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Estimating continental river basin discharges using multiple remote sensing data sets

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ABSTRACT

Rivers act as a source of fresh water for terrestrial life, yet the discharges are poorly documented since the existing direct observations are inadequate and some observation stations have been interrupted or discontinued. Discharge estimates using remote sensing thus have a great potential to supplement ground observations. There are remote sensing methods established to estimate discharge based on single parameter derived relationships; however, they are limited to specific sections due to their empirical nature. In this study, we propose an innovative method to estimate daily discharges for continental rivers (with river channel widths >800 m (Birkett and Beckley, 2010)) using two satellite derived parameters. Multiple satellite altimetry data and Moderate Resolution Imaging Spectroradiometer (MODIS) data are used to provide a time series of river stages and effective river width. The derived MODIS and altimetry data are then used to optimize unknown parameters in a modified Manning's equation. In situ measurements are used to derive rating curves and to provide assessments of the estimated results. The Nash–Sutcliffe efficiency values for the estimates are between 0.60 and 0.97, indicating the power of the method and accuracy of the estimations. A comparison with a previously developed empirical multivariate equation for estimating river discharge shows that our method produces superior results, especially for large rivers. Furthermore, we found that discharge estimates using both effective river width and stage information consistently outperform those that only use stage data.

1. Introduction

River discharge measurements are essential for flood management, climate studies, and water resources management. Knowledge of river flow propagation speed, i.e., the time for flows to pass downstream, is critical for watershed modeling, flood prediction, and managing reservoirs (Brakenridge et al., 2012). Therefore, there is a great need for long-term, continuous, spatially consistent, and readily available discharge data.

River discharges are currently recorded at river gauging stations. However, the availability of gauging station records is generally decreasing in most parts of the world, with data for some areas either completely unavailable or difficult to access for timely use in operational flood forecasting and disaster prevention (Dai & Trenberth, 2002; Dai, Qian, Trenberth, & Milliman, 2009). Tourian, Sneeuw, and Bárdossy (2013) compiled a time series plot of the number of stations with available discharge data from the publicly available data of the Global Runoff Data Centre (GRDC). This time series indicates a decline in the total monitored annual stream flows between 1970 and 2010. Inadequate discharge observation has become a major problem in both developing and underdeveloped countries, as a majority of stations are no longer in operation (Calmant & Seyler, 2006). Similarly, the commitments of participating countries to initiatives such as the International Hydrological Decade (1965–1974), which was the basis for the assessment of water resources conditions worldwide, have been seriously decreasing (Vörösmarty et al., 2001). In addition to the decrease in the number of stations that contribute to the Global Runoff Database, some stations have discontinuous datasets. These data gaps present a challenge for

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making useful analyzes. Furthermore, current data collection efforts are mainly focused on individual development projects in different countries. This trend has produced a patchwork of datasets that span short periods of time, with restricted spatial coverage and limited availability.

Satellite altimetry, whose application over land has increased in recent decades, is an interesting alternative for recording periodic variations in water level in continental environments with acceptable accuracy. It appears to be a highly promising source of information that may be used to complement ground station data. The ability of satellite altimeters to monitor continental water surfaces and to measure their stage has been demonstrated for continental waters (Calmant & Seyler, 2006; Jarihani, Callow, Johansen, & Gouweleeuw, 2013; Koblinsky, Clarke, Brenner, & Frey, 1993; Sulistioadi et al., 2015), and this method has been used to provide estimates of river discharge (Sneeuw et al., 2014). Recent studies demonstrate a growing interest in deriving discharge estimates from remote sensing via spectral bands (Brakenridge, Nghiem, Anderson, & Mic, 2007; Temimi et al., 2011) and altimeters (Leon et al., 2006). In addition to discharge estimation, attempts to use remote sensing data (river width or water surface elevation) as surrogates for in situ measurements in hydrological model calibration have also been tested (Sun, Ishidaira, & Bastola, 2012a,b). A fundamental requirement for estimating river discharge lies in the ability to realistically estimate spatial hydraulic variables, e.g., river width and water surface heights, and to establish a relationship between interrelated hydraulic variables that can then be used to estimate other variables such as depth (Mersel, Smith, Andreadis, & Durand, 2013).

Traditionally, the hydraulic characteristics of stream channels including depth (d), width (w), and velocity (v) are measured quantitatively at a ground observation stations, and these parameters vary with discharge as simple power functions at a given river cross-section. Consequently, the structure primarily used for river discharge measurements is the channel cross-section. The total instantaneous water flux (Q), in m^3/s or ft^3/s, through the cross-section is equal to the product of the mean cross-sectional flow as in Eq. (1), as averaged from numerous ground station measurements taken across the stream (Smith & Pavelsky, 2008).

$$Q = w \times d \times v. \quad (1)$$

According to Leopold and Maddock (1953), the functions derived for a given cross-section and among various cross-sections along the river only differ in the numerical values of the coefficients and exponents in accordance with Eqs. (2), (3), and (4).

$$w = aQ^b \quad (2)$$

$$d = cQ^f \quad (3)$$

$$v = kQ^m \quad (4)$$

where a, b, c, f, k, and m are empirical constants.

Since the estimates of river discharge require the utilization of w, d, and v, any attempts to neglect one of the parameters contributes to increased errors. For instance, Bjerklie, Moller, Smith, and Dingman (2005) estimated in-bank river discharge using remotely sensed width information and channel slope but acknowledged that this model is a less accurate method compared to discharge estimation models that include width, depth, and slope (Bjerklie, Lawrence Dingman, Vorosmarty, Bolster, & Congalton, 2003). Most discharge estimation methods use regression based relationships between remotely measured parameters (e.g., w or stage) and in situ measured discharge via the stated equations (Smith & Pavelsky, 2008; Tarpanelli, Barbetta, Brocca, & Moramarco, 2013). Unfortunately, this approach is not suitable for all river environments (LeFavour & Alsdorf, 2005). For some river sections, e.g., a rectangular cross-section, changes in water height yields negligible changes in the width but significant changes in the flow. This precludes the use of a w-based estimation equation (Sun et al., 2012b). The reverse is true in flat terrains/river sections where changes in river width yield negligible changes in river heights, e.g., the Diamantina River in Central Australia (Jarihani, Callow, McVicar, Van Niel and Larsen, 2015; Jarihani, Larsen, Callow, McVicar and Johansen, 2015). This rules out the use of an estimation equation based on d.

Consequently, utilizing the river stage level from satellite altimetry data in conjunction with other space-based parameters, e.g., river width and river surface velocity from Synthetic Aperture Radar (SAR) (Bjerklie et al., 2005), should generate estimates of discharge that are superior to those based on a single parameter.

Several researchers have reviewed the types of river hydraulic information that can potentially be observed from space-based platforms and have produced several general relationships that utilize this information for the development of a wide range of river discharge estimation equations (Alsdorf, Rodríguez, & Lettenmaier, 2007; Bjerklie et al., 2003; Tang, Gao, Lu, & Lettenmaier, 2009). In all cases, the success of discharge estimation using remote sensing derived parameters depends on the accuracy of estimate parameters, e.g., width and stage, and the ability to accurately derive the parameters that cannot be directly observed from space, e.g., velocity and bathymetry depth. Since these initial studies, various approaches have been used to estimate discharge by considering a wide range of strategies to improve outcomes (Table 1).

On the basis of the previous studies listed in Table 1, four approaches to estimating river discharge using remote sensing can be summarized as follows:

a) Measure water level variation using satellite altimetry data. These measurements are then converted to river discharge on the basis of a rating curve between satellite-derived "water level" and in situ measured discharge.
b) Correlate satellite derived water surface area with in situ measured discharge, and then infer river discharge from satellite data on the basis of the water area–discharge rating curve.
c) Using hydraulic equations, estimate river discharge from the measurement of hydraulic variables from satellite and/or other remotely obtained information.
d) Using remotely sensed data, i.e., river flow widths, to approximate the newly discovered characteristic scaling law that has been termed at-many-stations hydraulic geometry (AMHG). AMHG halves the number of parameters required by traditional hydraulic geometry, thus paving the way for discharge estimation solely from remote sensing (Gleason & Smith, 2014).

The first approach uses satellite altimetry data (Birkinshaw et al., 2010; Tarpanelli et al., 2013). The second approach relies on changes in river width (Pavelsky, 2014; Smith & Pavelsky, 2008). The third approach has been invoked by several researchers (Bjerklie et al., 2005; Bjerklie et al., 2003; LeFavour & Alsdorf, 2005; Negrel, Kosuth, & Bercher, 2011). The last approach marks a breakthrough in discharge estimation using remote sensing without requiring any in situ measurements or a priori information. Gleason, Smith, and Lee (2014) advanced the AMHG discharge retrieval approach via additional parameter optimizations and the study performed a validation for 34 gauged rivers that span a diverse range of geomorphic and climatic settings. This study reported successful retrieval in channel discharges for a variety of rivers. However, there were exceptions which include braided rivers, low-b rivers (i.e., having a mean cross-sectional at station hydraulic geometry b value <0.1), and rivers displaying extreme variability in discharge as manifested in the tested arid-climate rivers. To address these exceptions, further studies are required that incorporate the currently used river width AMHG with the at-station hydraulic geometry Eqs. (2) and (3). An approach that could estimate river discharge solely from remotely obtained hydraulic data, i.e., width, depth and velocity,