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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).