Role of Land–Water Classification and Manning's Roughness Parameter in Space-Borne Estimation of Discharge for Braided Rivers: A Case Study of the Brahmaputra River in Bangladesh

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Abstract*—The proposed Surface Water and Ocean Topography (SWOT) mission will provide global, space-based estimates of water elevation, its temporal change, and its spatial slope for terrestrial water bodies. Using derivations of water slope from the Shuttle Radar Topography Mission (SRTM) elevation data, river bathymetry and Manning's equation, the potential of SWOT for discharge estimation of large braided rivers in humid climates, such as the Brahmaputra river, was found to be promising (Jung *et al.*, in *Earth Surface Processes and Landforms*, 2009). In this study we extend the work on assessing SWOT for braided rivers to understand the sensitivity of two river hydraulic parameters to discharge estimation: 1) section factor $(AR^{2/3})$ derived from land–water classification and in-situ river bathymetry and 2) Manning's roughness coefficient. For braided rivers, the first parameter, is intimately dependent on how braided rivers are classified of the multiple channels (water) and in-stream braided bars (land) that consequently dictates the accuracy of wetted perimeter and area of flow estimation from water elevation data. We show that the use of the minimum water elevation data at a river cross section minimizes estimation of section factor which consequently minimizes outlier discharge estimation reported in the Jung *et al.* [12] study. We also show that by treating roughness coefficient "flexible" as a calibration parameter, discharge estimation from SRTM elevation data can be further improved through trial and error manual optimization. Our sensitivity study illustrates the value of treating section factor and roughness coefficient as calibration parameters for data assimilation systems that use SWOT observables to estimate river discharge in braided rivers.

***Index Terms*—Braided river, discharge estimation, satellite, SWOT and SRTM, uncertainty.**

I. INTRODUCTION

THE heritage of two decades of research conducted on evaluating the potential for measuring discharge from space (e.g., Koblinsky *et al.* [13], Birkett *et al.* [6], Kouraev *et al.* [14], Frappart *et al.* [8], [9], Leon *et al.* [16], among others) has now morphed into a proposed satellite mission dedicated to space-based surface discharge measurements (Alsdorf and Lettenmaier, [1], Alsdorf *et al.*, 2003, Bjerklie *et al.* [5]). This proposed satellite mission is named the Surface Water and Ocean Topography mission (SWOT), and has been recommended by the National Research Council Decadal Survey [17] to measure ocean topography as well as water elevation over land. With a launch date timeframe around 2015, SWOT instruments in space would provide global sampling of terrestrial water bodies with average channel widths greater than 50 m, and would achieve precision of a few centimeters when averaged over $\sim 1\ \mathrm{km}^2$ of river area. The technology for SWOT is a Ka-band radar interferometer, described in detail by Alsdorf *et al.* [2]. SWOT water surface elevation measurements (h) will reveal the dynamics of temporal variations $(\partial h/\partial t)$ and spatial variations $(\partial h/\partial x)$ of water levels of a wide variety of terrestrial water bodies (lakes, rivers, wetlands) in a manner hitherto unrecorded by conventional stream gauging networks.

A braided river is a channel that consists of a network of small channels separated by small and often temporary islands called braid bars. Although braided rivers represent a minor subset of the world's river systems, they represent important water bodies for the following reasons: 1) the utility of satellite techniques for discharge estimation of braided rivers has not been fully explored; 2) braided rivers frequently shift channels during floods; thus the reinstallation of gauges and related bathymetric surveys are required frequently when using in situ methods to estimate discharge—this consequently makes ground-based discharge estimation very time consuming and expensive. It is appropriate to mention at this stage of earlier pioneering studies by previous researchers. Bjerklie *et al.* [5] carried out a study with a focus on devising a methodology to estimate in-bank discharge for single channel rivers from remotely sensed hydraulic data. Digital and aerial orthophotos were used for identifying maximum channel width and water surface width estimation. Synthetic aperture radar (SAR) images were used to extract channel slopes for the estimation of discharge using statistical relationships. Smith *et al.* [18] have also extended the applicability of SAR images for discharge estimation in ungaged basins. The effective width and discharge were correlated with a power law functions. These functions then served as rating curves for estimation of instantaneous river discharge from space. Readers are

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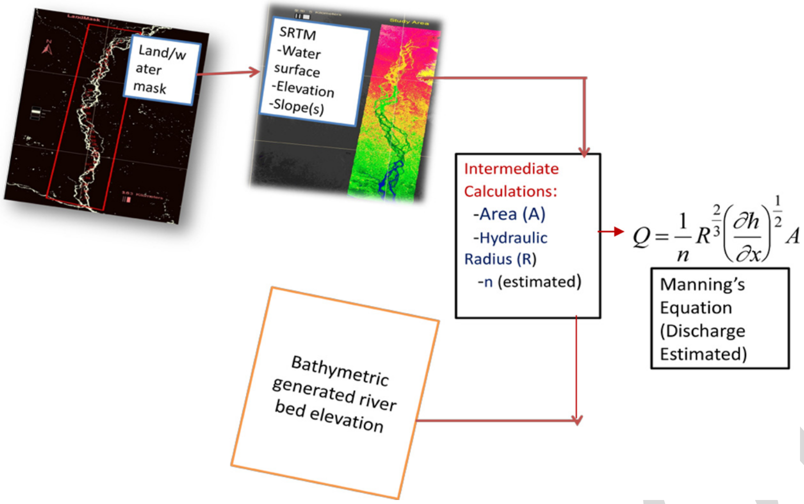

Fig. 1. Major steps followed in Jung [12] to estimate discharge: The land/water classification mask was used to create a spatial grid for associating all hydraulic parameters at their respective locations along the river reach. The SRTM DEM generated water surface slope and elevation values at all points needed. The hydraulic parameters (Area, hydraulic radius) were calculated based on these values. The Manning's equation is used to estimate the discharge at those points.

referred to a comprehensive review of previous work on space borne discharge estimation of rivers using SAR data by Smith [19].

In order to assess the utility of SWOT for discharge estimation in braided rivers, Jung *et al.* [12] recently reported a case study on the Brahmaputra river using the Shuttle Radar Topography Mission (SRTM) measurements of $\partial \mathrm{h}/\partial \mathrm{x}$. The one-time SRTM mission provided a global coverage of digital elevation data using interferometry. The proposed SWOT mission will also use radar interferometry for water level estimation at a global scale. Hence, SRTM can be considered a good analogue of the proposed SWOT mission because of certain common features. In combination with in situ bathymetry measurements, water elevation and slope, it was possible to calculate discharge from SRTM elevation data within 2.3% accuracy for the low flow (non-Monsoon) season.

Although results reported by Jung *et al.* [12] are promising at face value, there were instances of outlier discharge estimates higher than the mean seasonal flow at several river reaches. In this study we therefore extend the work on assessing SWOT for braided rivers to understand the sensitivity of two river hydraulic parameters to discharge estimation: 1) section factor $(\mathrm{AR}^{2/3})$ derived from land–water classification and in-situ river bathymetry and 2) Manning's roughness coefficient. For braided rivers, the first parameter, hydraulic radius, is intimately dependent on how braided rivers are classified of the multiple channels (water) and in-stream islands/bars (land) that consequently dictates the accuracy of wetted perimeter estimation from water elevation data. The specific question we seek to answer is *How important are hydraulic river parameters of wetted perimeter and Manning's roughness in minimizing instances of outlier discharge estimates in braided rivers using space borne elevation data?*

For the benefit of readers, we overview the analysis of Jung *et al.* [12] by reproducing their work "as is" and demonstrate first-hand the instance of outlier discharge for the case of Brahmaputra river (Section II). This is followed by an exploration of different slope profiles within the river reach in conjunction with land–water classification and bathymetry data (Section III-A). The idea in this section is to refine the estimation of section factor through more consistent separation of water elevation data from land elevation data. In Section III-B a sensitivity analysis is performed on various roughness coefficients to understand how discharge estimation is impacted. Finally, in Section IV, we present the conclusions of our study.

II. SPACE-BORNE ESTIMATION OF BRAHMAPUTRA DISCHARGE USING SRTM ELEVATION DATA

The general approach that is usually used for space-based discharge estimation from water elevation data is shown in Fig. 1. This is the same approach employed in Jung *et al.* [12] that we have reproduced here "as is". The approach can be summarized as comprising the following steps: 1) using LANDSAT data, river cross sections are delineated of the multiple streams (water) and braided bars through supervised classification against in-situ land data; 2) elevation of water pixels along the river cross section are identified from SRTM data; the slope of water surface is derived in this step; 3) using steps #1 and #2 collectively, the hydraulic radius and area of flow are calculated from in-situ bathymetry data at each river cross section; 4) Manning's equation is applied to estimate discharge at the river cross sections.

The study area is located in Bangladesh. Bangladesh is dominated by three great rivers—the Brahmaputra-Jamuna, Ganges, and Meghna—that combine to feed sediment into one of the world's largest deltas in the Bay of Bengal (Fig. 2). The "Jamuna" is the local name given to the river for its entire length in Bangladesh up to the confluence with the Ganges river. Hereafter, the word "Jamuna" is interchanged with "Brahmaputra". The Shuttle Radar Topography Mission (SRTM) provided elevation data on a near-global scale to generate the most complete high-resolution digital topographic database of Earth. The 90 m × 90 m (3 arc seconds) resolution data segments of

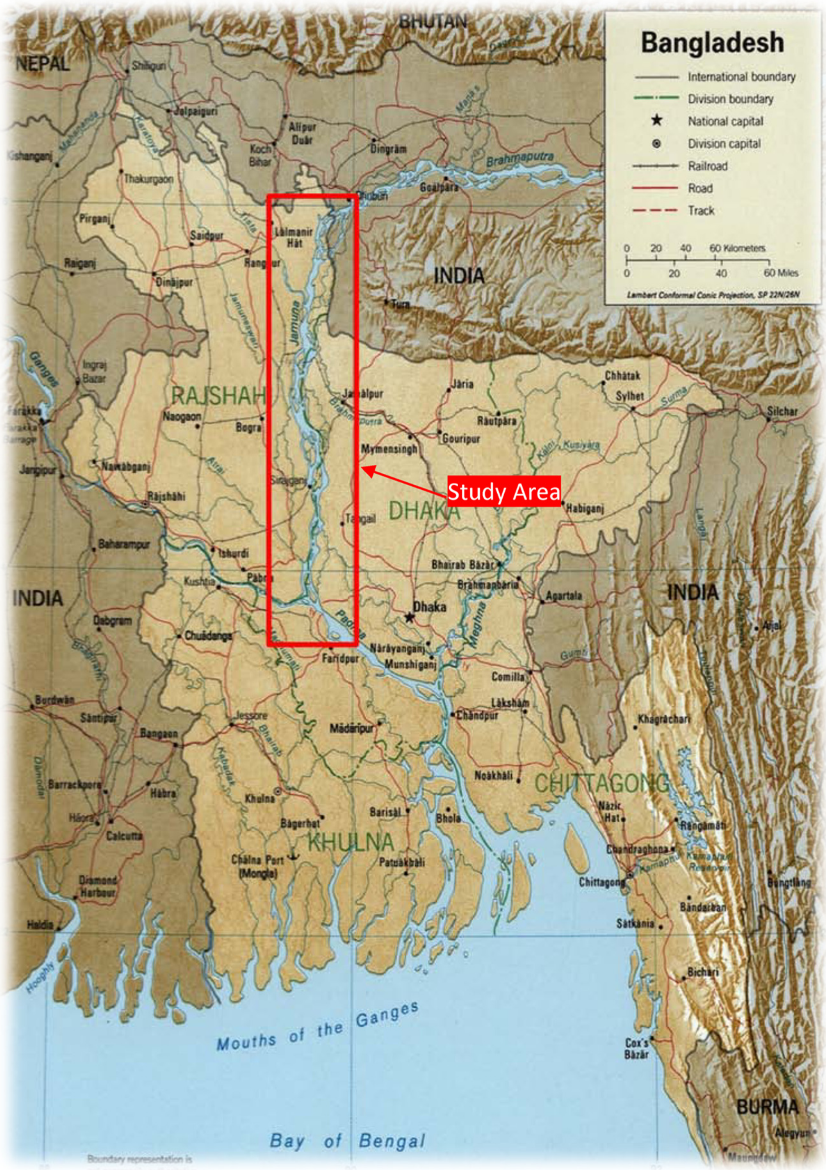

Fig. 2. Study area—the Brahmaputra (Jamuna) river (Source: www.jrcb.gov.bd).

the SRTM digital elevation model (DEM) images for the study area were captured and merged together (Fig. 3).

River bathymetry data *were* collected from the Institute of Water Modeling (IWM), Dhaka, Bangladesh. This bathymetry data are usually surveyed by coupling of Differential Global Positioning System (DGPS) and Echosounders. The sampling year of the bathymetry data was 1998–1999. There were 37 bathymetry transects along the Brahmaputra river as shown in Fig. 4. A sample river cross-section data of Brahmaputra river is shown in Fig. 5 to demonstrate the “braided” nature of the river with the presence of multiple streams and bars. Measured (in-situ) discharge data were collected from Flood Forecasting and Warning Center (FFWC), Dhaka, Bangladesh that matched as close as possible with the SRTM overpass date of February 20, 2000.

The land/water classification mask, which is necessary for delineating accurately the multiple streams and braided bars and consequently critical for estimating hydraulic parameters, was derived from two LANDSAT-7 images acquired for February 19, 2000 (similar to the Jung *et al.* [12] study). To differentiate the water bodies from land within the Brahmaputra river, the LANDSAT 7 image was reclassified using ground data to yield a binary (0–1) mask of land or water.

The Manning’s equation was used to estimate the discharge at the 37 transects. By coupling the surface water level with the river bathymetry data, the hydraulic parameters (flow area, slope, and hydraulic radius) that are required as input to Manning’s equation were derived. However, because the SRTM elevation data do not explicitly identify any given pixel as water or land, the land–water classification mask derived from LANDSAT imagery was used to extract water elevation data from SRTM data as a function of river reach length or flow distance (see Fig. 7). Next, to estimate the water surface slope, a line was fitted to the water surface elevation data vs.

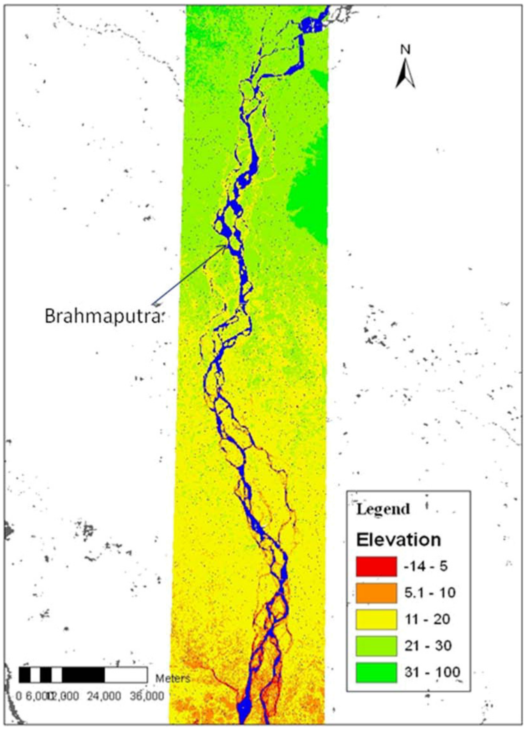

Fig. 3. The extent of SRTM DEM used in the study The various elevation value ranges within the study area are indicted by different colors ranging from 0 m to 150 m (above mean sea level).

flow distance in Fig. 7. A polynomial of several orders (1st degree–5th degree) was fitted to these points. Since all the polynomial lines represented almost similar goodness of fit, the first degree polynomial, similar to Jung *et al.* [12], was used to represent the water surface elevation.

The water surface slope was then determined in the same way by the polynomial fit. According to LeFavour and Alsdorf [15], the minimum reach length required to determine river slope was given by: $\text{Reach Length}_{\text{minium}} = 2\sigma/\text{Slope}_{\text{minium}}$, where σ is the standard deviation from the mean. The slope of the first-degree polynomial was deliberately made to represent the minimum slope for the Brahmaputra river because the measurements were from the yearly low flow (non-monsoon) stage. The result of the computation implied that a minimum reach length of 160 km can be represented by a single linear fit while for lengths greater than 160 km two linear fits yielded more realistic slope values. This allowed for a more accurate slope estimate for the whole reach by accounting for the variable nature of slope along the river reach. In this study, the downstream half was best fit with a first degree line having a slope of 7.4 cm/km while the upstream half was best fit with a first degree line having a slope of 8.5 cm/km (Fig. 8).

The hydraulic radius (R) and cross sectional area of flow (A) were calculated from the knowledge of bathymetric elevation and water surface elevation. Area of flow was obtained using the trapezoidal method and two bed slopes were used. For the braided silty sand Brahmaputra river a value of 0.025 was used as a Manning's roughness coefficient to reproduce estimates by

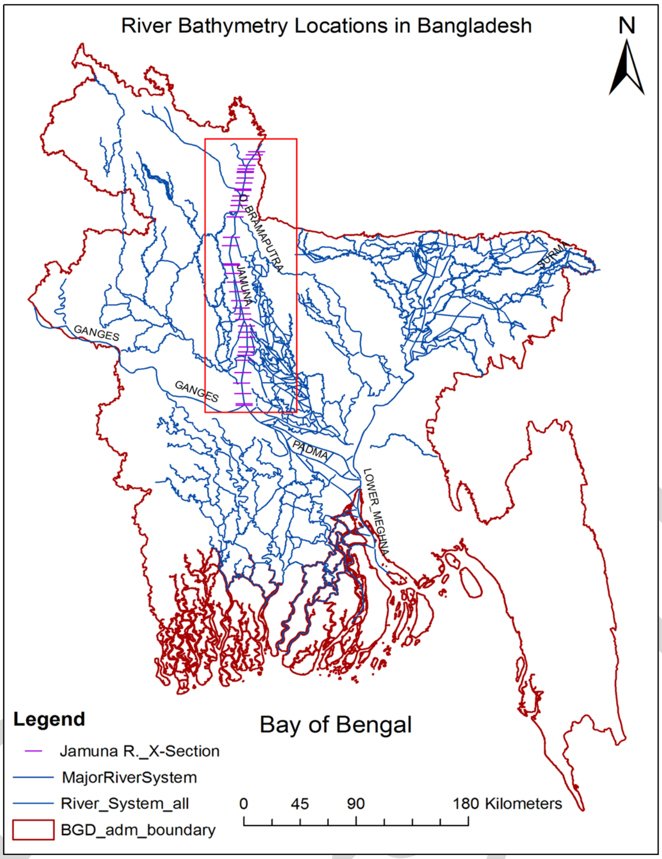

Fig. 4. Brahmaputra (Jamuna) river bathymetry locations sampled by Institute of Water Modeling (Bangladesh). Discharge was estimated for these 37 locations using the river bed elevation information from sampled bathymetry and water surface slope values generated from the SRTM data.

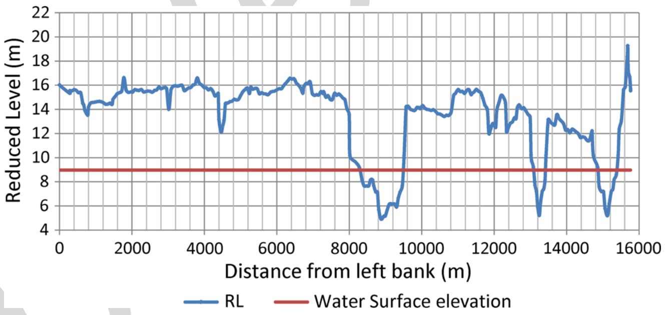

Fig. 5. A typical river cross-section showing the braided nature of the Brahmaputra River at 92 km upstream of the confluence with Ganges (Fig. 2). RL represents reduced level derived relative to a local benchmark point called Public Wares Department (PWD) benchmark.

Jung *et al.* [12]. Finally, our reproduction of discharge estimates from SRTM elevation data for Brahmaputra river by Jung *et al.* [12] is shown in Fig. 9. It can be seen clearly from this figure that there are three distinct outliers (shown as crossed out in figure). These outlier discharge estimates exceed mean seasonal flow by a factor of about 4–5, and will probably be a more pervasive issue for SWOT for braided rivers during the high flow season. We call these outliers "anomalous" because of the sudden and steep drop in discharge estimates immediately downstream of these locations. In the next section, we report our sensitivity

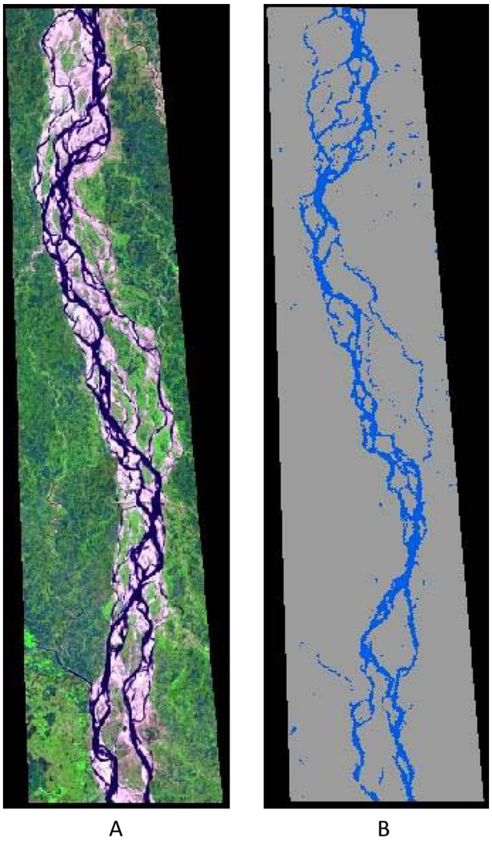

Fig. 6. LANDSAT-7 land/water classification mask used in the study.

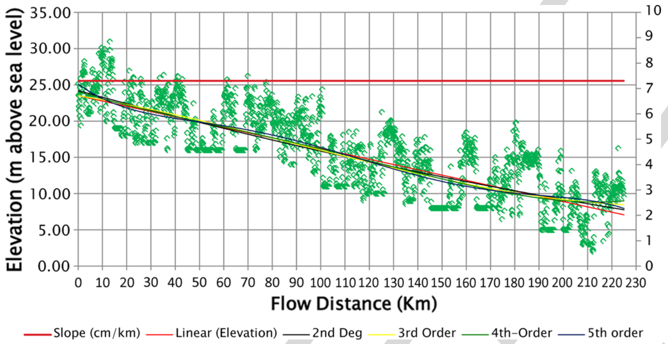

Fig. 7. Polynomial fit to water level elevation vs. length. For different orders (1st degree–5th degree) a polynomial line was fit for the given data points from SRTM.

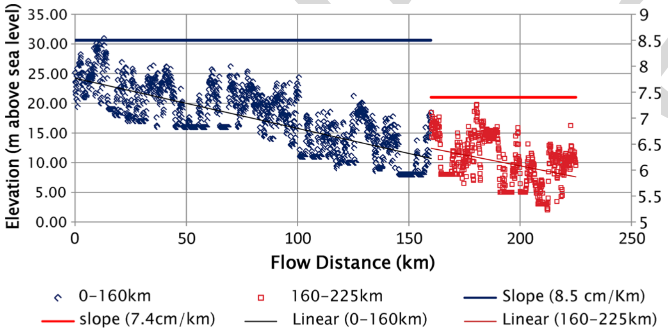

Fig. 8. Water surface elevations (on left vertical axis) with two first degree fit lines. A slight decrease in river slope (shown on right axis) occurs in the downstream segment of the river which is leveraged in this study.

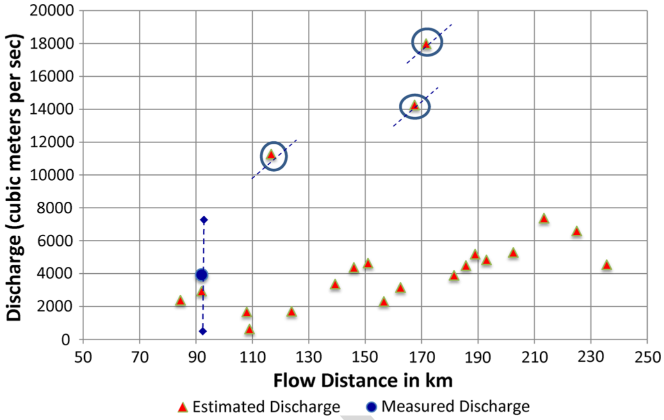

Fig. 9. The result of the discharge estimation “as is” according to Jung *et al.* [12] is shown. The three outliers between flows distances of 110 km–190 km are shown as crossed out.

study of two hydraulic parameters with the specific aim of eliminating such outlier estimates.

III. SENSITIVITY ANALYSIS OF HYDRAULIC PARAMETERS

A. *Refinement of Section Factor Calculations*

We first explored the effect of the land water classification mask on the observed anomalies (outliers) on discharge estimates in Fig. 9. Looking at these outliers in Fig. 9, it is clear that the most likely cause for severe overestimation is probably due to overestimation of either hydraulic radius or slope or both. Because the hydraulic radius computation for braided rivers is intimately linked to delineation of channels (as water) and braided bars (as land) that impacts derivation of wetter perimeter and area of flow, we focused on hydraulic radius as the primary proxy of section factor and a source of the discharge anomalies.

First, the land/water classification mask and the LANDSAT image out of which the mask was produced were analyzed to observe the locations of the outliers and see if the anomaly was the result of discrepancy in the mask to meticulously identify land and water. Fig. 10 shows both the mask and the LANDSAT image. It is evident from the figure that at the location of outliers on the river reach, the LANDSAT image is not meticulously represented in the mask since some water portions of the LANDSAT is represented as land in the classification mask. In addition to that, the mask only identifies water and land but doesn’t explicitly identify the features of the land with respect to the actual topography. Further supervised classification might have revealed those points as inhabited islands relatively higher elevation than the surrounding bathymetric points. Therefore, these wrongly classified braided regions may have contributed to an abrupt rise in the elevation values. If these pixels are mistakenly classified as water, then the hydraulic radius and section factor calculation is likely to be overestimated.

A more rigorous filtering of the elevation values was therefore made by further classifying the SRTM elevation data across the 37 river transects. We used the following data filtering methods: 1) minimum elevation, 2) most frequent elevation, 3) average elevation, and 4) average elevation first

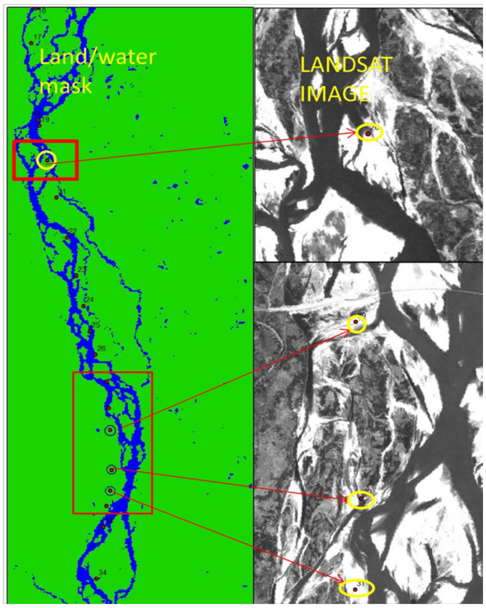

Fig. 10. The left panel representing the land (green color) and water (blue color) is extracted from the LANDSAT image (right panel) by image classification schemes. Location of the three bathymetry transects along the river reach (between 110 km–190 km of flow distance) where discharge measurement is severely overestimated leading to outliers as shown in the lower red box in lower left panel. The upper red box represents the location of the gauging station at Bahadurabad.

removed of highs (see Figs. 11 and 12). The motivation for this filtering technique stemmed from the reasoning that the water level along a river cross section should be fairly uniform during the low-flow season and thus, one uniform elevation value for water level should be used for derivation of hydraulic radius at a given cross section. Fig. 11 shows the polynomial trends that were fitted to the different elevation filtering to derive the slope of water level along the river reach. Although variation in elevation values at different points along the reach is observed for the various categories, the water surface slope represented was within the range of 8.8 cm/km to 9.5 cm/km (8.84 cm/km in this case), which is somewhat higher than the slope values previously used by Jung *et al.* [12]. Fig. 12 shows that the discharge computed using slope and hydraulic radius derived from the filtering scheme of “minimum” water elevation (across a transect) represents a far superior estimation of discharge. The anomalous estimates are reduced and the overall agreement with observed discharged is also improved (Fig. 12).

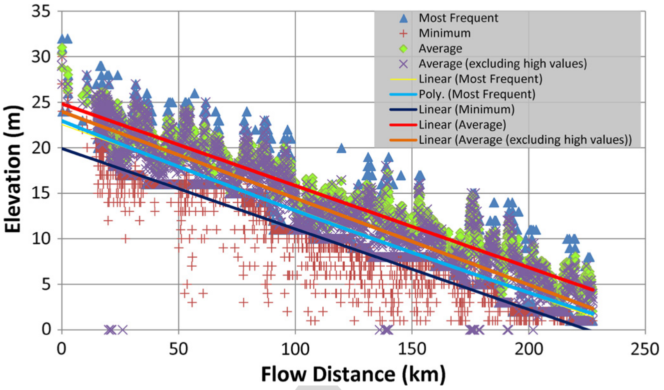

Fig. 11. Modified elevation value records after data filtering at the river cross sections to identify the most representative hydraulic parameters for the estimation of discharge.

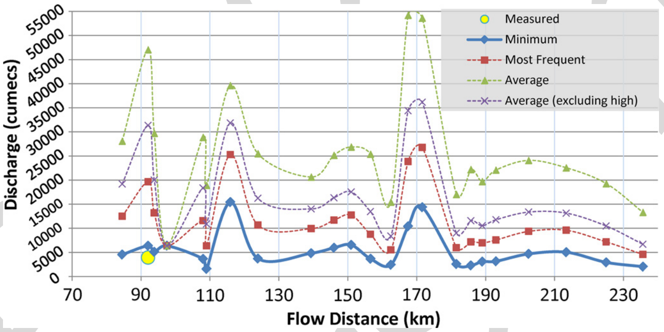

Fig. 12. Corresponding discharge estimates for each elevation data filtering scheme shown in Fig. 11 using a Manning’s roughness value of 0.025.

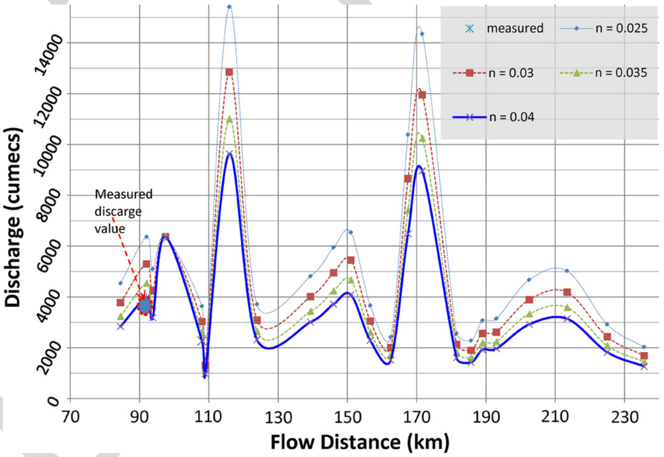

Fig. 13. Sensitivity of discharge estimate for various Manning’s roughness values with a Manning’s n value of 0.04 showing the closest agreement to measured value.

B. Manning’s Roughness Coefficient

As noted earlier, the discharge was computed by using Manning’s roughness value of 0.025 which is a fairly representative value for silt-bed rivers like Brahmaputra. Lack of sufficient discharge gauging stations along the Brahmaputra (only one station at “Bahadurabad” in the study area) made it difficult to automatically optimize (or calibrate) by using this single discharge value. Hence, in this case, we first carried out a sensitivity analysis of the section factor (AR2/3) to observe the variation downstream and make sure the plausibility of the A and R data at the outlier locations. As it is shown on Fig. 14(a) and (b), a similar type of pattern like that of the discharge is observed at the outlier and all other locations of the bathymetry. Since it is reasonable to assume that there can be flaws in the bathymetric measurement, the possibility of high bias in the estimation of discharge at these locations is not unlikely. Moreover, the A and R values depend on the width of the channel which is extracted from the land–water mask; this makes the issue of explicitly determining the width very crucial. The elevations values at the points of the bathymetry station are indicative of the wetted perimeter and the area. It is evident that these elevations are higher at the outlier locations. It follows that a minor misrepresentation of the surface water elevation or land–water classification can result in an enormous overestimation of discharge. This can be further

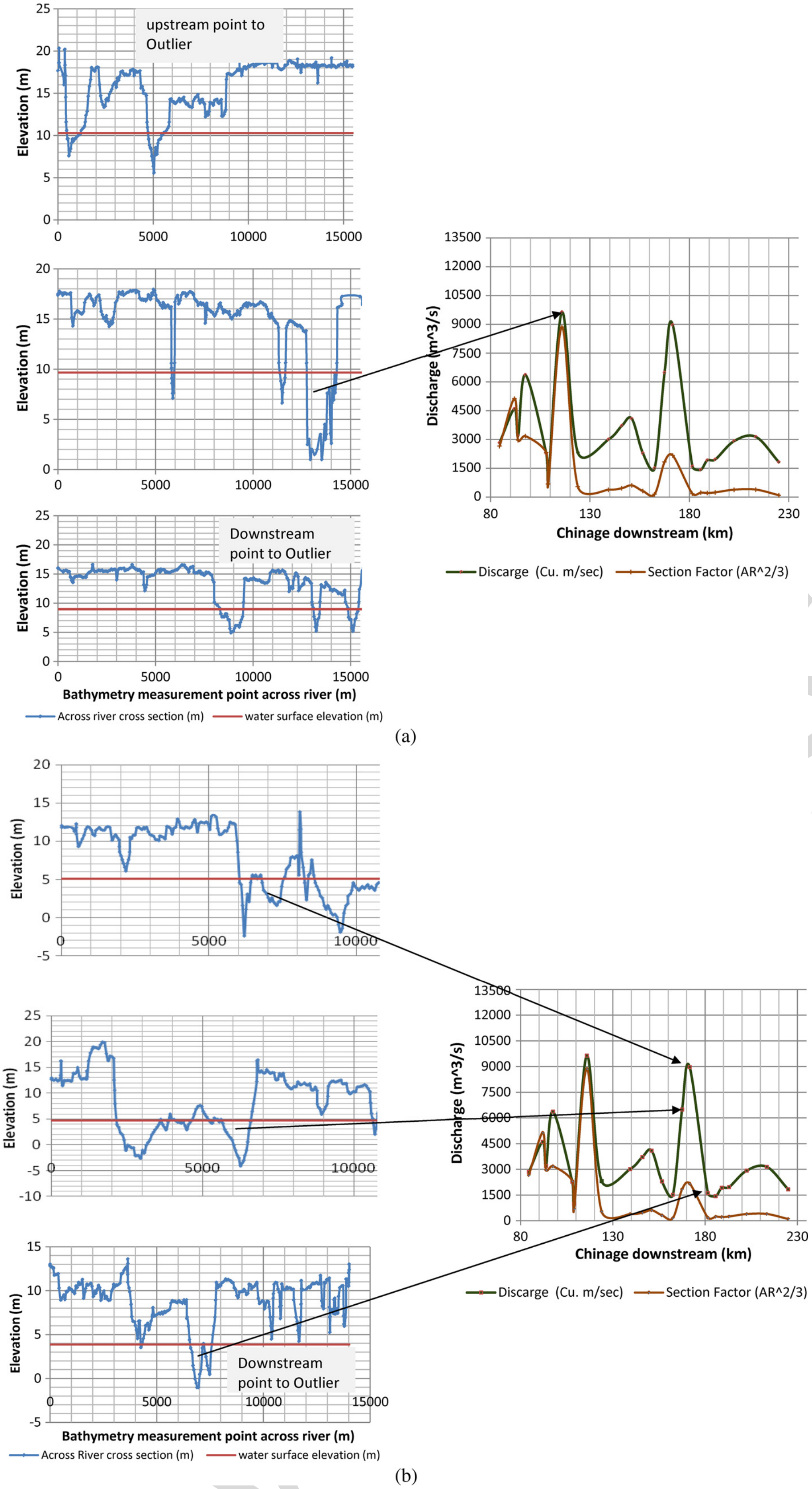

Fig. 14. (a) and (b): Right panel—variation of the section factor $(\mathrm{AR}^{2/3})$ along the river reach (units in $\mathrm{m}^{8/3}$); left panels—the respective river bathymetric elevations to observe the variation of bathymetric readings upstream, at and downstream of the outliers.

attributed to the extraction of elevation values from the SRTM (vertical noise of approximately ±5 m as well as the delineation of the water body from the land–water mask.

Next, we carried out a sensitivity analysis with respect to Manning’s roughness value by varying it within the allowable range from 0.01 to 0.04. The idea behind doing this was to minimize the overestimation of the discharge that is observed in Fig. 13. The figure shows more accurate estimates of discharge when a Manning's n of 0.04 is used along with our refined choice of water elevation data discussed in 3.1. The three outlier estimates are significantly reduced and modified to levels comparable to expected flow at those locations. It is therefore evident that a properly calibrated roughness value combined with modified hydraulic radius computations can significantly minimize the chances of an outlier estimate for braided rivers whenever it is not possible to correct the errors posed by the remote sensing observations. Our revised estimate is also within 1.3% of the measured value at the gauging station location (compared to 2.3% reported by Jung *et al.* [12]).

IV. CONCLUSION AND RECOMMENDATIONS

This study was performed to demonstrate potential improvements in estimation of discharge for braided rivers for SWOT where outliers will likely be very pervasive at certain river cross sections not accurately classified of the multiple streams and islands. Our sensitivity study indicates that the use of a consistent minimum water elevation as a filtering technique at river cross sections minimizes estimation uncertainty of section factor which consequently minimizes anomalous discharge estimation. Our study also showed that by treating roughness coefficient "flexible" as a calibration parameter, discharge estimation from SRTM elevation data can be further improved through trial and error manual (or automatic) optimization.

The broader impact of our sensitivity study is on flood forecasting of transboundary flow by downstream nations in large international river basins (such as Bangladesh in the Brahmaputra basin) where real-time information on discharge in the upstream transboundary regions can significantly increase forecasting lead time [10]. For such international basins (that comprise about 40% of the earth's land mass), space-borne methods are the only viable alternative to overcome the paucity of in-situ measurements and the lack of agreement for data sharing among riparian nations (Balthrop and Hossain [4], Hossain [11]). Our study shows the value of treating hydraulic radius and roughness coefficient as calibration parameters for data assimilation systems that use SWOT observables to estimate river discharge in braided rivers. In today's data assimilation systems for continuous prediction of river discharge from space-borne observables, hydrology and river hydraulics models forced with surface and/or satellite observations are used to model surface water profiles, and then corrected as satellite observations on water elevation become available (Durand *et al.* [7], Andreadis *et al.* [3]). Subsequently, the most recently updated predictive model is fed forward to estimate discharge for the time step (prediction or forecasting). In such data assimilation systems, treating roughness and water elevation across a river cross section as state-space variables will tremendously reduce the occurrence of outliers in SWOT discharge estimates for braided rivers.

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