fig. 1. Rivers originating from the Tibetan Plateau (a) and the flowchart of satellite-based approaches for daily discharge estimation (b).

where, n is the roughness coefficient; R is the hydraulic radius ($=A/P_{wet}$) (m), having P_{wet} (m) as the wetted perimeter and S as the slope of river bed [12].

For wide river segments ($w > 400$ m), such as the middle to downstream sections of large TP rivers, it is possible to estimate river discharge completely from multiple remote sensing-derived datasets [12]. This approach follows Eq. (1), with the average river velocity (assuming a uniform velocity) estimated first. Using the cloud-free MODIS (Moderate Resolution Imaging Spectroradiometer) images, the temporally-variable river width measurements for 2 river segments spaced a particular distance apart can be mapped in order to illustrate/quantify time lag. The flow velocity is then calculated by combining the time lag with the distance between the 2 sites used for the width measurement, leading to a resultant velocity. The roughness coefficient can be estimated from existing look-up tables, and the river channel slope is obtained from the DEM (digital elevation model) averaged over the river channel. An empirical equation is further adopted to estimate the water depth of the river [12]. In the end, the temporal water depth changes can be obtained by modulating the estimated river water depth to the water level changes derived from satellite radar altimetry (e.g., Envisat, Jason-1, Jason-2, Jason-3, and so on), and river width changes from high-spatial-resolution spectral images (e.g., Landsat and others). Performance evaluation was rigorously carried out for 2 cross-sections of the middle Yangtze River. For these 2 cross-sections, the river discharges were estimated with the Nash-Sutcliffe coefficient > 0.5 [12]. Since this approach for estimating streamflow depends entirely on satellite images, it represents a promising technique for use in the ungauged rivers of the TP. It should be mentioned that the temporal resolution of estimated discharges via this method is generally limited by the temporal resolutions of the available spectral images and satellite altimetry datasets.

For narrow river segments (w < 400 m) of small- to medium-sized rivers on the TP (e.g., most headwater catchments or major tributaries), current satellite altimetry is not suitable for estimating river discharge due to its coarse spatial resolution, although future SWOT altimetry is promising. For these small- to medium-sized TP rivers, a satellite-precipitation-based method or a river-width-based method is suggested to estimate discharge time series, both of which require in-situ calibration with historical discharges (at least 1 hydrological year) or a priori knowledge of river hydraulics in order to develop a rating curve between river discharge and its relevant meteorological or hydraulic variables.

(1) Satellite-precipitation-based method. Since human interference is often limited over high-mountain rivers, it is possible to use satellite-based precipitation products (e.g., TRMM or GPM) to estimate river discharge with a fine temporal resolution (e.g., daily) by neglecting anthropogenic discharge influences. The basin-averaged precipitation over the upper area of a river cross-section can be calculated from the continuously-available gridded satellite precipitation. Utilizing historical discharge records, the rating curve between the filtered (using an exponential smoothing filter) basin-averaged precipitation and basin-outlet discharge can be derived for the target cross-section. With the obtained rating curve and the continuously available satellite precipitation datasets at high temporal resolutions (e.g., hourly or 3-hourly), the daily discharges of most non-glacier-fed TP rivers can be estimated. This method, however, is confined to catchments with little glacier coverage and relatively accurate satellite precipitation data. When extending this approach to river segments dominated by cryospheric melts (from glaciers, snow, and frozen soil), additional energy factors such as air temperature and incoming solar radiation should be carefully considered during rating-curve development. The multi-variant linear regression method that is used should factor in not only continuously-available satellite precipitation, but also routinely-available air temperature or solar radiation from operational reanalysis datasets, such as MERRA-2 and GLDAS.

(2) River-width-based method. This approach is relatively simple, and largely depends on the capability to reasonably derive the river width (w) hydraulic variable. The crux of this method involves deriving the rating curve between the historical time-series of w (acquired from satellite images) and discharge Q (from observed daily records) for a specific river cross-section. Of course, the temporal resolution of the estimated discharges derived by this method is confined to the temporal resolution of the available spectral images (e.g., Landsat).

To our knowledge, the 2 methods complement one other, thus providing daily discharge estimates for most of the narrow river segments on the TP. On the one hand, the river-width-based method can be applied to any river segments having historical discharge data or *a priori* knowledge of river hydraulics, although it limited by the coarse temporal resolution of available spectral images. On the other hand, although the satellite-precipitation-based method is only applicable to river basins that have experienced little anthropogenic influence, it can provide high-temporal-resolution discharge estimates.

Thus far, the proposed approach for wide river segments (w > 400 m) has been evaluated for the middle stream of the Yangtze River [12]. This method will be further investigated/evaluated for rivers on the TP using upcoming high-spatial-resolution satellite altimetry, such as SWOT. The techniques designed for narrow river segments (w < 400 m) are currently being implemented on the main stream of the upper Brahmaputra River (Nuxia hydrological station, using the satellite-precipitation-based method) and the Lhasa River (Tanggya hydrological station, using the river-width-based method).

In summary, remote sensing technology holds promise for estimating the daily discharges of TP rivers, although most of the current approaches for river discharge estimation require either *in-situ* calibration or *a priori* knowledge of river hydraulics, thus precluding their application to ungauged or remote rivers. Improving/refining temporal resolution is the major challenge when using satellite altimetry to monitor water level changes. Obviously, neither the Envisat, with its 35-day temporal resolution, nor the Jason 2, with its 10-day resolution, can replace the daily records measured by ground-based gauges. However, upcoming new missions such as Jason-3, Jason CS, Sentinel-3a and b, as well as SWOT will very likely mitigate this issue.

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2019.03.015.

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Lei Wang is now a full professor and group leader at Institute of Tibetan Plateau Research, Chinese Academy of Sciences (CAS), and the CAS Center for Excellence in Tibetan Plateau Earth Sciences. His current research is focused on climate change and water cycle over the Third Pole region, for an improved predictability of regional water resources and water-related disasters.