Journal of Hydrology 540 (2016) 670–687

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Constructing river stage-discharge rating curves using remotely sensed river cross-sectional inundation areas and river bathymetry

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ARTICLE INFO

Article history:
Received 4 February 2016
Received in revised form 1 June 2016
Accepted 11 June 2016
Available online 25 June 2016
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Jennifer Guohong Duan, Associate Editor

Keywords:
Landsat TM imagery
Digital elevation model
River bathymetry
The Manning's coefficient
The Manning's equation
Inundation area
River stage and discharge
The Bernoulli equation
Gradually varied open channel flow
Nonlinear constrained global optimization

ABSTRACT

Remote sensing from satellites and airborne platforms provides valuable data for monitoring and gauging river discharge. One effective approach first estimates river stage from satellite-measured inundation area based on the inundation area-river stage relationship (IARSR), and then the estimated river stage is used to compute river discharge based on the stage-discharge rating (SDR) curve. However, this approach is difficult to implement because of a lack of data for constructing the SDR curves. This study proposes a new method to construct the SDR curves using remotely sensed river cross-sectional inundation areas and river bathymetry. The proposed method was tested over a river reach between two USGS gauging stations, i.e., Kingston Mines (KM) and Copperas Creek (CC) along the Illinois River. First a polygon over each of two cross sections was defined. A complete IARSR curve was constructed inside each polygon using digital elevation model (DEM) and river bathymetric data. The constructed IARSR curves were then used to estimate 47 river water surface elevations at each cross section based on 47 river inundation areas estimated from Landsat TM images collected during 1994–2002. The estimated water surface elevations were substituted into an objective function formed by the Bernoulli equation of gradually varied open channel flow. A nonlinear global optimization scheme was applied to solve the Manning's coefficient through minimizing the objective function value. Finally the SDR curve was constructed at the KM site using the solved Manning's coefficient, channel cross sectional geometry and the Manning's equation, and employed to estimate river discharges. The root mean square error (RMSE) in the estimated river discharges against the USGS measured river discharges is 112.4 m^3/s. To consider the variation of the Manning's coefficient in the vertical direction, this study also suggested a power-law function to describe the vertical decline of the Manning's coefficient with the water level from the channel bed lowest elevation to the bank-full level. The constructed SDR curve with the vertical variation of the Manning's coefficient reduced the RMSE in the estimated river discharges to 83.9 m^3/s. These results indicate that the method developed and tested in this study is effective and robust, and has the potential for improving our ability of remote sensing of river discharge and providing data for water resources management, global water cycle study, and flood forecasting and prevention.

1. Introduction

River discharge, the volumetric rate of water flow passing a cross section of a river, is essential to water supply planning and management, reservoir management and operation, hydropower generation, flood prediction and control, understanding of the global water cycle, and other hydrological applications. Although we can directly measure river discharge through establishment and operation of river gauging stations, many watersheds in the world are ungauged or poorly-gauged for several reasons, such as the cost to install and maintain gauging stations, inaccessible areas, and politically unstable regions, especially in developing countries. Even in some developed countries, the cost of installation and operation of gauging stations greatly limits the number of river gauging stations installed. For example, the cost for the United States Geological Survey (USGS) to install a gauging station is between $20,000 and $35,000, and the annual operational cost is about $20,000 (e.g., Fekete and Vörösmarty, 2007). Because of a shortage of funding, the number of gauging stations in the United States is decreasing (e.g., Vorosmarty et al., 1996; IAHS, 2001; Bjerklie et al., 2003; Hannah et al., 2011). Many major flood events around the world were not adequately measured (Cloke and Pappenberger, 2009), and many gauging network programs for

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http://dx.doi.org/10.1016/j.jhydrol.2016.06.024
0022-1694/

worldwide major rivers, not to mention medium and small rivers, are shrinking (Hannah et al., 2011).

Directly measuring river discharge is often difficult because of the irregularity in river channels and variability of flow velocity in both vertical and horizontal directions. Therefore, to directly measure river discharge, a cross section is often divided into a number of sub-cross sections, and in each sub-cross section, a number of flow velocities at different flow depths are measured and averaged resulting a mean flow velocity for that sub-cross section. Then the river discharge is computed as the sum of all mean flow velocity multiplied by sub-cross section area. This method is also known as the velocity-area method (Mosley and McKerchar, 1992), but it is costly, labor intensive, and time consuming to directly measure river discharge using the velocity-area method. To save cost, labor and time, river discharge is usually inferred from the measurement of river stage based on the pre-defined or pre-observed stage-discharge rating (SDR) curve (Buchanan and Somers, 1969; Olson and Norris, 2005). River stage is the height of water surface above a nearby reference point. However, some field surveys to measure river discharge and stage simultaneously are still needed for constructing the SDR curve before the established gauging station at a cross section can be fully operational. Moreover, the stage-discharge relationship is not static but rather varies with time, since the processes of erosion and sediment deposition occurring in river channels and riverbanks can alter the shape of these channels. Therefore, a periodic check of SDR curves against the direct measurements is needed. This is yet another reason why maintaining river gauging stations is cost-, labor-, and time-intensive (Hannah et al., 2011).

In addition to the traditional stage-discharge rating curve method, the acoustic Doppler current profiler (ADCP) has evolved to be a useful tool for measuring streamflow since the 1990s (e.g., Morlock, 1996; Costa et al., 2000; Mueller, 2003; Simpson, 2001; Simpson and Oltmann, 1993; Mueller and Wagner, 2006; Oberg and Mueller, 2007; Mueller et al., 2013). The ADCP has three important advantages compared to the conventional current-meter discharge measurement: (1) the ADCP measurement is faster, (2) the ADCP can measure streamflow in highly dynamic and flood flows; and (3) the ACDP can measure continuous 3-D water velocity profiles (Hirsch and Costa, 2004). However, there are still some limitations associated with the ADCP, such as time required for post-processing data, the impact of the sediment concentrations on the accuracy of the ADCP velocity measurement, and un-measureable areas at the water surface and near the channel bed. In addition to these limitations, the ADCP's unfeasible nature of continuously monitoring discharge determines that the traditional rating curve method will still be the dominant method for continuously monitoring discharge at gauging stations around the world in the near future.

Since the 1990s, remote sensing of discharge and river stage has progressed rapidly (e.g., Smith, 1997; Alsdorf et al., 2007; Schumann et al., 2009; Pavelsky et al., 2014). Most remote sensing methods for measuring discharge and river stage published in the literature can be classified into four types: (1) estimating river stage and discharge using satellite-measured inundation area (e.g., Smith et al., 1995, 1996; Hamilton et al., 1996; Pietroniro et al., 1999; Al-Khudhairy et al., 2002; Xu et al., 2004; Zhang et al., 2004; Brakenridge et al., 2005, 2007; Temimi et al., 2005; Ashmore and Sauks, 2006; Smith and Pavelsky, 2008, 2009; Pan and Nichols, 2013; Pan, 2013; Pan et al., 2013; Cai et al., 2015); (2) measuring water surface elevation using satellite altimetry data (e.g., Koblinsky et al., 1993; Birkett et al., 2002; Coe and Birkett, 2004; Kouraev et al., 2004; Calmant and Seyler, 2006; Leon et al., 2006; Bhang et al., 2010; Jarihani et al., 2013); (3) integrating satellite observations with topographic data to determine river stage and discharge (e.g., Brakenridge et al., 1998; Bjerklie et al., 2005; Matgen et al., 2007; Schumann et al., 2008a, 2008b; Tarpanelli et al., 2013; Gleason and Smith, 2014; Gleason et al., 2014; Pavelsky, 2014; Gleason and Wang, 2015); and (4) combining satellite data and hydraulic models to compute discharge (e.g., Bates et al., 1997, 2006; Horritt and Bates, 2002; Andreadis et al., 2007; Roux et al., 2008; Durand et al., 2008, 2014; Jung et al., 2013; Domeneghetti et al., 2014).

Among these four types of methods, the first approach to estimate discharge and river stage using the satellite-measured inundation area (SMIA) is more popular and commonly used. One possible reason for this popularity is that inundation area is relatively easy to measure from space compared with altimetry point measurements of water surface elevation. Another reason is that rapid advances in optical and microwave remote sensing technology have produced a large number amount of high-resolution satellite and airborne images (e.g., QuickBird, WorldView, and GeoEye). However, the SMIA is usually used to estimate river stage first, and then discharge is determined based on the stage-discharge rating (SDR) curve. To estimate river stage from the SMIA, it is necessary to use the inundation area – river stage relationship (IARSR). Smith (1997) showed that the relationship between inundation area and water level is unique and can be used to estimate river stage. However, observed data for constructing the IARSR are often insufficient. For ungauged watersheds, river stage measurements are not available. For gauged watersheds, river stage measurements may be available, but the river stage measurements may not have been recorded on the same days as the inundation areas were measured from space.

One possible approach to construct the IARSR is to use the SMIA along with satellite-measured river stage at the same cross section measured at the same time. The inundation area is generally estimated from optical or microwave satellite imagery, and water surface elevation can be determined from satellite-borne radar or lidar data. Since inundation area and water surface elevation measurements are obtained from different satellites at times that seldom coincide, these satellite measurements cannot be used to construct the IARSR. A future satellite launch may solve this problem. NASA's Surface Water Ocean Topography (SWOT) mission, capable of measuring both water elevation and inundation area at the same time and providing invaluable data for hydrologists (Biancamaria et al., 2015; Durand et al., 2014; Pavelsky et al., 2014; Garambois and Monnier, 2015), is in the planning stage. While the SWOT mission has great potential, the satellite will not be launched until 2020, so there are still uncertainties associated with the mission. Therefore, there are two challenging problems associated with remote sensing of river stage and discharge at ungauged river cross sections using the satellite-measured inundation area: (1) how can IARSR curves be constructed without ground-based river stage measurements? and (2) how can SDR curves be constructed without ground-based river discharge measurements?

River stage refers to water surface elevation relative to a reference level known as a datum. Unlike direct satellite altimetry water surface elevation measurements, optical or microwave satellites can only provide information on the boundary between water body and dry riverbanks or the flooded area, without any direct information about water surface elevation. To utilize satellite imagery to retrieve river stage, a relationship between river stage and the boundary between water body and riverbanks or inundation area must be established first. There are several studies on this issue that established relationship between river stage and channel width (Pavelsky, 2014), or matched ground control points along riverbanks (Xu et al., 2004; Zhang et al., 2004). Since a channel width at a particular river stage is determined only by two points which are the water edges on the right and left riverbanks, the channel width approach is similar to matching ground control