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Inter-comparison study of water level estimates derived from hydrodynamic–hydrologic model and satellite altimetry for a complex deltaic environment

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ABSTRACT

Riverine deltas are hydrologically one of the most active terrestrial bodies supporting an intricate network of rivers, a highly unsteady flow regime, high agricultural productivity and large population centers. Understanding the complex hydrology of riverine deltas is challenging due to the paucity of conventional ground-based measurements on river water levels and flows that result in large spatial and temporal sampling gaps. One way to bridge this sampling issue is to employ hydrodynamic models in combination with remotely-sensed water level elevation data from satellite altimetry in a data assimilation framework. However, a good understanding of the performance of models and altimetry is required beforehand. Using Bangladesh as an example of a complex delta, an inter-comparison study was therefore performed for water level estimates derived from the two methods: 1) satellite altimetry and 2) hydrodynamic–hydrologic modeling framework. The Envisat mission was selected for satellite altimetry-based water level data. For the modeling framework, a calibrated 1-D hydrodynamic model, HEC-RAS, was set up for the major rivers of Bangladesh using in-situ river bathymetry, gaged stream flow and water level data. Envisat water level estimates were generally found to be exceeded by the model-based values by 0.20 m and 1.90 m for Monsoon and dry seasons, respectively. In general, the average RMSE between Envisat and modeled estimates is more than 2.0 m. The closest agreement with altimetry was observed during the high flow Monsoon season over the Brahmaputra river. Envisat estimates are found to disagree most with model-based estimates for small to medium-sized river basins that are mountainous and flashy. This inter-comparison study provides preliminary guidance on the relative weights to assign for each type of estimate when designing a data assimilation scheme for optimal water level prediction in ungaged basins.

1. Introduction

Riverine deltas are landforms created where the river drains into an ocean, estuary or lake. The sediment deposition over long periods of time makes deltas hydrologically one of the most active terrestrial bodies. Some of the unique hydrologic features are: 1) intricate network of rivers resulting in high drainage density; 2) low spatial gradients of stream flow that gives rivers a tendency to overflow into floodplains during the wet season; and 3) highly unsteady water regime in the delta created by fast flowing upstream boundary conditions and tidal changes in downstream estuary. The easy availability of fresh water and fertile soils has resulted in most of the world's deltas hosting large population centers, complex irrigation systems and a water sensitive eco-system. This is especially true for Ganges–Brahmaputra–Meghna (GBM), Mississippi, Niger, Senegal, Okovango and Mekong deltas. Today, deltas provide livelihood to about half-billion people around the world. More than 200 million people live inside the humid deltas where many of the world's mega cities (e.g., Dhaka, Bangkok, and Karachi) continue to withdraw water at an unsustainable rate (Vörösmarty et al., 2009).

Given how intimately water supports large population centers, agricultural productivity and the fragile eco-systems, an accurate understanding of the terrestrial hydrology is key to achieving sustainable water resources development in riverine deltas. However, three specific issues make this understanding of hydrology very difficult: 1) because most riverine deltas are located at the downstream most end of international river basins, these deltas require basin-wide hydrologic measurements from upstream nations that are often unavailable (Hossain and Katiyar, 2006) or declining (Shiklomanov et al., 2002); 2) the extremely low spatial gradients demand detailed two-dimensional knowledge of river structure for hydrodynamic modeling of the low-energy stream flow (Paudyal, 2002); and 3) increasing human impoundment of upstream rivers makes prediction inside the downstream deltas by stand-alone hydrologic models difficult (Vörösmarty et al., 2009; Hossain et al., 2009).

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One way to overcome the aforementioned challenges is to make optimal use of water level estimates available from proxy (non-direct) sources. Two such sources that are more widely accessible than gaged in-situ hydrologic data are: 1) space-borne estimates of river water level from altimetry; and 2) physically modeled water level estimates from a hydrodynamic–hydrologic modeling framework. Satellite altimetry has progressed considerably over the last decade to become a viable alternative over ungaged basins for many hydrologic applications (e.g., Birkett, 1995, 1998; Schumann et al., 2009). On the other hand, simulation of water level dynamics at very close spacing along the river reach is possible using a hydrodynamic model ingested with river flow simulated by a calibrated hydrologic model and precipitation that is usually more widely available than gaged stream flow data (Montanari et al., 2009). These water level simulations can then be frequently merged with space-borne estimates of water levels to maximize water level detection accuracy within a data assimilation framework (Schumann et al., 2009; Neal et al., 2009). One such data assimilation scheme that is widely used in water level prediction is the Kalman filter (Andreadis et al., 2007). This scheme requires the estimate of the covariance matrices of the difference between the truth and the forecast and the difference between the truth and the observation. A good understanding of how the water level estimates from altimetry and hydrodynamic approach compare to each other can therefore help accurately approximate these covariance matrices for Kalman filter scheme.

It has already been reported that the use of wide-swath interferometry (such as the Shuttle Radar Topography Mission, SRTM) and satellite radar altimetry (such as JASON-1/2, Envisat) hold promise (Lee et al., 2009; Birkett, 1998) for modeling the low spatial gradient rivers that are common in deltaic environments (Woldemichael et al., 2010; Alsdorf et al., 2007; Andreadis et al., 2007; Durand et al., 2008; Smith and Pavelsky, 2008). However, there has not been, to the best of our knowledge, a comprehensive inter-comparison study of satellite altimetry for river level detection with model-based estimates where physical complexities (tidal flow in the estuarine region and high velocity flow in upstream) and institutional challenges (lack of gaged flow and water level data from upstream transboundary regions) may limit the individual effectiveness of each data type.

This study performed an inter-comparison study between the satellite altimetry mission, Envisat, and a hydrodynamic-modeling approach in detecting river water levels in deltaic environments. A calibrated 1-D hydrodynamic model, HEC-RAS, was set up for the major river network of Bangladesh delta using in-situ river bathymetry, gaged stream flow and water level data. The specific questions this study asks are *What is the level of agreement between satellite altimetry derived and hydrologic–hydrodynamic model simulated water stage data? How does this agreement vary as a function of season and basin type?*

It may be appropriate to mention at this point that satellite altimetry-based and hydrodynamic model-based elevation data originate from fundamentally different methodologies and data backgrounds. We recognize that for a fair and balanced comparison, one should strive to 'reformat' these two datasets to a common level that uses the same extent of background information (for example, satellite altimetry do not use gaged water level information for calibration unlike the hydrodynamic model based approach). While the lack of a consistent background may raise concerns, which are understandable, we would also like to emphasize that there is no convincing reason to believe that such an inter-comparison would not be useful, given the greater potential of each data when used in conjunction with the other in an assimilation system (Montanari et al., 2009; Neal et al., 2009, Schumann et al., 2009).

This study is organized as follows. Section 2 describes study region, data and methods used in this study. Section 3 dwells on the calibration and validation of the 1-D hydrodynamic model using in-situ river bathymetry and a hydrologic model to generate water level simulations at very close spacing. Section 4 summarizes the comparison of water levels between Envisat and HEC-RAS as a function of basin type, season (flow regime) and detection capability for varying thresholds. Finally Section 5 summarizes the general findings and future directions of research.

2. Study region, data and methods

2.1. Study region

The Bangladesh delta was chosen as the study region. Extensive in-situ hydraulic and hydrologic data were available to the authors through a Memorandum of Understanding (MOU) with the Institute of Water Modeling (IWM) of Bangladesh and Tennessee Technological University (TTU). Bangladesh is also a representative case of the world's riverine deltas faced with the three common hurdles outlined earlier (see Fig. 1). For example, most of the river flow (>90%) entering Bangladesh (which comprises about 7% of total Ganges–Brahmaputra–Meghna–GBM-basin area) is generated in upstream regions of India and Nepal. The lack of a data sharing treaty or basin-wide ground instrumentation means that flow data in transboundary regions is unavailable at timescales of operational forecasting (daily) (Balthrop and Hossain, 2010; Hossain, 2007). One of the rivers, the Ganges, is already impounded immediately upstream of the India–Bangladesh border (Fig. 1), wherein the regulated nature of flow during the dry season limits the effectiveness of stand-alone hydrologic models to predict flow downstream into Bangladesh. Inside Bangladesh, a dense drainage network comprising more than 300 rivers, make the delta one of the most riverine in the world (Fig. 1). Although these hurdles are experienced in most of the river deltas around the world (e.g. Niger, Senegal, Okovango, Mekong and Nile), the availability of high resolution and quality controlled hydrologic datasets inside Bangladesh make our selected study region a good test-bed for an inter-comparison study.

2.2. Data

The data used in this study were of two types: 1) in-situ data comprising river cross section (bathymetry) and water stage data; 2) remotely sensed water level data from the Envisat altimeter mission. Extensive river bathymetry data from 226 cross sections was used for the setting up of the hydrodynamic model HEC-RAS for the major rivers of Bangladesh. Fig. 1 provides a map of the rivers Ganges, Jamuna (local name for Brahmaputra), Old Brahmaputra, Surma, Padma and Meghna (estuary) for which HEC-RAS was set up. Fig. 2 shows sample bathymetry data of a river. Bathymetry data were measured from left bank to right bank across the river by coupling of Differential Global Positioning System (DGPS) and Echosounder. The distance from left bank (x) and bed level (z) was incorporated as a tabular form in the HEC-RAS model (Fig. 2).

The bed level for bathymetry was referenced with respect to the Public Works Datum (PWD) of Bangladesh, which is established by the Department of Public Works, Bangladesh. The PWD datum is 0.46 m below the Mean Sea Level (MSL) datum. Collected bathymetry data were entered in the model according to the survey chainage for each schematized river (discussed next in Section 2.3 under Methods). Measured water stage data was available from the Bangladesh Water Development Board (BWDB) at daily time step for five river locations in Bangladesh (Fig. 1). Each of these locations provided unique insights about the flow regime and was therefore ideal for comparing Envisat with modeled estimates as a function of basin type and flow regime. Gaged water stage measurements were available for regulated flow (Ganges), high velocity and steep gradient flow (Brahmaputra/Jamuna), tidal flow (Lower Meghna) and flashy–mountainous flow (Upper Meghna) (Fig. 1).

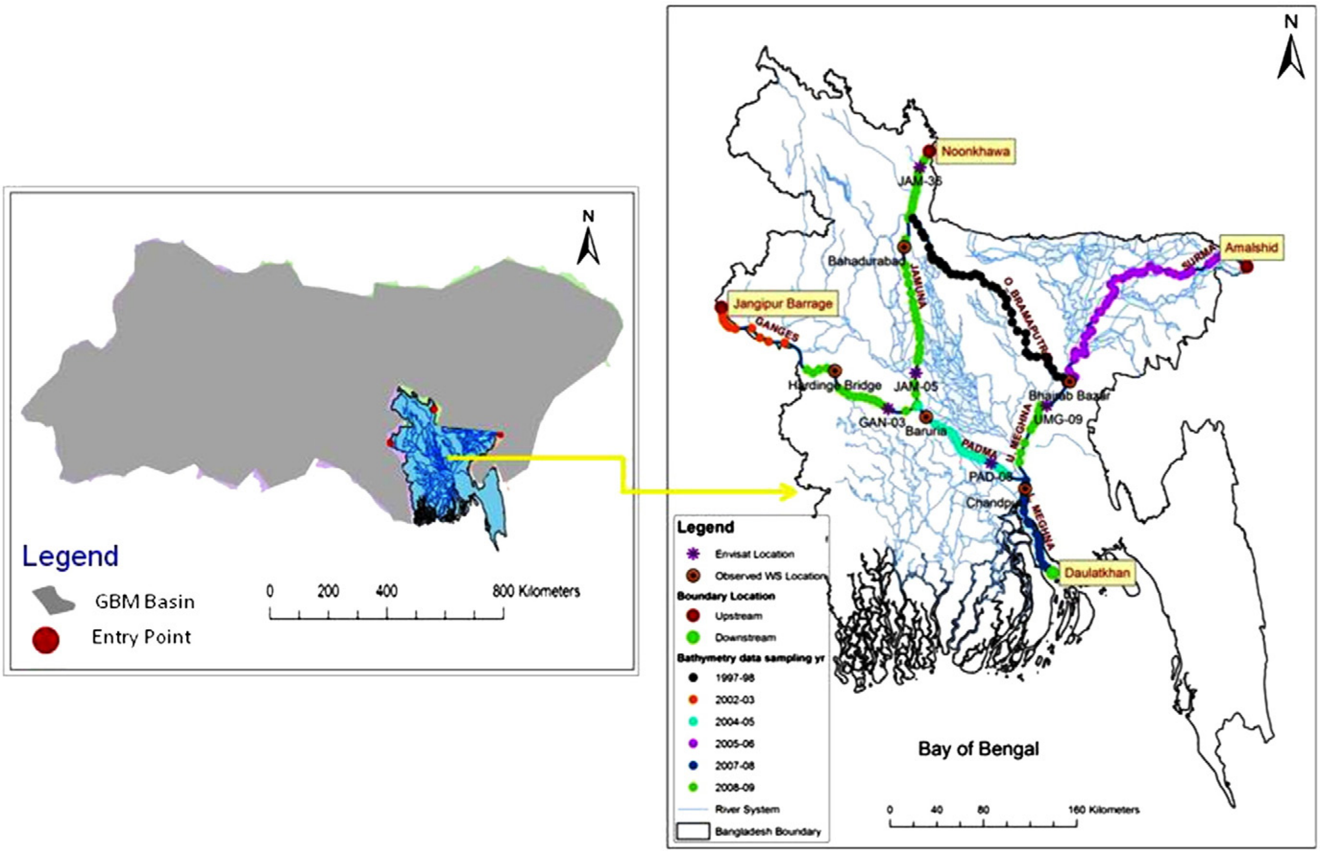

Fig. 1. Left panel — Bangladesh river delta as the study region. Bangladesh is a representative example of world's humid deltas with all the common hurdles of upstream flow regulation, transboundary nature of flow (red circles indicate the entry point for transboundary flow) and intricate river network. The gray colored regions of the basin are transboundary to Bangladesh; Right panel — location of in-situ bathymetry sampling data at 226 river cross sections (with sampling year), Envisat altimeter tracks, gaged water stage data and boundary flow data for Bangladesh.

Satellite radar altimetry has been successfully used for water level monitoring over large inland water bodies such as the Great Lakes (Morris and Gill, 1994; Birkett, 1995) and the Amazon basin (Birkett, 1998; Birkett et al., 2002), which have higher chances to be processed as ocean-like return. However, a significant amount of data loss can occur during the periods of stage minima due to the

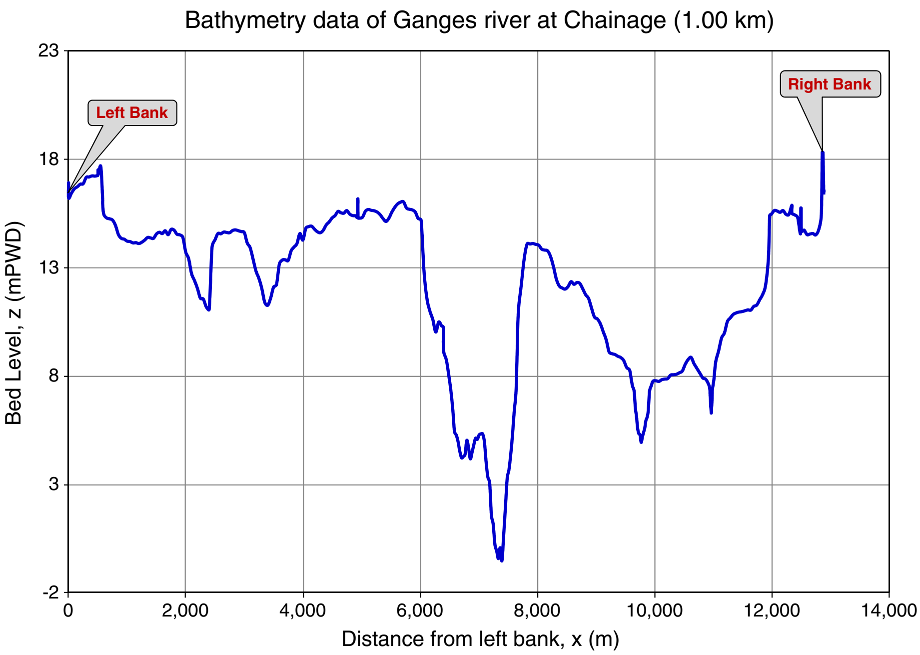

Fig. 2. Sample in-situ bathymetry data at a cross section in Ganges river at 1 km chainage. Here the location for 1 km chainage 1 km upstream of the 0 km chainage is shown in Fig. 3. The Y axis represents the elevation of the river bed with respect to the Public Works Department (PWD) datum. The PWD (datum) is at 0 m on the y axis.

interruptions to the water surface by the surrounding topography. Furthermore, the radar return from a relatively small water body can be distorted. These limitations can be partially overcome by retracking individual waveform (Lee et al., 2010, 2009). In this study, we used Envisat (**Envi**ronmental **Sat**ellite) 35-day repeat orbit 18-Hz retracked data (~350 m along-track sampling) to estimate water elevation. While there are four different retracked measurements in Envisat Geophysical Data Record (GDR) using OCEAN, ICE-1, ICE-2, and SEA ICE retrackers (Benveniste, 2002), we used the ICE1-retracked (Bamber, 1994) measurements which have been demonstrated to be the most suitable for inland water bodies among the four retrackers (Frappart et al., 2006; Lee et al., 2010) although Silva et al. (2010) recently showed that ICE-1 and ICE-2 both equally worked well over the Amazon River. Relevant instrument corrections, media corrections (dry troposphere correction, wet troposphere correction calculated by the French Meteorological Office (FMO) from the European Centre for Medium-Range Weather Forecasts (ECMWF) model, and the ionosphere correction based on the Global Ionosphere Maps (GIM)), and geophysical corrections (solid Earth and pole tides) to the Envisat range measurements have also been applied.

The Envisat mission altimeter tracks over Bangladesh are shown in Fig. 1. A point to note is that the mean river width at these tracks during the high flow Monsoon season can be anywhere from 2 to 5 times larger than that during the low flow (non-Monsoon) season. For example, this means that for Jamuna, the width can vary from 600 m (dry season) to 3000 m (Monsoon). This is an important issue to keep in mind considering that the accuracy of water level retrievals by altimetry can depend strongly on the river width at the cross track.

2.3. Methods

The period of investigation selected for this study was 2003–2005. The main hydrodynamic modeling tool used in this study was HEC River Analysis Software (RAS), developed at the Hydrologic Engineering Center (HEC), which is a division of the Institute for Water Resources (IWR), U.S. Army Corps of Engineers. This hydrodynamic modeling software allows one-dimensional steady and unsteady flow river hydraulic calculations. It contains four modules, namely steady flow water surface profile computations, unsteady flow simulation, movable boundary sediment transport computations, and water quality analysis. In this study, water surface profile computation module of HEC-RAS (version 4.0) was used to simulate daily water stage of the major rivers of Bangladesh. The basic computational procedure is based on the solution of one-dimensional energy equation. The reader is referred to Appendix 1 for further details on the hydraulic nature of water level computation in HEC RAS.

HEC-RAS was schematized at the 226 river cross section locations (Fig. 3) to allow simulation of water level dynamics at close spacing. Using chainage information from bathymetry survey, each cross section data was entered in HEC RAS schematization system. Daily flow measurements (rated from water level observations) were used at the three most upstream entry points (for each river) in Bangladesh near the India–Bangladesh border (shown in red circles in Fig. 1 as Jangipur Barrage, Noonkhawa and Amalshahid). For the downstream boundary, HEC-RAS was forced with measured tidal water stage data at the most downstream point named Daulatkhan on the Lower Meghna river close to the Bay of Bengal (see Fig. 1).

Having set up HEC-RAS and forced it with observed water stages, daily simulation of water level was carried out for the period of 2003–2005 at the 226 river cross sections. It is important to note that the water level simulations by HEC-RAS are essentially a daily 'average' while Envisat estimates are instantaneous at a specific over passing time. Because steady state water level computations were performed for each day in HEC RAS, we assumed that any temporal mismatch (instantaneous versus model predicted average) would be negligible. Also, because Envisat mission generated and HEC-RAS model simulated water stage data were not in same datum, Envisat water stage data needed to be converted to the same datum as HEC-RAS

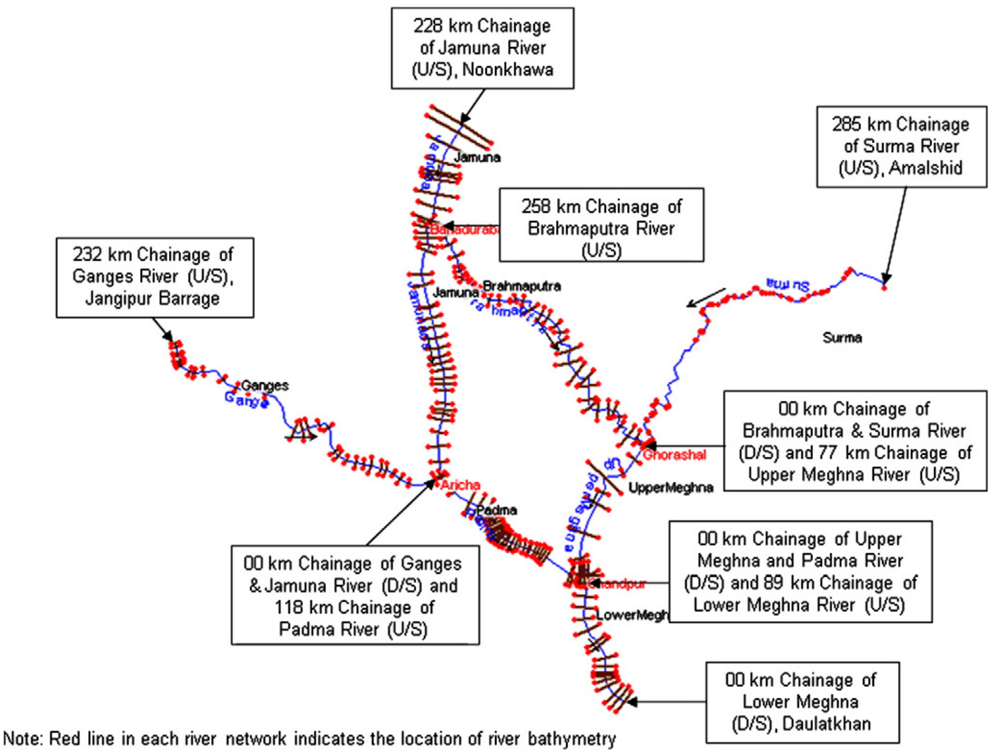

Fig. 3. Schematization of the 226 river cross sections with measured bathymetry sampling data for HEC-RAS using chainage information.

water stage data (i.e., the PWD datum used in Bangladesh for gaging water stage). The methodology used for the datum conversion is described in Appendix 2 and is based on the computation of anomalies.

For the sake of inter-comparison, 'error' was defined as the scalar difference between water stage data from Envisat and HEC-RAS, although it should be borne in mind that both are essentially estimates. As a reminder to readers, the purpose of this study was to explore the variability of one data type relative to another. Later (in Section 3), the various hydrologic implications and the potential for using both these estimates to better flow prediction will be discussed. Various inter-comparison metrics for Envisat and model estimated water level were made, namely; mean error, root mean squared error (RMSE), correlation and Probability of Detection (POD).

For POD computation, first a threshold water level value was defined to compute the 'hits' and 'misses'. If the absolute difference between Envisat and HEC RAS water level (i.e., degree of agreement) remained within the threshold, then the event was termed a 'Hit' (H). If the difference exceeded the threshold, the event was termed a 'Miss' (M). Five thresholds (tolerance) water levels (0.25 m, 0.5 m, 0.75 m, 1.0 m, 1.25 m, and 1.5 m) were chosen. With the Hits and Misses defined, POD was then computed as follows,

$$\text{Probability of Detection, POD} = \frac{H}{H+M} (\text{worst} = 0, \text{ ideal} = 1) \quad (1)$$

3. Model calibration and validation

The Manning's roughness coefficient (n) and the coefficient of expansion/contraction (k) were set as key HEC-RAS parameters to calibrate. Fig. 4 shows an example of a sensitivity analysis for calibration of roughness for the Jamuna river. It can be observed that simulated water stage converges to the observed water stage with a systematic selection of the n-value, showing that model calibration of roughness can improve the accuracy of model simulation significantly. Based on such sensitivity analysis, calibrated n-values were selected for each schematized river section (see Table 1). Values of 0.10 and 0.30 were kept as universal coefficient of contraction and expansion losses, respectively, for the entire HEC-RAS modeling domain. According to the HEC-RAS Hydraulic Reference Manual (available at: http://www.hec.usace.army.mil/software/hec-ras/documents/hydref/), these values are very typical for large rivers.

Table 1
Calibrated Manning's n-value for schematized rivers in HEC RAS.

SL	River	n-value		
		Left Bank	Channel	Right bank
1	Jamuna	0.022	0.020	0.022
2	Brahmaputra	0.022	0.020	0.022
3	Padma	0.020	0.018	0.020
4	Ganges	0.020	0.018	0.020
5	Lower Meghna	0.027	0.025	0.027
6	Upper Meghna	0.027	0.025	0.027
7	Surma	0.012	0.010	0.012

The output of the HEC-RAS model is shown against observed water stage data in Fig. 5a, b, c and d at locations where river stage measurement was gaged using ground instrumentation of BWDB. For the Jamuna river, the HEC-RAS model simulated water stage was in close agreement with the observed data, with slight overestimation of the flood waves (Fig. 5a). Although a close agreement was observed for the Ganges river, HEC-RAS had a tendency to slightly overestimate the peaks (Fig. 5b). For the Padma river (at a location downstream to Ganges), HEC-RAS simulated small tidal-like oscillations that observed water level did not seem to experience. This could be an effect of upstream propagation of the tidal flow in lower boundary in HEC-RAS simulation. However, the general trend was well picked by HEC-RAS (Fig. 5c). For Lower Meghna river, slight overestimation of the peaks and underestimation of the low flow was observed in simulated water stage (Fig. 5d). Overall, the RMSE against gaged water level data was found to be around 1 m. A point to note herein is that a similar assessment of Envisat against gaged water level data was not possible as none of the gaging station locations matched closely with the altimeter tracks. The altimeter track closest a gaging station is about 40 km apart (on Padma river, see Fig. 1).

4. Results and discussion

Envisat derived water level estimate was compared with HEC-RAS simulated water levels at the four altimeter tracks over Ganges, Upper

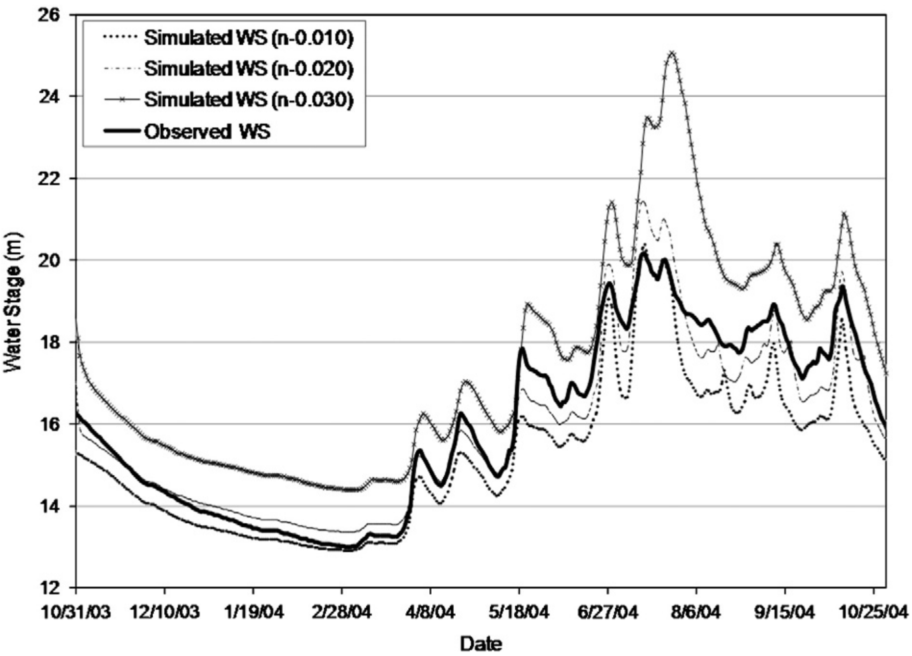

Fig. 4. Sensitivity analysis of n-value at Jamuna river (chainage 151 km in Fig. 3) with respect to observed and simulated water stage data.

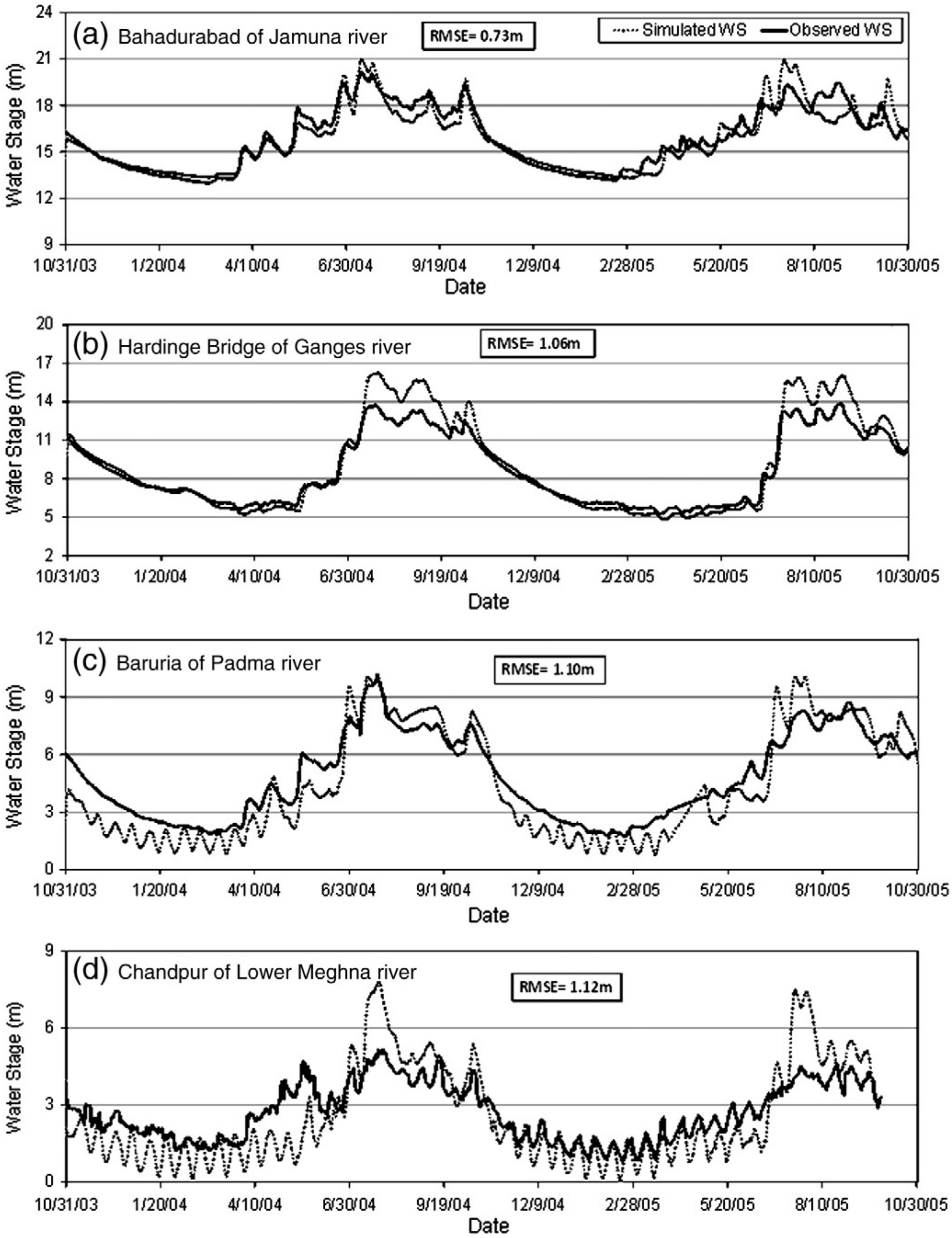

Fig. 5. Plot of HEC-RAS simulated and observed (gaged) water stage data (at four locations — see Fig. 2) for the period of October 31, 2003 to October 31, 2005.

Meghna and Jamuna (Fig. 6). For Jamuna river, where there are two Envisat tracks, comparison with the upstream most track near Noonkhawa is shown (for location of altimeter tracks refer to Fig. 1). Although the trends (rising and recession limbs) of the hydrograph match well, there is a general tendency for Envisat to underestimate water level during a rising flood event and overestimate during a receding flood event when compared to modeled estimates. This discrepancy is seen to be the highest for the highly flashy Meghna river followed by the regulated Ganges river.

Table 2 summarizes the overall inter-comparison as a function of basin type and season (low-dry season and high-Monsoon season). It confirms that the agreement of Envisat is generally higher for the flooding season (Monsoon; June–September) than the dry season (October–May). Perhaps the regulation of flow (or lack of it) explains the high (or low) uncertainty in detecting water levels for Ganges (or Brahmaputra) river. Flow regulation, which HEC-RAS model set up accounted for by using the actual flow measured immediately downstream of the Ganges impoundment, can make water levels more random (less steady) on the specific days of the Envisat overpass. Another plausible reason may be that the Brahmaputra is a high flow velocity river on a steeper gradient, making flow often times more supercritical during the Monsoon season. Consequently, the water level fluctuations are considerably less (and hence resulting in higher agreement with HEC RAS data) for the same amount of discharge change compared to the Ganges or Meghna rivers. The low degree of agreement for Meghna basin indicates that Envisat may not be appropriate for assimilation with model estimates for optimal water level detection in flashy and mountainous regions with its 35-day repeat pass.

In the previous section, it was noted that HEC-RAS had a general tendency to overestimate water levels during high flows and underestimate during low flows. Given that Envisat water level estimates could not be directly validated against observed water level as the cross tracks did not coincide with the available gaging stations, it cannot be

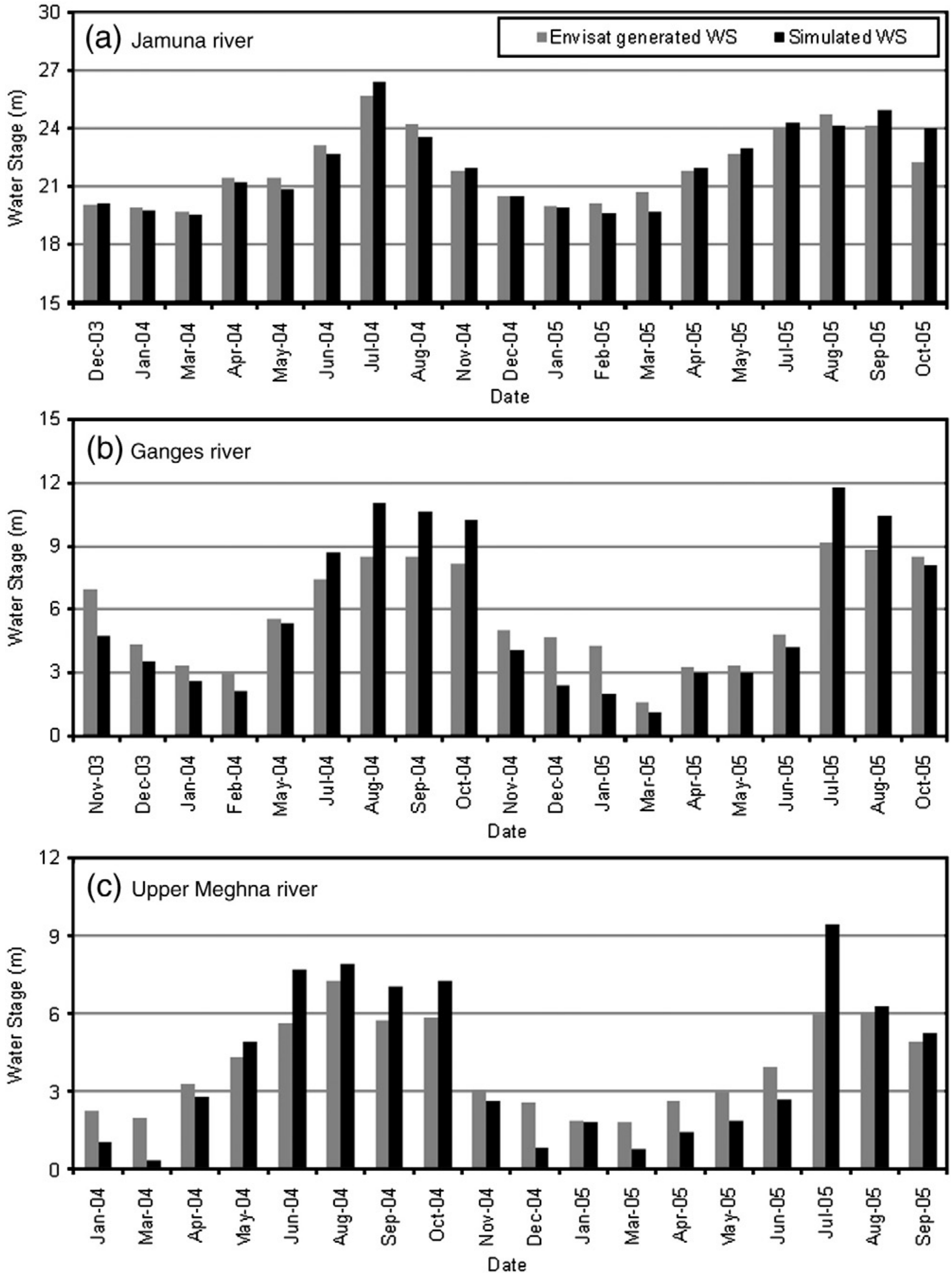

Fig. 6. Comparison of Envisat generated river water level with HEC-RAS simulated water levels at three altimeter tracks (a) — Jamuna (near Bahadurabad) (b) — Ganges and (c) Upper Meghna.

established categorically in this study that Envisat would follow a similar trend for low and high flows (under and overestimation) as HEC-RAS. In fact, there is always a possibility that Envisat may have the ability to detect water levels better during the low flow (and narrow river width)

Table 2
Inter-comparison of Envisat and HEC-RAS water level data as a function of basin and season. Here, 'error' is defined for the sake of inter-comparison as the scalar difference between Envisat and HEC-RAS data (i.e., Envisat–HEC RAS).

Basin/season	Mean error (m)	RMSE (m)	Correlation
Brahmaputra Basin	−0.09	0.67	1.00
Ganges Basin	−1.20	2.35	0.85
Meghna Basin	−2.35	2.76	0.91
Monsoon Season	−0.23	1.72	0.98
Dry Season	−1.90	2.38	0.99

scenarios as Envisat appears to overestimate compared to HEC-RAS during the low flows. Such overestimation by Envisat (from HEC-RAS) may offset the underestimation by HEC-RAS (from observation) to yield more accurate water level detection during the non-Monsoon season by Envisat. Such a possibility needs to be considered for constraining water level predictions by a hydrodynamic model in a data assimilation framework.

Table 3 summarizes the comparison of Envisat with HEC RAS in terms of POD. If the margin of agreement (i.e., threshold) is relaxed beyond a 1.5 m depth of water level, Envisat has about 65% chance of agreeing with modeled estimates within that threshold for the Brahmaputra river. Meghna river has the lowest POD followed by Ganges, while the Monsoon season experiences more success for the river water level by Envisat to match with HEC RAS compared to the dry season. However, for a lower margin of agreement (or threshold) of 0.25 m, Envisat agrees with HEC-RAS for about 30% of the overpasses while for other rivers, this

Table 3
Joint probability (POD) that the water level detected by Envisat is equal or not exceeded by a threshold value from the water level detected by HEC-RAS.

Threshold value (m)	POD value				
	Brahmaputra basin	Ganges basin	Meghna basin	Monsoon	Dry season
0.25	0.30	0.10	0.05	0.14	0.20
0.50	0.38	0.17	0.05	0.24	0.22
0.75	0.50	0.20	0.05	0.33	0.24
1.00	0.58	0.24	0.11	0.41	0.29
1.25	0.63	0.34	0.16	0.49	0.35
1.50	0.65	0.34	0.21	0.51	0.37

agreement is lower (Table 3). Naturally, considerable care should be exercised when merging altimeter estimated water level with model estimates for optimal water level detection.

Given that the comparison of Envisat in terms of POD is dependent on the threshold (or agreement) level assigned, a controlled simulation study was performed to translate the error in water level estimates to error in estimated discharge (or vice versa). This was done by systematically increasing or decreasing the observed flow values in HEC-RAS at the three entry (upstream boundary) points of the model domain (Jangipur barrage, Noonkhawa and Amashid). The corresponding change in average water level for each river reach was then quantified as a function of the change in the upstream boundary condition flows. This flow versus water level relationship is an important behavior to identify because satellite altimetry techniques measure space-borne observables that are directly related to the water level and not related to discharge. Fig. 7 shows how this relationship varies for the Jamuna, Ganges and Surma rivers. In general, a given % of mismatch in water level detection between the two data types translates to at least twice as much % of mismatch in flow estimation. The Jamuna river is seen most sensitive to mismatch in water level detection with a 1% mismatch in water level equating to about a 5% mismatch in flow estimation. Overall, such a relationship is expected to provide guidance on the design of an assimilation scheme based on altimeter water level data.

5. Conclusions

Understanding the complex hydrology of riverine deltas is challenging due to the limitations of conventional ground-based measurements on river levels and flows. An inter-comparison study was therefore performed for water level estimates derived from two competing methods: 1) satellite altimetry and 2) hydrodynamic–hydrologic modeling approach. The Envisat mission was selected for satellite altimetry-based water level data. For the modeling framework, a calibrated 1-D hydrodynamic model, HEC-RAS, was set up for the major rivers of Bangladesh using extensive in-situ river bathymetry, stream flow and gaged water level data.

Generally, the likelihood of an in-situ water level gaging station matching closely in location with the altimetry tracks is very low even for the most instrumented basins. Hence, given the considerably lower RMSE of HEC-RAS estimates against gaged water level data (~0.70 m–1.20 m) and considerably higher RMSE between HEC-RAS and Envisat (0.70 m–2.40 m), this study indicated that model estimates from a calibrated set up may be an alternative for benchmarking inland altimetry data where in-situ gaging is not available for the high flow Monsoon season. For the low flow season, there is a possibility that the overestimation by Envisat (from HEC-RAS) may offset the underestimation by HEC-RAS (from observation) to yield more accurate water level detection during the non-Monsoon season by Envisat. Such a possibility needs to be considered when using Envisat estimates for constraining water level predictions by a hydrodynamic model in a data assimilation framework.

The highest level of agreement between Envisat and HEC RAS was observed for high flow Monsoon season for the Brahmaputra basin. As a rule of thumb, the conditions ripe for optimal merging of Envisat data with modeled estimates in a deltaic environment may be generalized as 'wet season with unregulated and steep gradient river flow in humid deltas.'

Our study findings have implications for the proposed Surface Water and Ocean Topography (SWOT) mission, which will be dedicated to space-based surface discharge estimation (Alsdorf et al., 2007). SWOT has been recommended by the National Research Council Decadal Survey (NRC, 2007) to measure ocean topography as well as water elevation over land. With a launch date timeframe around 2020, SWOT main payload, a wide swath interferometric altimeter, 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 ~1 km^2 of river area. Given that SWOT accuracy, precision and sampling frequency would represent a significant improvement over current nadir and pulsed-limited altimeters, a

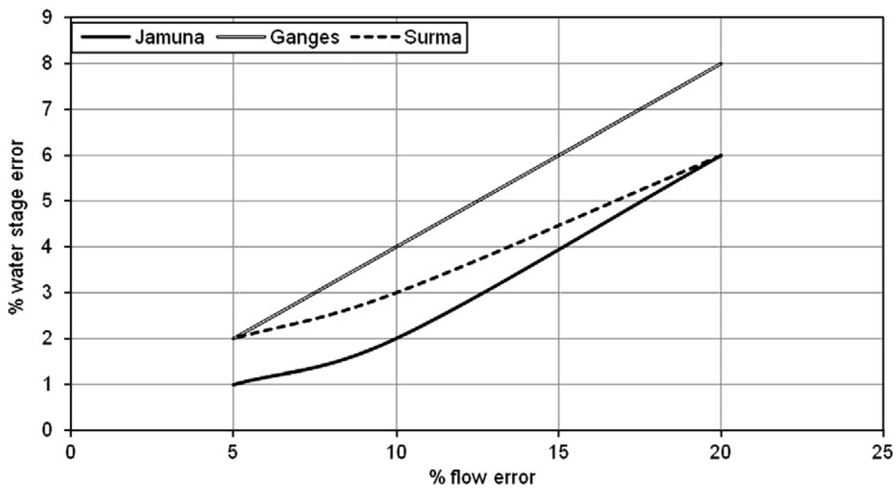

Fig. 7. Relationship between relative mismatch in water level and flow estimates between Envisat and HEC-RAS, respectively. Here the mismatch is termed as 'error'. [note: Surma is the local name for the main river in the Upper Meghna basin that is flashy and mountainous].

key area of research would now be to understand how effectively SWOT measurements can be assimilated in a hydrologic–hydraulic framework for routine estimation of flow and water levels in complex deltaic environments.

As a first cut, a natural extension of this work is therefore to extend the HEC-RAS setup over the entire 300+ rivers (small and large) in Bangladesh for which there exists more extensive in-situ bathymetry data. Such a set up would increase the number of altimeter cross tracks for inter-comparison as a function not only of season or basin type, but also of river morphology (river width, bed slope, drainage area, depth of river bed etc.). Consequently, a statistically more rigorous understanding can be achieved on the combined use of SWOT elevation data with modeled estimates from a hydrodynamic–hydrologic framework in the Bangladesh study region. Work is under way along this direction and we hope to report it in a future publication.

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Appendix 1. Water level computation in HEC-RAS

HEC-RAS (version 4.0) is currently capable of performing one-dimensional water surface profile calculations for steady gradually varied flow in natural or constructed channels. Subcritical, supercritical, and mixed flow regime water surface profiles can be calculated. The basic computational procedure is based on the solution of the one-dimensional energy equation.

Energy losses are evaluated by friction (Manning's equation) and contraction/expansion (coefficient multiplied by the change in velocity head). The momentum equation is utilized in situations here the water surface profile is rapidly varied. These situations include mixed flow regime calculations (i.e., hydraulic jumps), hydraulics of bridges, and evaluating profiles at river confluences (stream junctions).

The energy equation is,

$$Z_2 + Y_2 + a_2 V_2^2 / 2g = Z_1 + Y_1 + a_1 V_1^2 / 2g + h_e, \qquad (A-1)$$

where:

Z_1, Z_2 elevation, Y_1, Y_2 = depth of water, V_1, V_2 = average velocities
a_1, a_2 velocity weighting coefficients, g = gravitational acceleration
h_e energy head loss

$$h_e = LSf + C\left[a_2 V_2^2 / 2g - a_1 V_1^2 / 2g\right] \qquad (A-2)$$

where,

L discharge weighted reach length
S_f representative friction slope between two sections and
C expansion/contraction loss co-efficient

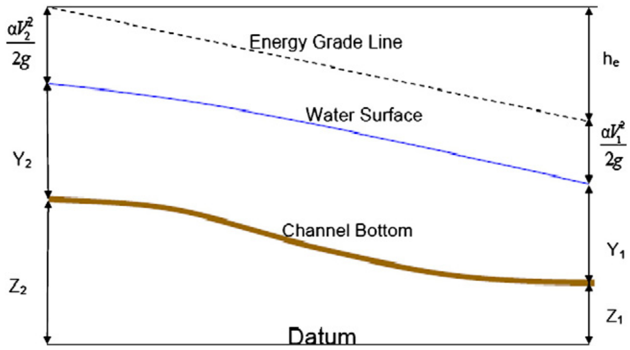

Fig. A.1. Representation of terms in the energy equation.

Conveyance calculation is done by Manning's equation: discharge, $Q = KS_f^{1/2} = Co/n^*AR^{2/3}S_f^{1/2}$, where: K = conveyance for subdivision, Co = 1 for metric units, and 1.486 for English units, n = Manning's roughness coefficient for subdivision, A = flow area for subdivision, R = hydraulic radius for subdivision (area / wetted perimeter), S_f = slope between two cross-sections.

Appendix 2. Methodology for datum conversion of Envisat elevation data

Envisat generated and model simulated water stage data is not in same datum. So, it is very important to establish a "reference level" to bring Envisat generated water stage data to the same datum of simulated (HEC-RAS) water stage data. For reference level estimation, mean value of the Envisat generated water stage data were deducted from mean value of simulated HEC-RAS water stage data. This reference value (equivalent to the HEC-RAS–Envisat anomaly) was then added to Envisat generated water stage data to convert Envisat water stage data to the same datum (PWD datum) of HEC-RAS simulated water stage data. A sample reference level estimation of Envisat generated water stage data is shown in Table A2.1.

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Table A2.1
Reference level estimation of Envisat generated water stage data of Jamuna river (chainage: 219 km).

Date	Simulated water stage (m)	Mean of simulated stage (m)	Envisat generated water stage (m)	Mean of Envisat generated water stage (m)	Reference level (m)	Envisat generated water stage w.r.to the datum of simulated water stage (m)
C1	C2	C3 = mean of C2	C4	C5 = mean of C4	C6 = C3–C5	C7 = C4 + C6
12/22/2003	20.13	22.02	−31.84	−29.92	51.94	20.10
1/26/2004	19.80		−32.01			19.93
3/1/2004	19.55		−32.24			19.70
4/5/2004	21.24		−30.53			21.42
5/10/2004	20.84		−30.47			21.48
6/14/2004	22.68		−28.83			23.11
7/19/2004	26.43		−26.25			25.70
8/23/2004	23.59		−27.76			24.19
11/1/2004	21.99		−30.16			21.79
12/6/2004	20.49		−31.48			20.47
1/10/2005	19.91		−31.99			19.96
2/14/2005	19.62		−31.82			20.13
3/21/2005	19.70		−31.21			20.74
4/25/2005	21.98		−30.15			21.80
5/30/2005	23.01		−29.28			22.66
7/4/2005	24.31		−27.85			24.09
8/8/2005	24.15		−27.23			24.72
9/12/2005	24.97		−27.78			24.17
10/17/2005	24.04		−29.67			22.27

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