Proof of Concept of an Altimeter-Based River Forecasting System for Transboundary Flow Inside Bangladesh

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***Abstract*—Recent work by Biancamaria *et al.* (*Geophysical Research Letters*, 2011) has demonstrated the potential of satellite altimetry to forecast incoming transboundary flow for downstream nations by detecting river levels at locations in upstream nations. Using the Ganges-Brahmaputra (GB) basin as an example, we assessed the operational feasibility of using JASON-2 satellite altimetry for forecasting such transboundary flow at locations further inside the downstream nation of Bangladesh by propagating forecasts derived from upstream (Indian) locations through a hydrodynamic river model. The 5-day forecast of river levels at upstream boundary points inside Bangladesh were used to initialize daily simulation of the hydrodynamic river model and yield the 5-day forecast river level further downstream inside Bangladesh. The forecast river levels were then compared with the 5-day-later "nowcast" simulation by the river model based on *in-situ* river level at the upstream boundary points in Bangladesh. Results show that JASON-2 retains good fidelity at 5-day lead forecast with an average RMSE (relative to nowcast) ranging from 0.5 m to 1.5 m and a mean bias (underestimation) of 0.25 m to 1.25 m in river water level estimation. Based on the proof-of-concept feasibility, a 4 month-long capacity building of the Bangladesh flood forecasting agency was undertaken. This facilitated a 20-day JASON-2 based forecasting of flooding during Aug 1, 2012 to Aug 20, 2012 up to a 5 day lead time in a real-time operational environment. Comparison against observed water levels at select river stations revealed an average error of forecast ranging from –0.4 m to 0.4 m and an RMSE ranging from 0.2 m to 0.7 m. In general, this study shows that satellite altimeter such as JASON-2 can indeed be an efficient and practical tool for building a robust forecasting system for transboundary flow.**

***Index Terms*—Brahmaputra, forecasting, Ganges, JASON-2, satellite radar altimeter, transboundary flow.**

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I. Introduction

Surface water does not flow according to political boundaries. It flows only according to the topographic limits and along gradients of the land surface. Yet more than 260 river systems of the world are subject to international political boundaries [39]. These basins are known as International River Basins (IRBs) and they have transboundary rivers flowing from one nation to another within the basin before draining to a lake or an ocean. A total of 145 countries are geographically part of an IRB, which represents more than 40% of the Earth's land mass [39].

Forecasting of transboundary flow in downstream nations of these IRBs however remains notoriously difficult due to the lack of basin-wide *in-situ* hydrologic measurements or its real-time sharing among nations. This difficulty is exacerbated by a combination of poor ground infrastructure and poor institutional capacity to manage water resources jointly among riparian nations [3]. Survey indicates that about 33 such downstream countries have more than 95% of their territory bounded within IRBs [15], [16], making such countries heavily dependent on hydrologic data from not just within their borders but also beyond from upstream nations. While transboundary river flooding represents only 9.9% of all recorded flood events, they account for 32% of all casualties, almost 60% of affected individuals, and 14% of financial damage [3]. The disproportionate relationship between occurrence and impact of transboundary floods can often be traced to the lack of real-time communication between countries on rainfall and stream flow data that are essential for flood monitoring [4].

Bangladesh, like several flood prone nations in IRBs around the world, represents one such classic example, where transboundary flow accounts for more than 90% of the surface water during the Monsoon season, and its operational forecasting capability remains severely limited to only a 3 day lead based

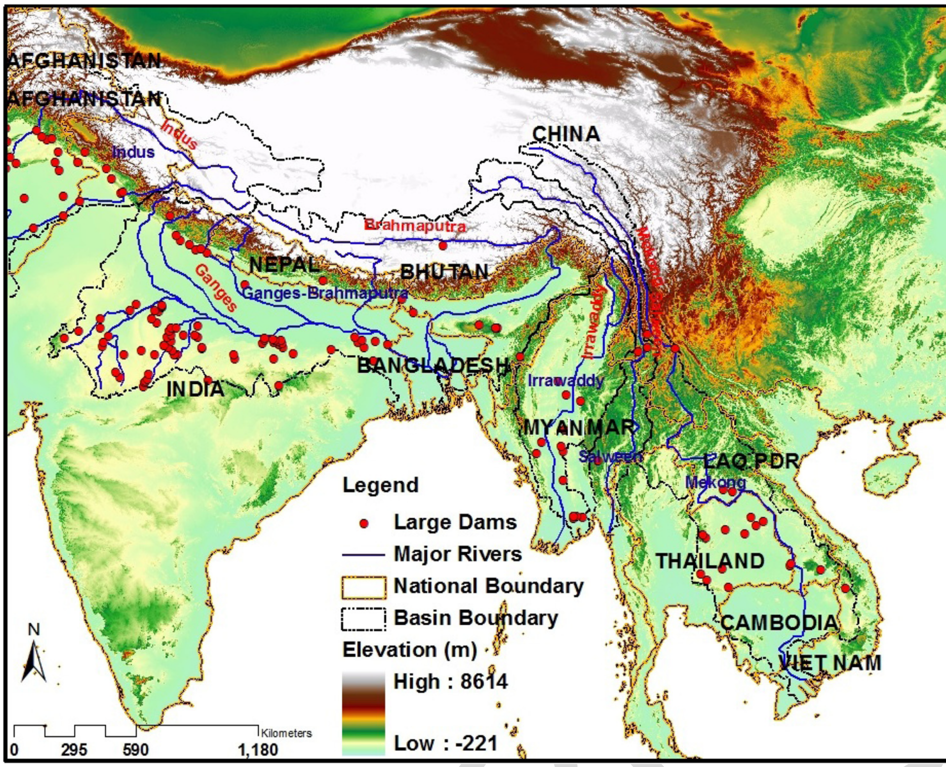

Fig. 1. Bangladesh as the low lying downstream-most nation of the Ganges-Brahmaputra basins. Red circles denote location of large dams or barrages that divert or regulate flow in the basins. The information on dams was obtained from the GranD dam database available at http://www.gwsp.org/85.html.

purely on persistence (Fig. 1). Two specific issues make the extension of the lead time difficult: 1) because Bangladesh occupies only 7% of the total drainage area of the Ganges-Brahmaputra (GB) basins, 90% or more of the required spatial coverage of hydrologic data is controlled by the upstream nations of India and Nepal [31]; and 2) increasing human impoundment of rivers by nations upstream of Bangladesh makes conventional forecasting based on standalone hydrologic and atmospheric/climate models very difficult (see Fig. 1 for location of dams) [17], [34], [36].

Recent studies, however, have shown that a combination of satellite estimates of rainfall and modeling can forecast stream flow in Bangladesh [29], [30]. Such studies collectively provide a very useful platform to address emerging challenges to forecasting dictated by the increasing impoundment of rivers upstream of flood-prone downstream nations. For example, as a low lying delta, Bangladesh is most vulnerable to unilateral human activity by the upstream nations, such as extraction, diversion and dam impoundment of river waters (Fig. 1). Some pertinent examples are the Farakka barrage on the Ganges (commissioned in 1976), and the recently revived Indian River Linking Project (IRLP) [28]. Such diversions stand to make persistence-based or hydrologic model-based forecasting less effective without prior knowledge of the day-to-day flow regulation schedule from India. Other notable and man-made issues are the plans by the Chinese Government to impound the Brahmaputra River in Tibet [14].

Thus, human intervention through extensive upstream flow regulation will likely be a critical factor in future that will control the downstream forecasting accuracy, no matter how well the forecasting system adequately represents the natural dynamics of atmospheric and terrestrial flows. However, if satellites could provide a proxy way of timely monitoring the upstream regulation of flow, such as estimating river level behind a dam or barrage, then the accuracy of a downstream forecasting system could be preserved at tactical timescales (days to weeks) of decision making. Using NASA/CNES TOPEX/POSEIDON (T/P) satellite altimetry measurements of water levels in India, Biancamaria *et al.* [5] have demonstrated exactly this point. Their work has revealed that it is feasible to practically forecast water elevation anomalies (i.e., fluctuations) during the critical Monsoon season (June to September) near the Bangladesh border. The T/P-based forecasting scheme reported a Root Mean Squared Error (RMSE) of about 0.40 m (0.6–0.8 m) for lead times up to 5-days (10 days) without having to rely on any upstream *in-situ* (gauge) river-level data. The need to extend forecasting lead time has a strong motivation from the standpoint of preventing loss of life and economic damages [1], [3].

Satellite-based flood forecasting is also important for gauging the societal value of the planned future NASA/CNES satellite hydrology mission called the Surface Water and Ocean Topography (SWOT). The body of research over the past two decades on evaluating the feasibility of measuring discharge from space (e.g, [6], [23], [26], among others) has now culminated in the planned SWOT mission dedicated to space-based surface discharge measurements using the concept of water elevations and slope [2]. With a launch date timeframe around 2019, SWOT's nadir Ka-band altimeter and wide-swath interferometric altimetry has an aim to provide global sampling of surface water elevations to derive discharge and water storage change for rivers with widths greater than 50 m, at an accuracy of a few centimeters when averaged over $\sim 1\ \text{km}^2$ of river area [2]. In particular, for the humid tropics (the focus of our study), where most of the world's populous delta nations (in international river basins) are located, the planned 22-day (maximum) repeat sampling of SWOT will provide at least two observations in three weeks over these humid tropics (see http://swot.jpl.nasa.gov). An innovative aspect of SWOT will be the estimate of water surface elevation and slope from the 120-km-wide swath interferometric altimeter (known as KaRIn, Ka-band Radar Interferometer) to measure the hydraulic gradient line of river flow. Combined with an estimate of the river width and the inundated area of flow that will also be available, SWOT represents currently the only space mission planned exclusively for discharge estimation over land.

It is important at this stage to briefly review the state of the art of river discharge estimation from a remote sensing perspective. Discharge can be estimated by utilizing the one of commonly extractable physical variables from space-borne observables, such as: 1) water level (height) change by radar altimeters (e.g., [2], [5], [22]); 2) river width/inundated area by passive microwave (PMW) sensors (e.g., [7], [9], [10], [20], [35]; see also http://floodobservatory.colorado.edu/IndexMapweb.htm); and 3) slope of water level change (e.g., [2], [18], [25], [38]). The slope-based techniques have only been assessed against Shuttle Radar Topography Mission (SRTM) measurements of water elevations over a small sampling period of 11 days in the year 2000.

Our study is specifically focused on the river water level (i.e., height) based technique of discharge estimation using radar altimeters. For large river basin, such as the one studied here (Ganges-Brahmaputra), there are sufficient altimeter ground tracks over major rivers and neighboring tributaries to collectively guarantee at least two samples per basin per day as an indication of flow. For example, for the Ganges-Brahmaputra basins, there are more than twenty JASON-2 ground tracks on the main stem rivers and neighboring tributaries. Second, the collective sampling of the constellation of nadir altimeters that can be expected to fly in the near future (JASON-2, AltiKa, JASON-3 and Sentinel-3) will considerably improve sampling further. We discuss the sampling issue later in Sections III and V. We believe that the synergistic use of all the techniques requires a thorough assessment of the individual methods.

This study extends the work of [5] and assesses the accuracy of a currently operational (as of June 2012) satellite altimeter—JASON-2—for forecasting transboundary flow (i.e., river levels in this case) at locations further inside the downstream nation of Bangladesh. This is achieved by propagating forecasts derived from upstream (Indian) locations through a hydrodynamic river model. The goal of this study is to answer the question—*how practically useful is satellite altimeter for forecasting flows further inside Bangladesh for the public?* Detailed knowledge of the forecasting accuracy of a purely altimeter-based system can help guide the future development of more complex schemes involving data assimilation [13], statistical regression and persistence methods [33], to extend further the forecast lead time.

The paper is organized as follows. Section II provides an overview of the study region (Bangladesh in the larger setting of the GB basins) and the forecasting domain. It also presents the hydrodynamic river model used for propagating the altimeter-based forecast further inside Bangladesh. Section III addresses the methodology. This comprises an overview of the JASON-2 altimeter and the derivation of forecasts from Indian river locations. This section also describes in detail how a daily streaming of 5-day forecast of river water level was created on the basis of the infrequent JASON-2 sampling over the GB basins. Finally, Section IV presents the results and discussions of study findings.

II. Forecasting Domain and Hydrodynamic River Model

The domain for testing the forecasting accuracy of altimeter-based system was Bangladesh (Fig. 2), which is the world's largest delta with extensive *in-situ* hydraulic and hydrologic data available to the authors through a Memorandum of Understanding (MOU) between the Institute of Water Modeling (IWM) of Bangladesh and Tennessee Technological University (TTU). As mentioned earlier, the lack of a data sharing treaty or basin-wide ground instrumentation in the GB basins means that flow data in transboundary regions is unavailable to Bangladesh at timescales of operational forecasting (daily) [4]. 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 standalone hydrologic models to forecast flow downstream into Bangladesh. Inside Bangladesh, a dense drainage network comprising more than 300 rivers makes the delta one of the most riverine in the world (Fig. 2).

Seventeen locations on the Ganges, Brahmaputra river system, inside Bangladesh were chosen for testing of the forecasting accuracy of JASON-2 altimeter. These 17 locations are also the stations where the Flood Forecasting and Warning Center (FFWC) of the Bangladesh Government provide official forecasts of river level to the public at a 3-day lead time during the Monsoon season. We deliberately selected these 17 warning stations with the view to engineer (for FFWC and the people of Bangladesh) an operational forecasting system based on altimetry for real-time decision making in the near future. The three main delivery mechanisms by which the general public gets access to this official 3-day forecast are the Internet (http://www.ffwc.gov.bd), cellphone text messaging, and state-run media (TV and radio). The stations *Noonkhawa* for the Brahmaputra river, *Jangipur Barrage* for the Ganges river and *Amalshid* for the Meghna river are the upstream-most locations of the current forecasting domain for Bangladesh. Hence, these locations represent the upstream boundary condition points for the hydrodynamic river model (discussed next), while the tidal station *Daulatkhan* in the Meghna estuary (near the Bay of Bengal) is the downstream boundary condition point (Fig. 2).

The hydrodynamic river model used in this study was the HEC River Analysis Software (RAS), developed at the Hydrologic Engineering Center (HEC), of the U.S. Army Corps of Engineers. This hydrodynamic modeling software allows one-dimensional steady and unsteady flow river hydraulics

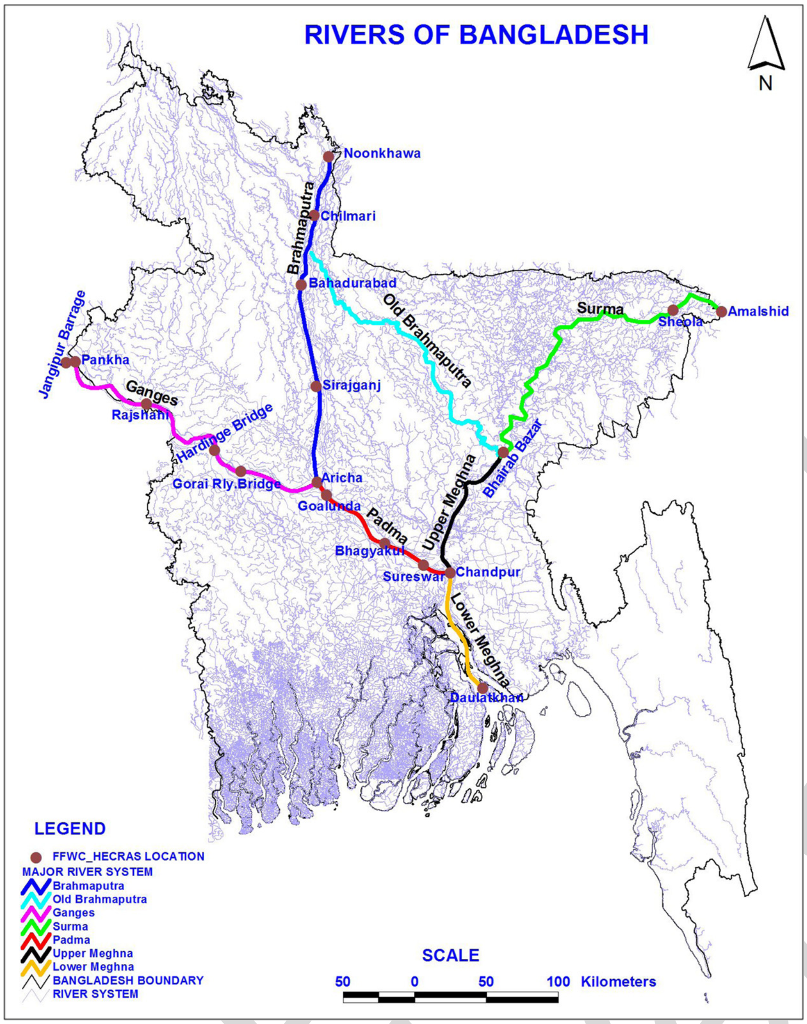

Fig. 2. The spatial domain for testing forecasting skill of JASON-2 altimetry inside Bangladesh. The major rivers shown here as solid and colored lines are modeled by the hydrodynamic river model HEC-RAS. Solid circles represent the 17 locations where the official forecasting agency of Bangladesh Government (Flood Forecasting and Warning Center-FFWC; http://www.ffwc.gov.bd) also issues 3-day public forecast of river levels during the Monsoon season.

calculations. In this study, the water surface profile computation module of HEC-RAS (version 4.0) was used to simulate the daily water level of the major rivers of Bangladesh shown in Fig. 3. We used the model set up that was developed and verified by Siddique-E-Akbor *et al.* [34], wherein HEC-RAS was used to compare the detection of river levels by satellite altimetry (ENVISAT in this case) against *in-situ* data or model-based simulations. For details on the model set up and simulation accuracy of nowcasting, the reader is referred to [34]. Herein, we provide only a very brief summary to help readers understand how altimeter-based forecasting skill was evaluated.

The HEC-RAS model was schematized at 226 river cross-section locations on the major rivers of Bangladesh, shown in Fig. 2 [34]. These river cross-sections were obtained from IWM as part of its periodic field campaign to update river bathymetry of major rivers during the post-Monsoon season. River bathymetry requires frequent check through field surveys because of the shifting nature and extensive bank erosion of Bangladesh rivers. The spacing between river cross-sections varied from 2.5 km to 10 km. This allowed the simulation of river-level dynamics at close spacing and consequently resulted in 17 locations that matched with FFWC forecast stations. Using chainage information from the bathymetry survey provided by the IWM, cross-section data was entered into the HEC-RAS schematization system.

Daily flow measurements (rated from river-level observations) were used at the three most upstream entry points (for each river) in Bangladesh near the India-Bangladesh border (Fig. 2). The rating curves for estimating discharge from river level had acceptable accuracy. For example, for the *Bahadurabad* station on the Brahamputra river, the 10-year climatologic RMSE and mean error in estimating discharge from river level was found to be 2485 m^3/s and 70 m^3/s, respectively (Fig. 3(a)). In terms of percentage of climatologic mean flow (20,563 m^3/s), the RMSE and mean error represent 12% and 0.3%, respectively. For the downstream boundary, HEC-RAS was forced with measured tidal river stage data at the most downstream point, *Daulatkhan* on the Lower Meghna river close to the Bay of Bengal (Fig. 2). During forecasting, it is acceptable to use *in-situ* (or nowcast) water level data at the downstream-most boundary point (near the ocean) since that is

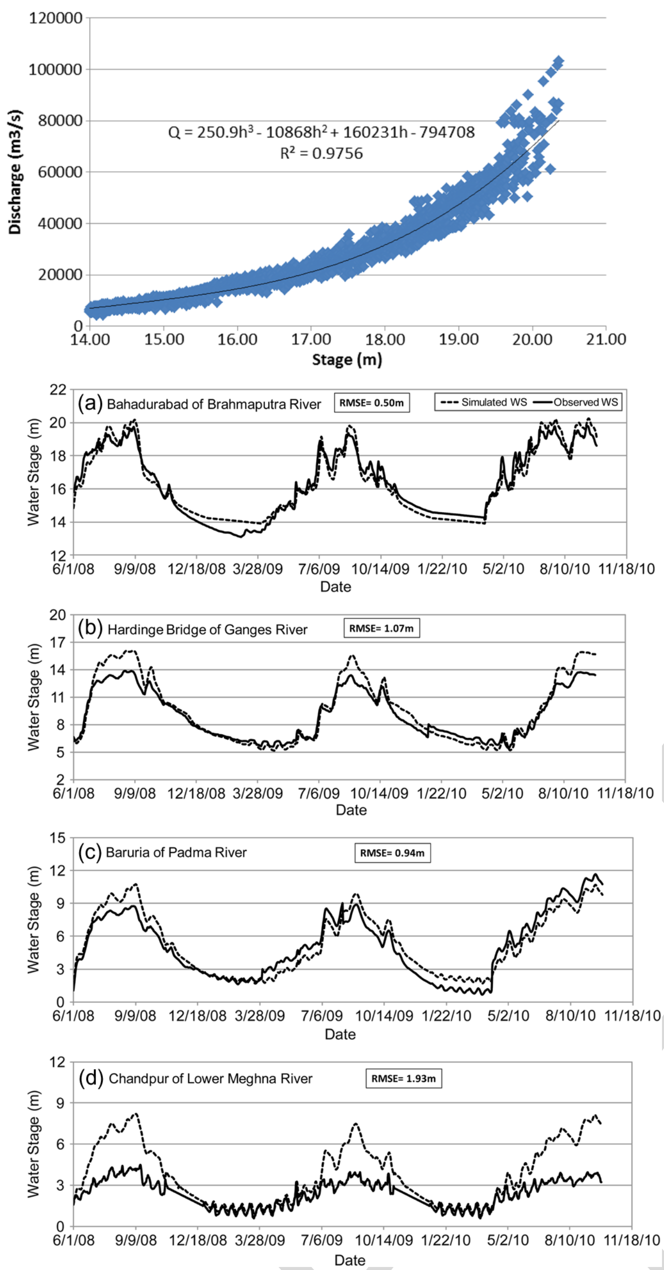

Fig. 3. (a) Discharge-versus-river-level (or stage) rating curve for the *Bahadurabad* station on the Brahmaputra river with the associated uncertainty (RMSE: 2485 m^3/s and Mean Absolute Error = 70 m^3/s). (b) Plot of HEC-RAS simulated and observed (gauged) water stage data (at four locations—see Fig. 2) for the period of June 2008 to October 2010 in nowcasting mode.

Derivation of Forecasting Rating Curves

Derivation of Forecasting Rating Curves (FRC) for various lead times at JASON-2 ground tracks at river locations inside India. For Ganges river ground tracks (virtual stations), these curves allow the forecast of river discharge at *Hardinge Bridge* Station (swapped as *Jangipur Barrage* during model run). For Brahmaputra river ground tracks, these curves allow the forecast of river discharge at *Bahadurabad* (swapped as *Noonkhawa* during HEC RAS model run).

↓

Estimation of 5-day forecast of River Discharge at Upstream boundary point of Model domain

Using independent data period (not used for derivation of forecasting rating curves), 5-day forecast of river discharge for upstream-most boundary points of HEC-RAS are estimated for each day (of the assessment period) by using the most recent JASON-2 scan available at Indian ground tracks and the pertinent FRC.

↓

Propagation of 5-day forecast of River Discharge through HEC RAS inside Bangladesh

HEC-RAS model is initialized each day with the 5-day forecast of river discharge at the upstream-most boundary points and then model runs performed at daily time step. For downstream most boundary point, in-situ river level data at *Daulatkhan* is used. The simulation of river levels in this manner at the 17 FFWC station locations (Figure 2) are then considered as '5-day forecast'.

Fig. 4. General methodology used for testing forecasting skill of JASON-2 inside Bangladesh using the hydrodynamic river model setup of HEC-RAS. See Fig. 6 for location of JASON-2 ground tracks used in this study.

the only type of information that an operational forecaster will have.

The simulation period for this study was 2008–2010. Fig. 3(b) shows the calibration of the HEC-RAS model for the period using *in-situ* boundary condition data (at upstream and downstream points) for the period. Calibration was performed manually against in-situ river-level measurements at sampled locations with the goal to minimize the RMSE of river-level simulation by HEC-RAS. The primary parameter that was iterated for calibration was Manning's roughness coefficient for each river segment (e.g., Ganges, Brahmaputra, and Meghna). Further details of calibration are provided in [34]. The simulated river-level data at the 17 FFWC locations derived from the calibrated HEC-RAS model and forced with *in-situ* boundary data was therefore considered as *nowcasting* data. This was then treated as reference for testing the forecasting accuracy of JASON-2.

Before presenting the methodology used in forecasting, it is important to discuss the representativeness of the HEC-RAS as the hydrodynamic for water level simulations. Fig. 3(b) shows that HEC-RAS systematically over-predicts the peaks with an increasing bias further downstream. One potential reason for this could be that the downstream water level boundary condition may be such that the model generates backwater and tidal effects further upstream that are not present in reality. Second, the HEC-RAS model, being essentially a 1-D model, may not be representing floodplain storage adequately for two key reasons: 1) the river cross-sections may not extend sufficiently far across the floodplain; 2) the inherent limitations of the 1D representation of HEC-RAS to simulate 2-D lateral overbank flow [19], [32].

III. Methodology

The general methodology for testing the accuracy of the altimeter forecasting inside Bangladesh is presented below and also summarized as a schematic in Fig. 4. First, quantitative relationships in the form of "rating curves" were derived at various river locations in upstream India that matched with the JASON-2 altimeter ground tracks (also known as "virtual stations"). Conventional rating curves quantify the instantaneous relationship between estimated discharge and measured river level. To avoid confusion, we call the relationships between upstream river-level anomalies and downstream river discharge "Forecasting Rating Curves" (FRC) because of the primary use in forecasting. The various river locations that formed JASON-2 ground track are shown in Fig. 5. Such FRCs were derived by establishing a graphical relationship between the instantaneous

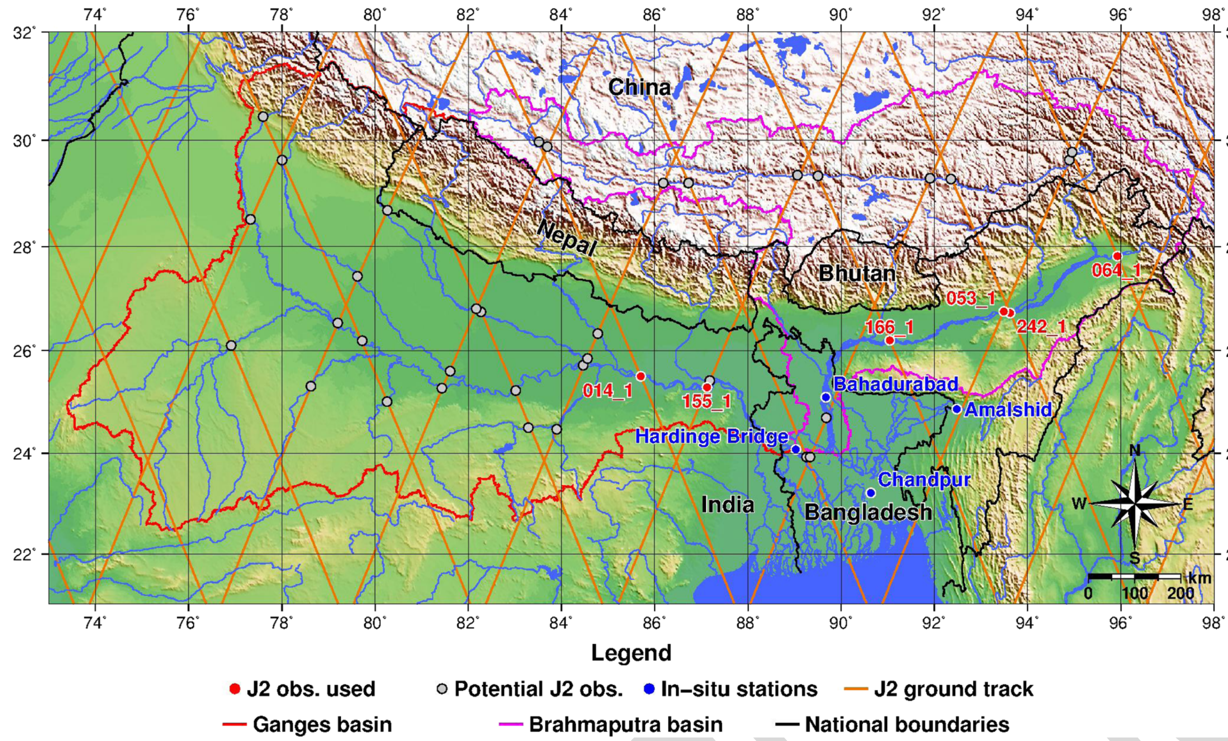

Fig. 5. Ground tracks or virtual stations of JASON-2 (J2) altimeter over the GB basin shown in orange lines and circles, respectively. The locations where the track crosses a river and used for deriving forecasting rating curves is shown with a circle and station number. Circles without a station number represent the broader view of sampling by JASON-2 if all the ground tracks on main stem rivers and neighboring tributaries of Ganges and Brahmaputra are considered.

altimeter water level anomaly estimates (i.e., anomaly relative to the calibration period, October 2008–June 2009, in this case) at upstream locations on Indian rivers to the downstream *in-situ* discharge at the upstream-most boundary points of the forecasting domain of Bangladesh.

We used the nearest *in-situ* river-level data pertaining to *Bahadurabad* (Brahmaputra river) and *Hardinge Bridge* (Ganges river), respectively, in accordance with the practice followed by [34]. As an example, Fig. 6 shows the 6-day FRC (i.e., for a lead of 6 days) derived for specific JASON-2 ground tracks over Indian locations of Ganges and Brahmaputra rivers. Development of the FRCs were guided by the previous work of [5] which investigated the relationships as a function of season (Monsoon and dry season) and lags. Historical data spanning October 2008–June 2009 was used to derive these FRCs at various lead times for all the JASON-2 ground track stations shown in Fig. 5.

We used the JASON-2 Sensor Geophysical Data Record (SGDR, product version "T") data set, which contains 20-Hz 104-sample radar waveforms, spanning from cycle 7 to 95 (September 2008–February 2011). Geophysical corrections (solid Earth and pole tides), and dry troposphere correction are applied. For these data, wet troposphere correction was calculated from the European Center for Medium Range Weather Forecasts (ECMWF) numerical weather prediction model, and an ionosphere correction derived from the Global Ionosphere Map (GIM) was also applied. Over non-ocean surfaces, various retracking methods have been developed to correct the deviation of the waveform leading edge from the nominal tracking gate (e.g., [12], [22], [27], [37]). JASON-2 data products contain retracked range measurements using the "ICE" retracker that is essentially a 30% threshold retracker using the mean power of the waveform calculated using the Offset Center of Gravity algorithm [40]. In this study, we adopted 50% threshold retracking which has been shown to perform well over inland water bodies for Jason-2 waveforms [24].

In the next step (Fig. 4), these FRCs were used to forecast 5-day-ahead river discharge at the upstream-most boundary points of the HEC-RAS model setup. An independent validation (assessment) period of July 2009–December 2010 was chosen for assessing the forecast accuracy of JASON-2. For this period, instantaneous JASON-2 river-level estimates at the upstream Indian river locations were used to derive the 5-day discharge forecast at *Hardinge Bridge* and *Bahadurabad* stations. Because JASON-2 revisit frequency at the same transboundary river ground track is never daily, a scheme was devised to allow daily computation of 5-day forecast of river levels at upstream boundary points of HEC-RAS set up using a combination of the most recent altimeter scan, FRC and interpolation (if necessary). This is elaborated in detail in the paragraph below.

In this study, the idea was to compute a 5-day forecast in a pseudo "operational mode" using information only from the altimeter itself. The altimeter data spanning October 2008–June 2009 was treated as "historical" (calibration) data that the forecaster had access to for derivation of *a priori* FRCs. For each upstream JASON-2 virtual station (i.e, numbered ground tracks in Fig. 5) on each river at Indian locations, an FRC for a given lead time was derived using the methodology used by [5]. These FRCs correspond to a power law fit between upstream JASON-2

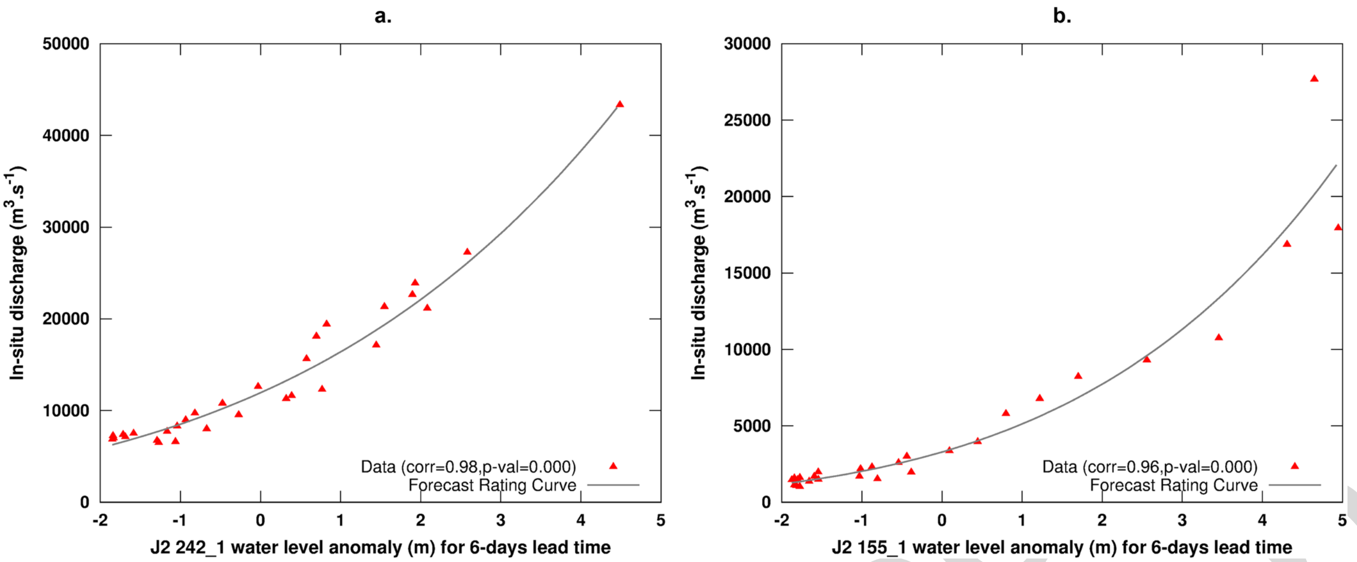

Fig. 6. Example of 6-day forecasting rating curves (FRC) for JASON-2 at ground track (virtual station) location 242_1 (Brahmaputra river—Fig. 2) for *Bahadurabad* station (left panel) and 155_1 (Ganges river—Fig. 2) for *Hardinge Bridge* station (right panel). These rating curves are derived on the basis of historical data during the calibration period (October 2008–June 2009). (a) Water level anomaly (m) ($\mathrm{corr} = 0.98$, $\mathrm{p \cdot val} = 0.000$); (b) water level anomaly (m) ($\mathrm{corr} = 0.96$, $\mathrm{p \cdot val} = 0.000$).

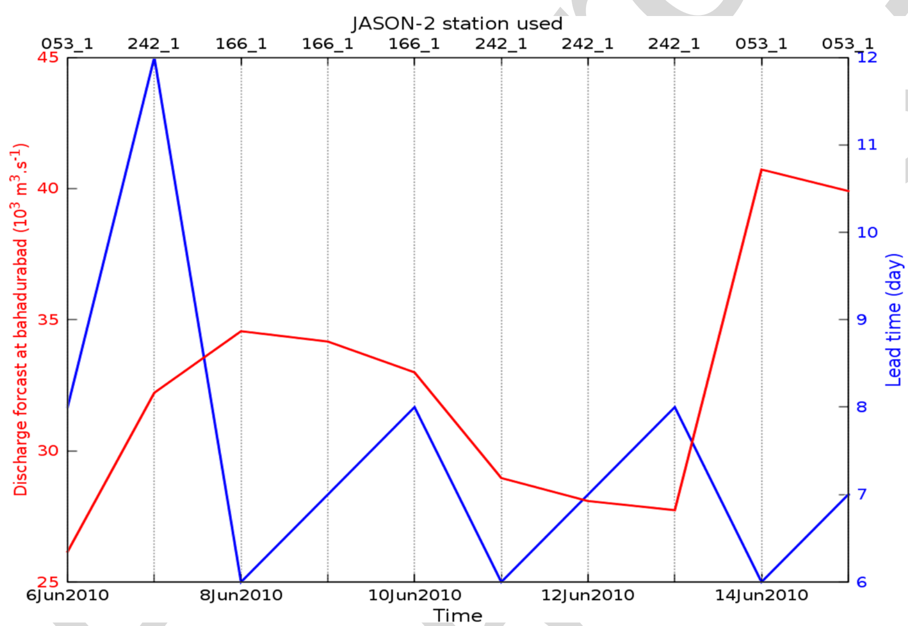

Fig. 7. Example of 5-day forecasted water level (red curve) at *Bahadurabad* on the Brahmaputra River (left y-axis) between 6 June 2010 and 15 June 2010 versus time (bottom x-axis). The blue curve corresponds to the lead time (right y-axis) of the JASON-2 FRC used to compute the forecasted water level. The top x-axis corresponds to the name of the JASON-2 virtual station of the pertinent FRC used for each day.

water level anomalies (lagged in time according to a specific lead time) and downstream *in-situ* discharge. This power law fit is actually derived by doing a linear fit of these two variables in the log space. An example of a 6-day lead time FRC is shown in Fig. 6 (grey straight-fit lines). Such FRCs have been computed for lead times ranging from 1 day to 20 days.

Using the period of July 2009–December 2010 for independent testing of altimeter-based forecasting, 5-day forecast of river discharge for every day at the upstream-most point of Bangladesh domain were "routinely" derived assuming an operational environment as follows. During the validation "test" period (July 2009–December 2010), the aim was to compute for each day, noted D, the 5-day later forecast discharge, using a water level/discharge rating curve as shown on Fig. 6, at *Bahadurabad* and *Hardinge Bridge* at the day of forecast, noted here as $\mathrm{D_f}$ (i.e., $\mathrm{D_f} = \mathrm{D} + 5$). To do so, the most recent JASON-2 observation in time from day D was selected for each upstream virtual station located in India. The date of the selected JASON-2 observation is referred as $\mathrm{D_{J2}}$ in the rest of this section. Thus, there are $\mathrm{D_f} - \mathrm{D_{J2}} = \mathrm{D} + 5 - \mathrm{D_{J2}}$ days between the JASON-2 observation and the day of forecast. So the forecast is done using the JASON-2 water level anomaly and the pertinent FRC computed from historical data for a lead time equal to $\mathrm{D_f} - \mathrm{D_{J2}}$. For the Brahmaputra, JASON-2 virtual stations 053_1 and 242_1 have been considered (Fig. 5). The FRCs at these locations had the lowest RMSE compared to *in-situ* measurements during the historical time period. On the Ganges, JASON-2 virtual stations 014_1 and 155_1 have

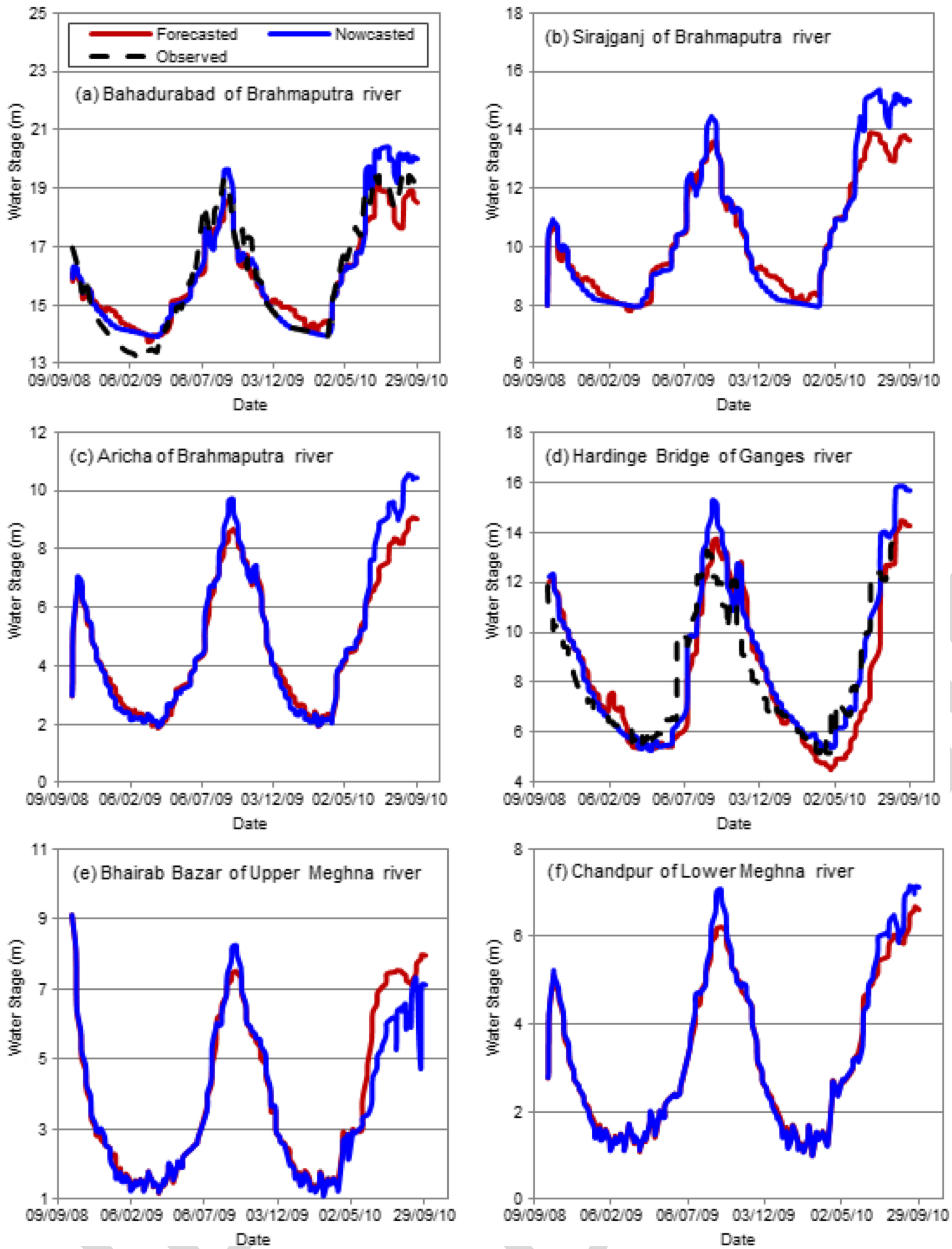

Fig. 8. Forecast (5 day) and Nowcast water level hydrographs at six river stations during the validation period of July 22, 2009 to September 30, 2010. Observed water level data are available only for Bahadurabad and Hardinge Bridge stations. For location of the stations, refer to Fig. 2 and Table I.

been used (Fig. 5). Whenever $D_f - D_{J2}$ exceeded 20 days (an unlikely scenario for JASON-2), the forecast was linearly interpolated from the two previous ones. This case did not occur during the July 2009–December 2010 time span. Finally, it has been considered that JASON-2 measurements have at least 1-day latency, meaning that the minimum lead time is equal to 6 days (i.e., $D_f - D_{J2} \geq 6$).

For example, let us consider the case of how the 5-day-ahead forecast water level at *Bahadurabad* was computed for D = June 8, 2010. This means that the forecast date is actually June 13, 2010 (i.e., D_f). The most recent JASON-2 measurement relative to June 8, 2010 was obtained from virtual station 242_1 on June 5, 2010 (D_{J2}) (Fig. 7). Thus, for forecasting river discharge for June 13, 2010 at *Bahadurabad* on the Brahmaputra River, an FRC for 242_1 with an 8-day lead time ($D + 5 - D_{J2}$) was used. Fig. 7 shows an example of such an "operational cycle" of computation for 5-day forecasted water level (red curve) at *Bahadurabad* on the Brahmaputra River (left y-axis) each day from June 6, 2010 to June 15, 2010 (bottom x-axis). The blue curve corresponds to the lead time (right y-axis) of the FRC used to compute the forecasted water level. The top x-axis corresponds to the name of the JASON-2 virtual station used to compute the forecasted rating curve for each day.

TABLE I
ERROR ANALYSIS OF JASON-2-BASED 5-DAY FORECAST USING NOWCAST AS REFERENCE. CHAINAGE IS MEASURED AS DISTANCE UPSTREAM FROM THE DOWNSTREAM-MOST POINT OF A RIVER SEGMENT. MAE—MEAN ABSOLUTE ERROR; RMSE—ROOT MEAN SQUARED ERROR

River Segment	Chainage (Km)	FFWC Station	Monsoon Season				Dry Season			
			Mean Error (m)	MAE (m)	RMSE (m)	Correlation	Mean Error (m)	MAE (m)	RMSE (m)	Correlation
Brahmaputra	228	Noonkhawa	-0.47	0.59	0.71	0.91	0.30	0.32	0.37	0.93
Brahmaputra	208	Chilmari	-0.51	0.62	0.75	0.91	0.28	0.30	0.35	0.94
Brahmaputra	151	*Bahadurabad*	-0.65	0.75	0.93	0.94	0.30	0.33	0.37	0.93
Brahmaputra	79	Sirajganj	-0.56	0.67	0.81	0.96	0.33	0.37	0.42	0.93
Brahmaputra	0	Aricha	-0.52	0.57	0.74	0.98	0.11	0.20	0.23	0.99
Ganges	232	Pankha	-1.11	1.33	1.54	0.96	-0.49	0.50	0.63	0.96
Ganges	166	Rajshahi	-0.82	0.97	1.10	0.97	-0.30	0.32	0.40	0.95
Ganges	96	Hardinge Bridge	-0.90	1.02	1.21	0.97	-0.55	0.58	0.66	0.97
Ganges	62	Gorai Rly Bridge	-0.69	0.81	0.98	0.97	-0.42	0.44	0.53	0.97
Padma	106	Goalanda	-0.51	0.56	0.73	0.98	0.11	0.19	0.22	0.99
Padma	52	Bhagyakul	-0.46	0.51	0.68	0.98	0.05	0.12	0.14	0.99
Padma	30	Sureswar	-0.39	0.43	0.58	0.98	0.02	0.08	0.10	1.00
Surma	285	Amalshid	-0.04	0.04	0.07	1.00	0.00	0.00	0.00	1.00
Surma	239	Sheola	-0.05	0.05	0.08	1.00	0.00	0.00	0.01	1.00
Upper Meghna	77	Bhairab Bazar	-0.35	0.48	0.58	0.98	0.01	0.12	0.16	1.00
Upper Meghna	17	Chandpur	-0.38	0.42	0.56	0.98	0.01	0.07	0.08	1.00
Lower Meghna	3	Daulatkhan	0.00	0.00	0.00	1.00	0.00	0.00	0.00	1.00

Once the 5-day-ahead forecast of river discharge, pertaining to the upstream-most boundary point, was derived for each day of the independent assessment (validation) period (July 2009–December 2010) according to the methodology elaborated above, the HEC-RAS model was next run at the daily time step. For each day, the model was initialized with the corresponding 5-day forecast of river discharge at the upstream-most boundary points for Brahmaputra and Ganges rivers. For the downstream most boundary point, *in-situ* river-level data at *Daulatkhan* was used "as is" due to practical limitations (see last paragraph of Section II). Also, for the upstream boundary point on Meghna river, *Amalshid* (Fig. 2), *in-situ* water level data was used. The justifications for using *in-situ* river-level data for the Meghna river are as follows: 1) there are no suitable JASON-2 ground track for the Meghna river in Indian locations (Fig. 5), and 2) the Meghna river contributes only an insignificant portion ($\sim$3.5%) of total transboundary flow (about 1,777 km^3 per year) into Bangladesh. The simulation of river levels inside Bangladesh in this manner at the 17 FFWC station locations (Fig. 2) were then considered as the *5-day forecast* for the specific date of the model run and compared with the *5-day later* nowcast shown in Fig. 3(b).

IV. RESULTS AND DISCUSSION

Because the proof-of-concept assessment of forecasting is done relative to nowcasting, which is model derived, it is first important to recognize the caveat that model simulations have inherent uncertainty. In this particular study, the HEC-RAS simulations suffered from an overall positive bias (overestimation) when compared to *in-situ* river-level measurements (see last paragraph of Section II). Nevertheless, the use of model-based nowcasting is the only way to comprehensively assess the accuracy of JASON-2 based forecasting inside Bangladesh at multiple locations where *in-situ* river-level measurements are not routinely available, and hence any persistence-based forecasting cannot be performed at those locations.

For a quantitative assessment of the accuracy of forecasting using JASON-2 altimeter data at upstream Indian river locations, the following assessment metrics has been derived: 1) mean error, 2) RMSE, 3) correlation and 4) mean absolute error. Here "error" is defined as the scalar difference between the JASON-2-based "5-day forecast" and the "5-day later" nowcast based on only *in-situ* boundary condition data. Furthermore, we assessed the skill for two distinct seasons: Monsoon season (July–September) and Dry season (October–June). Finally, we analyzed accuracy as a function of distinct river segments of the forecasting domain. Herein, there were six distinct river segments (or stretches): Ganges, Brahmaputra, Padma, Surma, Upper Meghna, and Lower Meghna. These river segments are shown in distinct color in Fig. 2. The purpose of breaking down the analysis per each river segment was to identify how the accuracy degraded as a function of flow distance downstream and river morphology.

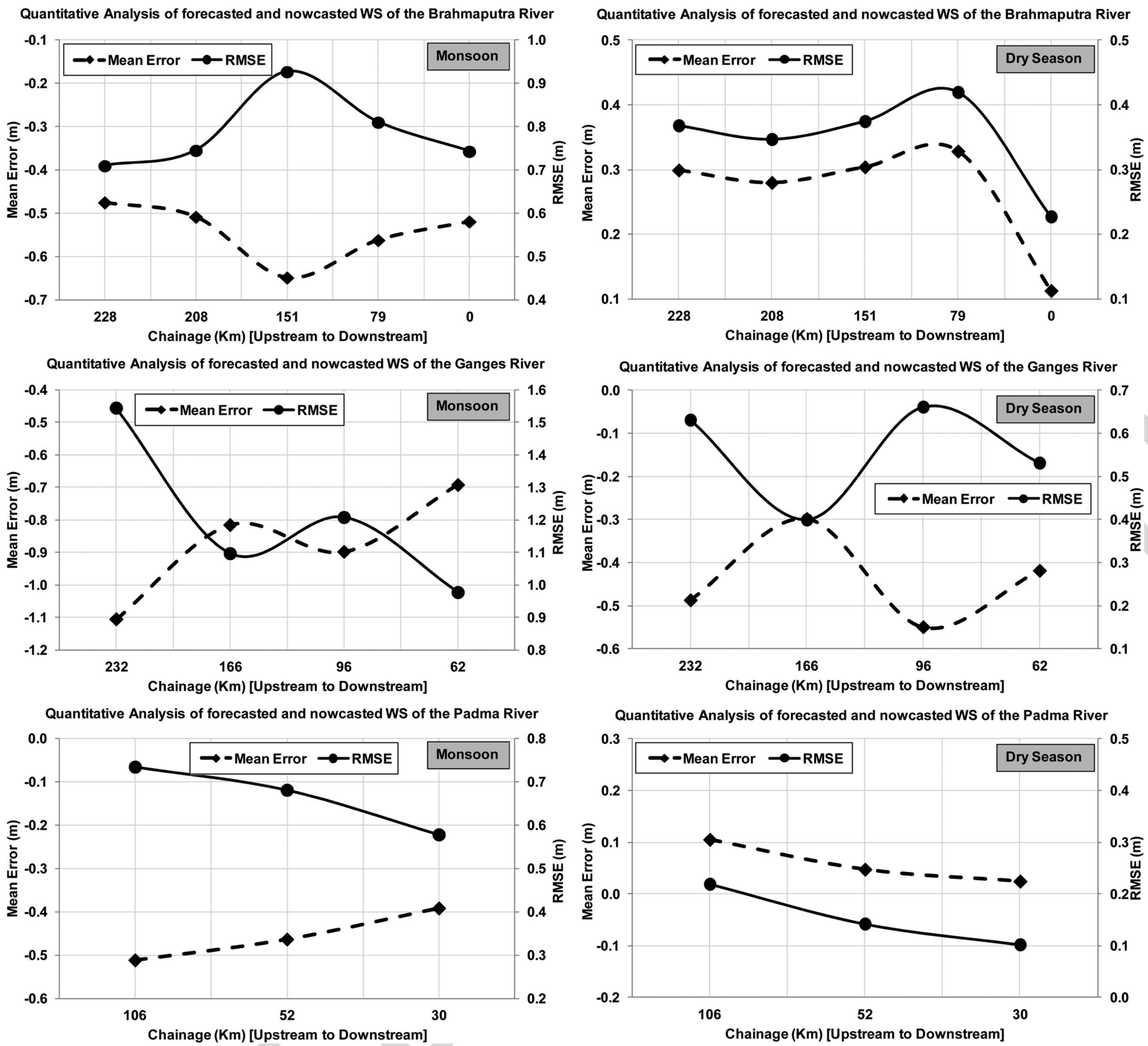

Fig. 9. Accuracy assessment as a function of season (left panel–Monsoon; right panel–dry season), river segments and flow distance downstream (chainage) (x-axis). Upper panels–Brahmaputra river; middle panels–Ganges River; lower panels–Padma River.

Fig. 8 shows the 5-day forecast hydrographs of river levels at six locations (at the various river segments shown in Fig. 2). In comparison to the nowcast hydrographs, the 5-day forecasts appear quite acceptable in following the trends and capturing the peak events. In fact, when compared to *in-situ* river-level data at the two gauging stations (*Bahadurabad* and *Hardinge Bridge*), the 5-day forecasting agrees a little more closely than the nowcast. The systematic overestimation of the HEC-RAS model appears to cancel out somewhat the systematic underestimation of the forecasting approach to yield a relatively more unbiased solution.

Table I and Figs. 9 and 10 summarize the performance of the JASON-2-based 5-day forecast at the 17 FFWC locations and also as a function of season and for the various river segments. Results show that JASON-2 forecasts retain good accuracy (relative to nowcast) at a 5-day lead with an average RMSE ranging from 0.5 m to 1.5 m and mean bias of 0.25 m to 1.25 m in estimating the river level. However, there is a consistent underestimation (negative mean bias) in forecasting of river levels. The forecasting accuracy of JASON-2 is generally found to be higher during the dry season compared to the Monsoon season. This can be a useful finding for water resources management at seasonal timescales for addressing problems such as droughts or saline water intrusion from the Bay of Bengal. A possible reason for higher accuracy (compared to nowcast and wet season) during dry season can be attributed to the extensive irrigation and diversion by India that leads to very steady but reduced flow into Bangladesh, thus making forecasting more accurate.

Except for the Brahmaputra river reach, the forecasting accuracy seemed relatively preserved as a function of downstream flow distance. An additional reason to keep in mind is that the stage variation used to estimate discharge can be less corre-

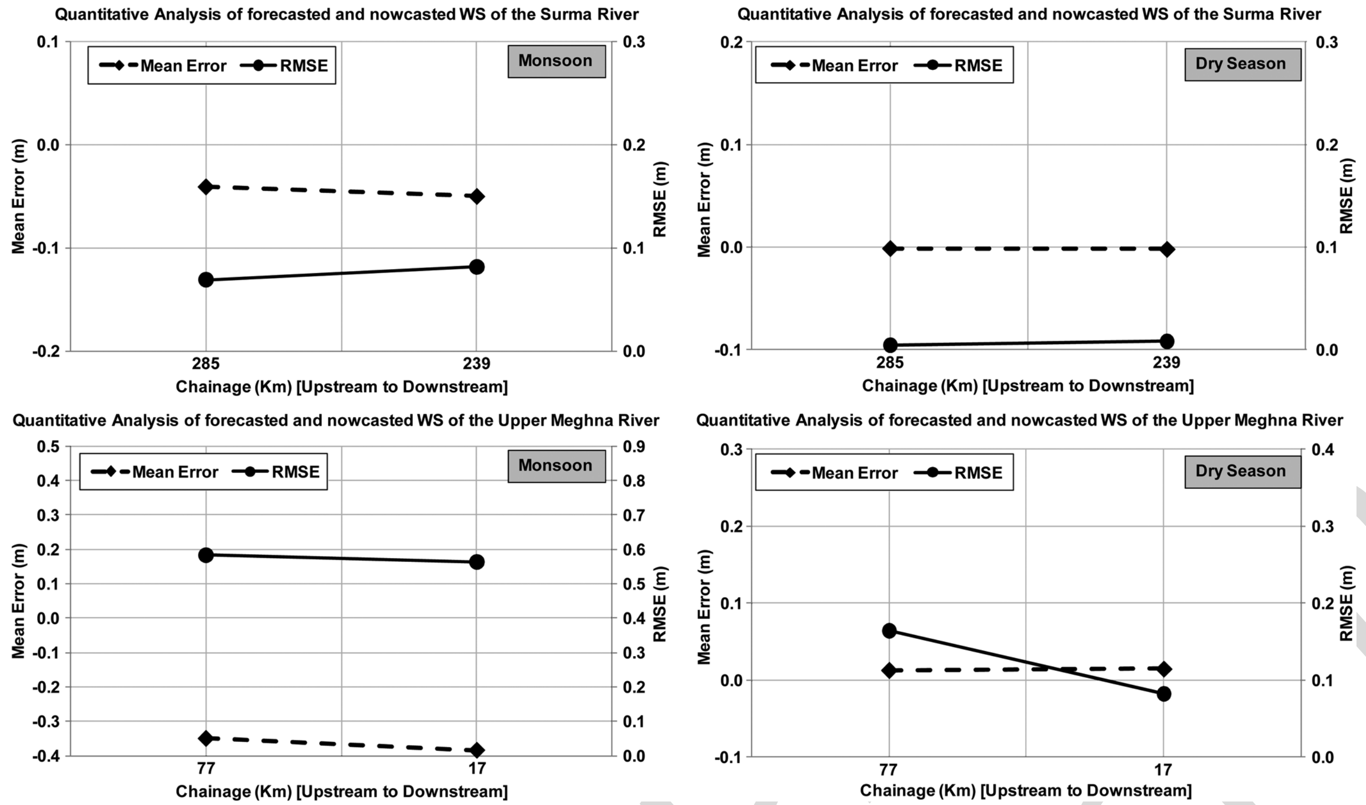

Fig. 10. Accuracy assessment as a function of season (left panel–Monsoon; right panel–dry season), river segments and flow distance downstream (chainage) (x-axis). Upper panels–Surma river; lower panels–Lower Meghna river.

lated for large rivers as the bank slopes decreases and the river cross-sectional area expands. A point to note is that the skill for the river segments of Surma and Upper and Lower Meghna rivers (Fig. 8) is not representative of the true forecasting potential of JASON-2, since these rivers pertain to the Meghna river basin (the smallest of the three basins) and used *in-situ* discharge data as the upstream-most boundary condition point in the forecasting domain. Fig. 11(a) and (b) depicts an overall graphical summary of the forecasting skill of JASON-2 as a function of downstream flow distance for each river segment and for the two seasons.

As indicated before, the satellite altimeter JASON-2 data are obtained using the 50% threshold radar waveform retracker, which has shown to have good performance for inland water [23], [24]. However, there has not been an elaborate *in situ* calibration of JASON-2 conducted to reveal whether a range bias exists. It has been shown that, for example, large bias could occur in river basins, e.g., the Amazon, for ENVISAT radar altimeter [11] due primarily to terrains surrounding the river and possibly also meteorological conditions. An uncorrected altimeter bias would have degraded the forecasting accuracy for this study.

A follow-up question that emerges regarding the proof-of-concept forecasting approach using JASON-2 satellite data is *What is the true accuracy (skill) of forecasting given that nowcasting has inherent uncertainty?* Armed with encouraging results for our proof-of-concept study shown previously, we next embarked on a real-time, truly operational and independent assessment of JASON-2 forecasting against observed water level measurements (where available). As part of a U.S. Department of State (Fulbright) project awarded to the first author, the flood forecasting staff of IWM were trained over a four-month period to independently learn, apply and troubleshoot the JASON-2 forecasting scheme in a real-time (day-to-day) environment. Once the training was complete, the staff then carried out a real-time operational forecasting of JASON-2 during a 20-day period spanning August 1, 2012 to August 20, 2012. Each day of this 20-day period, the 5-day water-level forecast at the upstream boundary condition locations of the HEC RAS domain was generated from JASON-2 data available at the shortest latency (called Interim Geophysical Data Records, IGDR). The HEC RAS set up used a 10-day spin-up (hindcast) to remove the effect of initial conditions. Thus, in total, HEC RAS was run each day for a period of 15 days (10-day hindcast and 5-day forecast) to generate the corresponding forecast water levels further inside Bangladesh.

Comparison against observed water levels at three river stations (*Bahadurabad*, *Sirajganj* on the Brahmaputra river, and *Hardinge Bridge* on the Ganges river) revealed an average error of forecast ranging from -0.4 m to 0.4 m and an RMSE ranging from 0.2 m to 0.7 m. Table II provides a statistical summary of the assessment of the JASON-2 forecast against observed water levels at these three locations. As an example for one location, *Sirajganj* on Brahmaputra river, Fig. 12 shows the comparison of the forecast water level against observed water levels at various lead times during the period of August 1, 2012 to August 20, 2012. In general, we clearly see that our choice of using nowcasting as the reference to establish proof-of-concept oper-

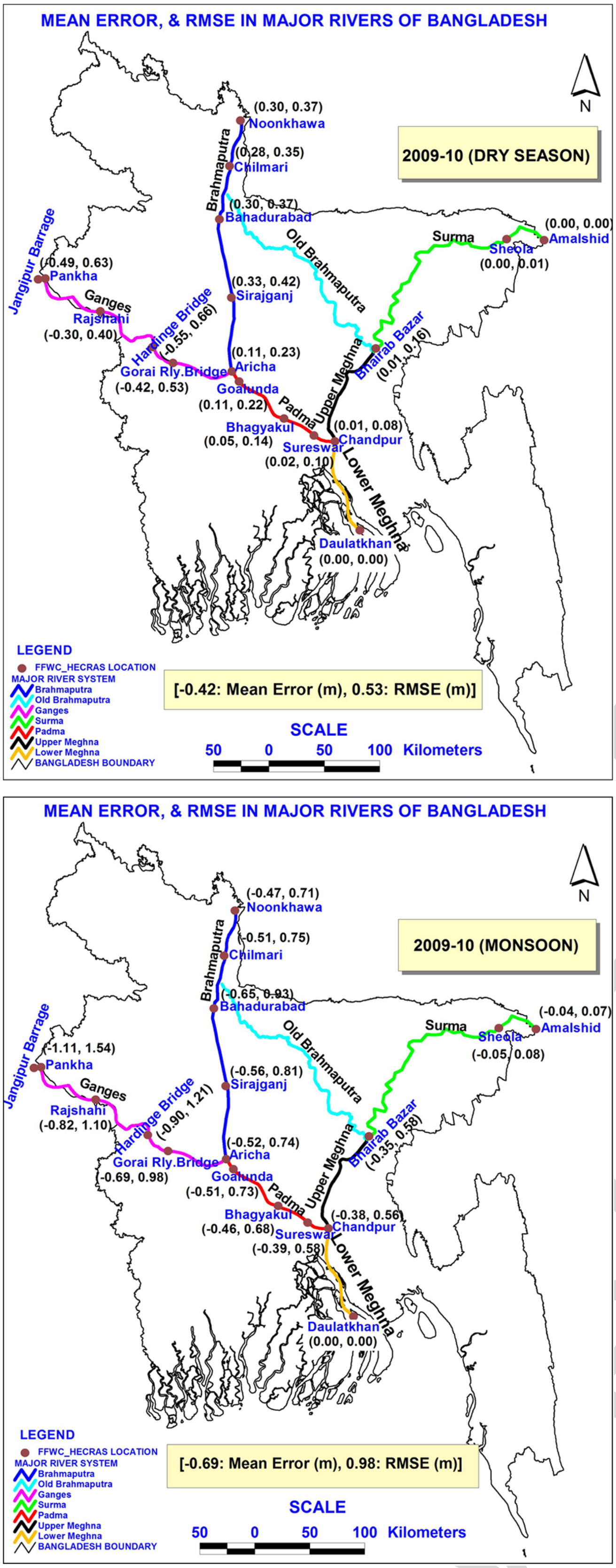

Fig. 11. (a) Accuracy of JASON-2-based 5-day forecast in terms of mean error and RMSE of river level at the 17 FFWC river stations inside Bangladesh during dry season. (b) Accuracy of JASON-2-based 5-day forecast in terms of mean error and RMSE of river level at the 17 FFWC river stations inside Bangladesh during Monsoon season.

TABLE II
INDEPENDENT ASSESSMENT OF JASON-2 5-DAY FLOOD FORECASTING AT THREE RIVER LOCATIONS (SEE FIG. 2 FOR LOCATIONS) AGAINST OBSERVED WATER LEVEL (RELATIVE TO LOCAL DATA) IN A REAL-TIME AND OPERATIONAL FRAMEWORK DURING AUGUST 1 TO AUGUST 20, 2012

Lead (day)	Correlation	Mean Error (m)	RMSE (m)
	Sirajganj		
1	0.990	0.419	0.660
2	0.993	0.380	0.690
3	0.980	0.358	0.721
4	0.960	0.330	0.789
5	0.949	0.387	0.803
	Hardinge Br.		
1	0.939	-0.396	0.105
2	0.787	-0.411	0.130
3	0.578	-0.431	0.217
4	0.305	-0.460	0.340
5	0.020	-0.434	0.467
	Bahadurabad		
1	0.985	-0.309	0.358
2	0.960	-0.274	0.424
3	0.936	-0.233	0.511
4	0.923	-0.207	0.601
5	0.905	-0.199	0.695

ational feasibility of JASON-2 scheme was not unfounded. In fact, the skill of forecasts at the 5-day lead time is now found to be more accurate against observed water level measurements. Overall, our study shows that satellite altimeters can indeed be an efficient and practical tool for building a robust forecasting system for transboundary flow for the developing world.

V. CONCLUSION AND PERSPECTIVES

This study provides a proof-of-concept of how an operational system can be implemented on the basis of satellite altimetry and the fundamentally intractable limitations of insufficient measurements and the transboundary nature of flood forecasting pose in developing nations. Generally, it is promising to observe that satellite altimeters (including JASON-2) are indeed quite capable of forecasting transboundary flow inside downstream nations at 5-day (or higher) lead time without complex data assimilation, time-series analysis and climate-based forecasting tools. This inherently implies that when such altimeter-based transboundary flow forecasting schemes are combined with current state-of-the-art methods involving statistical regression or climate, the potential for extending the lead time, as well as handling unscheduled issues with regulation of flow by upstream nations, can be tremendous. The more important question is however on operational sustainability. The current suite of concurrently flying altimeters such as JASON-1, JASON-2, ENVISAT (this mission ended in May 2012), CryoSat-2 and SARAL/AltiKa are essentially science-discovery missions with a finite life span of 5–7 years and not tailored for the operational needs of an agency (such as NOAA GOES or Landsat of the USGS). *Thus, how can such an altimeter-base forecasting system be made operationally sustainable in the long term with near-real-time data availability to the public?*

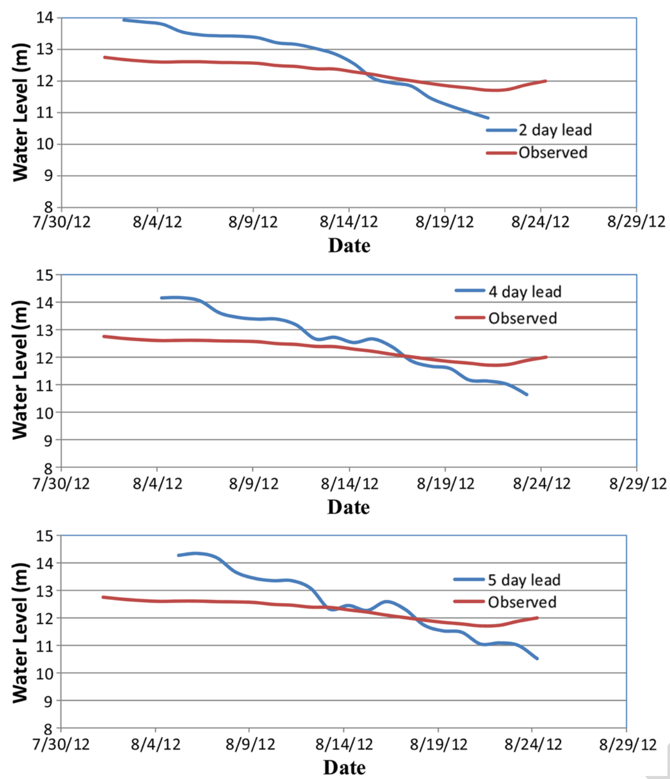

Fig. 12. Assessment of JASON-2 5 day flood forecasting at *Sirajganj* (see Fig. 2 for location) on the Brahmaputra river against observed water level (relative to local data) in a real-time and operational framework during August 1 to August 20, 2012. The forecasts were generated entirely and independently by Bangladesh Flood Forecasting Agency staff.

We contend that although the answer to the above question has not been identified yet by the scientific community, it is only through concept demonstration and operational feasibility studies, such as ours, that nations will step forward as invested stakeholders and plan to launch more operational satellite altimetry missions. Data products from JASON-1/2 are largely available in near-real time, either by efforts of respective cognizant space agencies, or by efforts of scientific investigators. It is worthwhile to note that after the JASON-2 and Envisat altimeters, JASON-3 is scheduled to be launched in 2014, and the AltiKa mission has been launched in 2013, following the 10-day and 35-day repeat orbits of JASON-2 and Envisat, respectively. In addition, ESA's Sentinel-3 (two-satellite constellation) will be launched in 2013. NASA/CNES' Surface Water and Ocean Topography (SWOT) wide-swath radar interferometric altimetry mission is also scheduled for launch in 2019. Of these planned altimetry missions, JASON-3 and Sentinel-3 are actually designated operational missions, dedicated to providing near-real-time data to the general public. Thus, there will be abundant satellite altimetry missions, scientific and operational missions, well into the foreseeable future. With such a prolonged window of data continuity and minimum latency, nations that need a more "sovereign" approach to forecasting their incoming transboundary flow, may now have the unique opportunity to create something truly operational for serving their society with longer lead times for adaptation.

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This study is dedicated to the people of Bangladesh and all other downstream nations prone to transboundary flooding for their resilience and strong desire to build enduring capacity ground up in managing floods.

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