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Discharge estimation in high-mountain regions with improved methods using multisource remote sensing: A case study of the Upper Brahmaputra River

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ABSTRACT

River discharge is an important variable in the water cycle that is related to water supply, irrigation, and flood forecasting. However, gauging stations are extremely limited across most high-mountain regions such as the Tibetan Plateau (TP), known as the Asia's water towers. Remote sensing, in combination with partial in situ discharge measurements, bridges the gap in monitoring river discharge over ungauged and poorly gauged basins. Of great importance for the successful retrieval of river discharge using remote sensing are river width (water surface area) and water level (water surface elevation), but it is challenging to retrieve accurate discharge values for high-mountain regions because of narrow river channels, complex terrain, and limited observations from a single satellite platform. Here, we used 1237 high-spatial-resolution images (Landsat series and Sentinel-1/2) to derive water surface areas with the Google Earth Engine (GEE), and satellite altimetry (Jason-2/3 and Satellite with Argos and AltiKa (SARAL/Altika)) to derive water levels for the Upper Brahmaputra River (UBR, the Yarlung Zangbo River in China) in the TP where the river width is typically less than 400 m. Using three power function equations, discharge was estimated for cross-sections around the four gauging stations in the UBR with triangular cross-sections outperforming their trapezoidal counterparts. It was also found that the equation combining both river width and water level produced the best discharge estimates whereas the other two equations (requiring either river width or water level as the input data) were complementary and could be used to extend the time series of discharge estimates. The Nash–Sutcliffe efficiency coefficient values for the discharge estimates range from 0.68 to 0.98 during the study period 2000–2017. The proposed method is feasible to estimate discharge in the UBR and potentially other high-mountain rivers globally.

1. Introduction

For hydrological studies and applications, such as flood forecasting, water supply management, and dam design, river discharge is undoubtedly a vital variable. Monitoring river discharge is also critical to developing a better understanding of changes in the water cycle and hydrological processes at river-basin scales and globally under climate change (Robert Brakenridge et al., 2012). However, the difficulty of obtaining long time series of discharge data, particularly over ungauged and poorly gauged basins, poses a considerable challenge for hydrologists. The uneven distribution of gauging stations in sparsely-populated areas, the huge expense associated with the maintenance of gauging networks (Bjerklie et al., 2003), and data sharing problems for transboundary rivers (Hossain et al., 2014) have all contributed to the inaccessibility of the data. Despite these difficulties, remote sensing has offered a supplementary means of obtaining streamflow information.

Although measuring river discharge directly is currently a difficult task either from gauging stations or space (Bjerklie et al., 2003; Neal et al., 2009), indirect measurement relying on hydraulic elements is feasible. Discharge estimation methods using remote sensing can generally be divided into two groups. The first group is direct estimation using indices that are sensitive to discharge regardless of the hydraulic characteristics of rivers. Brakenridge et al. (2007) adopted the ratio of the calibration area (for land pixels in brightness temperature) to the measurement area (for water pixels) as the sensitive index using the Advanced Microwave Scanning Radiometer (AMSR-E) band at

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Table 1

Summary of different approaches for estimating river discharge using remote sensing (this current paper is also added). Key results are coded as follows: (1) use of an index sensitive to river discharge for estimation, (2) use of a single hydraulic variable sensitive to discharge, and (3) combination of multiple satellite missions and variables related to discharge. There is no code in the "Key results" column for study results unrelated to either of these codes.

Study	Data used	Key results
Tarpanelli et al. (2017)	MODIS, Jason-2, and Envisat	3. Discharge estimation and forecasting performed through combining MODIS and radar altimetry
Sichangi et al. (2016)	MODIS, Jason-2, and Envisat	3. River width obtained from MODIS and water level from satellite altimetry jointly used with respect to the shape of the cross-sections
Tarpanelli et al. (2015)	MODIS and Envisat	3. MODIS (for flow velocity) and Envisat (for water level) used to estimate discharge
Liu et al. (2015)	Landsat and Envisat	3. Remotely sensed data (water level and water extents) used to calibrate the hydrologic model that provides estimates of river discharge.
Durand et al. (2014)	Airborne optical imagery and LiDAR digital terrain model	3. Water surface elevation and slope jointly used to estimate discharge based on the Metropolis algorithm
Pavelsky (2014)	RapidEye and Landsat imagery	2. River width-based rating curves used to monitor discharge
Tarpanelli et al. (2013)	MODIS	1. Ratio of calibration area (land pixels, expressed as surface reflectance) to measurement area (water pixels) used as an index for estimating discharge
Brakenridge et al. (2007)	Advanced Microwave Scanning Radiometer (AMSR-E)	1. Ratio of land pixels to water pixels used as a sensitive index
Leon et al. (2006)	TOPEX/Poseidon and Envisat	2. Water level from satellite altimetry used to estimate discharge using rating curves.
Brakenridge et al. (2005)	MODIS	2. River width used to estimate discharge
Bjerklie et al. (2005)	Synthetic Aperture Radar (SAR), aerial and digital orthophotos, and topography maps.	3. River width and channel slope used to estimate discharge.
This study	Landsat 5, 7, and 8, Sentinel-1/2, Jason-2/3, and SARAL/Altika	3. River width and water level jointly used to estimate river discharge based on the formulas specifically designed for triangular cross-sections.

36.5 GHz. An empirical formula was developed by fitting the ratio with in situ discharge measurements. Simple and feasible as this method is, it tends to underestimate peak flow.

Revilla-Romero et al. (2014) evaluated the performance of this method and found it applicable to areas with sparse vegetation and rivers wider than 1 km. Tarpanelli et al. (2013) further extended this method to the application of the MODerate resolution Imaging Spectroradiometer (MODIS), because the near-infrared (NIR) band remains highly sensitive to water bodies. Temimi et al. (2011) computed the polarization ratio variation index (PRVI) using AMSR-E for discharge estimation. Ling et al. (2012) took islands in rivers as an indicator and constructed the relationship between the variations of island area and discharge.

In general, the first group focuses on statistical methods to derive river discharge. Thus, its accuracy and transferability to other rivers under different flow regimes and geomorphological settings are somewhat questionable. Another way to monitor river discharge using remote sensing involves the retrieval of hydraulic variables related to discharge such as water surface area, slope, and water level, either solely or jointly, prior to its estimation using various hydraulic equations (Birkinshaw et al., 2014; Bjerklie et al., 2003; Michailovsky et al., 2013; Smith et al., 1996).

River width or inundation extent has the potential to reflect variations in discharge. Previous studies have shown the application of MODIS images in discharge estimation (Brakenridge and Anderson, 2006; Smith and Pavelsky, 2008; Tarpanelli et al., 2013). As was shown in a review by Smith (1997), use of radar and optical remote sensing for inundation extent mapping is feasible. Based on the fact that different cross-sections within a given river reach exhibit a common log-linear relationship, Gleason and Smith (2014) developed at-many-stations hydraulic geometry using a specific scaling law for rivers. Vörösmarty et al. (1996) discovered that correlation existed between monthly discharge and river width. Van Dijk et al. (2016) used optical and microwave-derived water extent to obtain monthly discharge estimates for rivers globally.

Furthermore, in combination with gauging records, radar altimetry satellites have been applied to obtain water level data and develop rating curves to estimate discharge. Free from the influence of cloud and weather, the ability of radar satellite altimetry to monitor water levels in continental water bodies has been demonstrated in many published studies (Frappart et al., 2006; Getirana et al., 2013; Michailovsky et al., 2013; Santos da Silva et al., 2010; Sulistioadi et al., 2015). For example, Leon et al. (2006) used rating curves with the form $q = a(H - z)^b$ (q is discharge, H is the water level, z is the height of zero flow obtained using the minimization of root mean square error (*RMSE*) between the measured discharge and the rated discharge, and a and b are the parameters calibrated using in situ discharge data) to estimate discharge based on water levels retrieved from satellite altimetry. Papa et al. (2010) produced a monthly data set of discharge in the Ganga-Brahmaputra River using altimetry-derived water levels based on rating curves (such as the power law functions).

The abovementioned methods rely heavily on single hydraulic variables or focus on sole data sources. Therefore, the temporal sampling can be much improved by considering the combination of multiple satellite platforms and the retrieval of multiple hydraulic variables (Tourian et al., 2017; Tourian et al., 2016). This will make a tremendous difference in river discharge estimation. For example, Bjerklie et al. (2005) proposed a method that combines synthetic-aperture radar (SAR), aerial orthophotos, and channel slope data to estimate discharge. Durand et al. (2014) used water level and slope data to estimate discharge based on the Metropolis algorithm at the River Severn in the United Kingdom. Tarpanelli et al. (2015) integrated MODIS with Envisat to estimate discharge even without a priori bathymetry information.

Developed from the Manning's equation, Sichangi et al. (2016) used Eq. (1) to estimate river discharge based on water levels and river widths from multiple satellite missions such as Envisat, Jason-2, and Terra/Aqua (MODIS) for continental rivers such as the Amazon and the Negro River.

$$q = aWD^{\frac{5}{3}} + b \tag{1}$$

where q is discharge, W is the river width, and D is the water depth defined as the difference between the water surface elevation and the minimum water level in the time series while a and b are parameters to be calibrated using partial in situ discharge measurements. A summary of existing methods related to monitoring discharge using remote sensing is presented in Table 1. However, these published studies did not address discharge estimation for mountainous rivers with narrow widths and triangular cross-sections, a domain that remains underexplored.

The overall objective of this study was therefore to estimate river discharge in mountainous regions using multisource remote sensing data and formulas specifically designed for triangular cross-sections. Processing hundreds or even thousands of satellite images for river