A Promising Radar Altimetry Satellite System for Operational Flood Forecasting in Flood-Prone Bangladesh

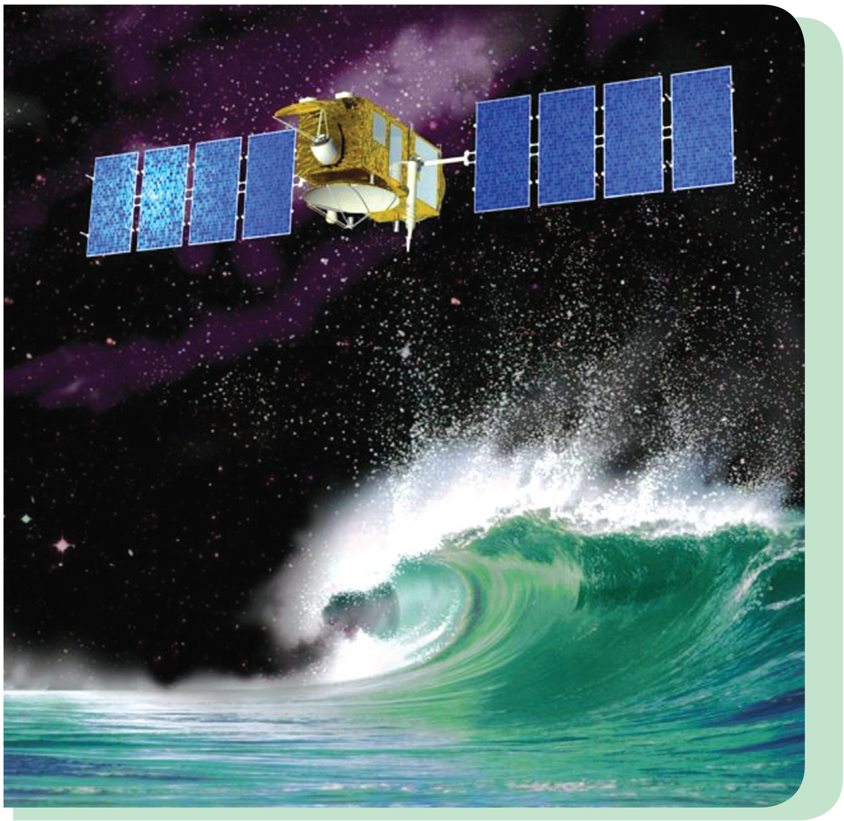


PHOTO COURTESY OF NOAA

Abstract—Building on a recent suite of work that has demonstrated theoretical feasibility and operational readiness of a satellite altimeter based flood forecasting system, we recently put a progressively designed altimeter based transboundary flood forecasting system to the ultimate test of real-time operational delivery in Bangladesh. The JASON-2 satellite altimeter, which was in orbit at the time of writing this manuscript, was used as the flagship altimeter mission. This paper summarizes the entire process of designing the system, customizing the workflow, and putting the system in place for complete ownership by the Bangladesh stakeholder agency for a 100 day operational skill test spanning the period of June 1 2013 through Sept. 9, 2013. Correlation for most of the flood warning stations ranged between 0.95 to 0.80 during the 1 day to 8 days lead time range. The RMSE of forecast typically ranged between 0.75m to 1.5m at locations where the danger level relative to the river bed was more than an order higher (i.e., >20m). The RMSE of forecast at the 8 days lead time did not exceed 2m for upstream and mid-stream rivers inside Bangladesh. The RMSE of forecast at the 8 days lead time exceeded 2m at a few estuarine river locations affected by tidal effects, where danger level

FAISAL HOSSAIN AND MEHEDI MASWOOD
Department of Civil and Environmental Engineering, University of Washington, Seattle, USA

A.H. SIDDIQUE-E-AKBOR AND WONDMAGEGN YIGZAW
Tennessee Technological University, Cookeville, USA

LITON CHANDRA MAZUMDER, TANVIR AHMED, MONOWAR HOSSAIN, AND S.M. SHAH-NEWAZ
Institute of Water Modeling, Dhaka, Bangladesh

ASHUTOSH LIMAYE
NASA Marshall Space Flight Center, Alabama, USA

HYONGKI LEE
Department of Civil and Environmental Engineering, University of Houston, Texas, USA

SUDIP PRADHAN, BASANTA SHRESTHA, AND BIRENDRA BAJRACAHRYA
International Center for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal

SYLVAIN BIANCAMARIA
LEGOS, France

C.K. SHUM
School of Earth Sciences, The Ohio State University, USA

F.J. TURK
Jet Propulsion Laboratory, Caltech, California, USA

Digital Object Identifier 10.1109/MGRS.2014.2345414
Date of publication: 17 October 2014

relative to river bed was smaller (i.e., <20m). Such a satellite altimeter system, such as one based on the JASON-2 altimeter, is now poised to serve the entire inhabitants of the Ganges-Brahmaputra-Meghna river basins as well as 30 or more flood-prone downstream nations currently deprived of real-time flow data from upstream nations.

1. INTRODUCTION

The fundamental hurdle to improving the flood forecasting capability of a downstream and highly flood-prone country like Bangladesh is well-known (*Hossain and Katiyar, 2006*; *Katiyar and Hossain, 2007*). Bangladesh, which receives more than 90% of its surface water from upstream nations during the Monsoon season of June-Sept, has been able to maintain a fairly comprehensive in-situ network within its boundary for flood monitoring since the 1990s (*Paudyal, 2002*). However, such a 'domestic' monitoring system over land covers only 7% of the total drainage area of the Ganges-Brahmaputra-Meghna river basins (*Webster et al., 2010*), and is therefore able to produce skillful flood forecasts only up to 3 days of lead time. A week-long lead time is considered the minimum for effective decision making in such humid, seasonally-flood-prone environments for farmers, rural inhabitants and national governance (*Nishat and Rahman, 2010*). However, the lack of measurement of flow and rainfall in near real-time over upstream regions of India due to a lack of an information sharing treaty (*Balthrop and Hossain, 2010*) and the absence of a basin-wide flow measurement infrastructure, have been reported as the key hurdle to improving institutional flood forecasting capacity of Bangladesh beyond 3 days (see http://www.ffwc.gov.bd; *Hossain et al., 2013a*).

CALLOUT CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT.

Bangladesh is not alone here with such a political curse. Earlier surveys by *Hossain and Katiyar (2006)* and *Bakker (2009)* indicated that about 33 countries have a majority of their territory 'locked' within a large river basin. Some examples are Cambodia, Pakistan, Senegal, Nigeria and Botswana. This fact makes these countries heavily dependent on flow information from the upstream nations in near real-time (*Paudyal, 2002*). While such transboundary river flooding represents less than 10% of all recorded flood events, they account for more than 30% of all reported casualties, almost 60% of affected individuals, and 14% of financial damage (*Bakker, 2009*). The disproportionate relationship between occurrence and impact of transboundary floods has also been attributed to the clear lack of institutional capacity for real-time communication of flood propagation status among upstream and downstream countries (*Balthrop and Hossain, 2010; Moffit et al., 2010; Bakker, 2009*).

As a response to this problem, several efforts have recently been undertaken to overcome the limitation through innovative ideas, using Bangladesh as a representative example for a feasibility assessment. For example, some studies have shown that a combination of satellite estimates of rainfall and hydrologic modeling can estimate or forecast stream flow in Bangladesh beyond 3 days of lead time (*Nishat and Rahman, 2009; Hopson and Webster, 2010; Webster et al., 2010, Hirpa et al., 2013*). Such studies also provide a very useful platform to address the emerging challenge of operational forecasting that is often made difficult by the increasing impoundment of rivers by upstream nations (*Siddique-E-Akbor et al., 2011*).

2. THE ROLE OF ALTIMETER SATELLITES IN TRANSBOUNDARY FLOOD FORECASTING

As noted from examples cited earlier (e.g. *Nishat and Rahman, 2009; Hopson and Webster, 2010; Hirpa et al., 2013*), there is now growing body of work using satellite remote sensing to predict or forecast discharge. We have recently argued that if satellites could provide an indirect way of measuring the upstream flow or water level, then the accuracy of a downstream forecasting system could be improved considerably (*Biancamaria et al., 2011*). In this regard, satellite altimeters, that can measure elevation of water bodies, are particularly effective. Satellite altimetry has progressed considerably over the last decade to become a viable alternative for many hydrologic applications (e.g., *Birkett, 1995; Schumann et al., 2009*). Using TOPEX/Poseidon (T/P) satellite altimetry measurements of water levels in India, *Biancamaria et al. (2011)* have demonstrated exactly this point very clearly. Their work proved the theoretical feasibility for forecasting water elevation fluctuations during the Monsoon season near the Bangladesh border. Such a T/P-based forecasting scheme reported an RMSE ranging from 0.6 m–0.8 m for lead times up to 5-days without having to rely on any upstream in-situ (gauge) river level data.

Demonstrating theoretical feasibility is necessary but not a sufficient condition for proving operational feasibility that is needed for building a stakeholder-owned system in a real-time environment (*Hossain et al., 2013a*). Theoretical feasibility does not necessarily consider the real-world practical constraints of data availability, data latency, sampling hurdles, format and model compatibility and user readiness. *Hossain et al. (2014)* therefore subsequently prototyped the *Biancamaria et al. (2011)* scheme as an operational concept considering many of these practical hurdles in order to consistently realize 5 days of lead time forecasts in a pseudo real-time environment. The currently in-orbit (at the time of writing this manuscript), JASON-2 satellite altimeter was used. The altimeter system is expected to be operational until the end of 2015 when a follow-up mission, JASON-3, is launched with the same inclination and sampling pattern for data continuity. Currently, altimeter data is made available in two latency formats. In the short latency format, known as "Interim Geophysical Data Record" (IGDR), data is made available on the internet within 18 hours of fly over. In the long latency format, the IGDR data is corrected for various issues and replaced as "Geophysical Data Record" (GDR) data. All JASON-2 data is made publicly available on the ftp site of ftp://avisoftp.cnes.fr maintained by the French National Space Agency (Centre National d'Etudes Spatiales or CNES). Herein, we describe very briefly the key features of this prototyped JASON-2 system that is described in greater detail in *Hossain et al. (2013)*.

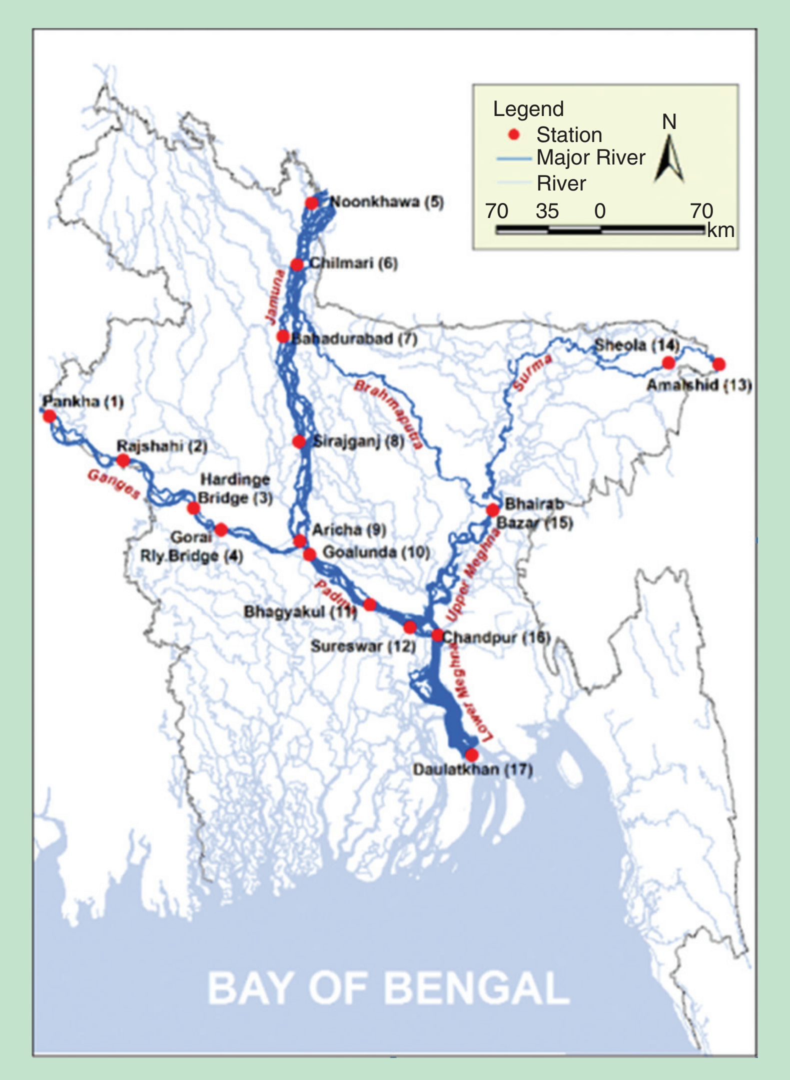


FIGURE 1. The spatial domain for testing forecasting skill of JASON-2 altimetry inside Bangladesh. Solid circles in red represent locations where the official forecasting agency of Bangladesh Government (Flood Forecasting and Warning Center-FFWC; http://www.ffwc.gov.bd) issues 3 day public forecast of river levels during the Monsoon season. The number in parentheses is the station id assigned for operational forecasting.

Seventeen (17) locations on the Ganges, Brahmaputra river system, inside Bangladesh were chosen for testing of the forecasting accuracy of JASON-2 altimeter (Figure 1). These 17 locations are also the stations where the Flood Forecasting and Warning Center (FFWC; http://www.ffwc.gov.bd) of the Bangladesh Government provides official forecasts of river level to the public up to only 3 days of lead time during the Monsoon season. The stations are mostly located along the banks of major rivers where there exists a sizeable farming, fishing and urban community. These 17 flood warning river stations were deliberately chosen with the eventual goal to engineer (for the FFWC) an operational and Government-owned forecasting system based on radar altimetry for real-time decision making in the near future. A hydrodynamic river model, HEC River Analysis Software (RAS), developed at the Hydrologic Engineering Center (HEC), was used (see *Siddique-E-Akbor et al., 2011* for more details). HEC-RAS allows one-dimensional steady and unsteady river flow/level hydraulics calculations. The unsteady water surface profile computation module of HEC-RAS (version 4.0; available at http://www.hec.usace.army.mil/software/hec-ras/) was used to simulate/forecast the daily water level of the major rivers at the 17 flood warning river stations (*Hossain et al., 2013b*).

The general design methodology for deriving altimeter-based forecasting inside Bangladesh can be summarized as follows. 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, these relationships between upstream river level anomalies and downstream river levels are referred to as "Forecasting Rating Curves" (FRC) because of the primary use in forecasting downstream water levels. The various river locations that formed JASON-2 ground track are shown in Figure 2. Such FRCs were derived by establishing a graphical relationship between the instantaneous altimeter water level estimates at upstream locations on Indian rivers to the downstream in-situ river levels at the upstream-most boundary points of the forecasting domain of Bangladesh (Figure 3; *Biancamaria et al., 2011*; *Hossain et al., 2013b*). Next, an FRC sampling scheme was devised to compute an "X" day forecast in an "operational mode" using information only from the altimeter itself. The aim was to compute for each day, noted D, the X-day later forecast discharge, using an FRC as shown on Figure 3, at upstream boundary locations of Bangladesh

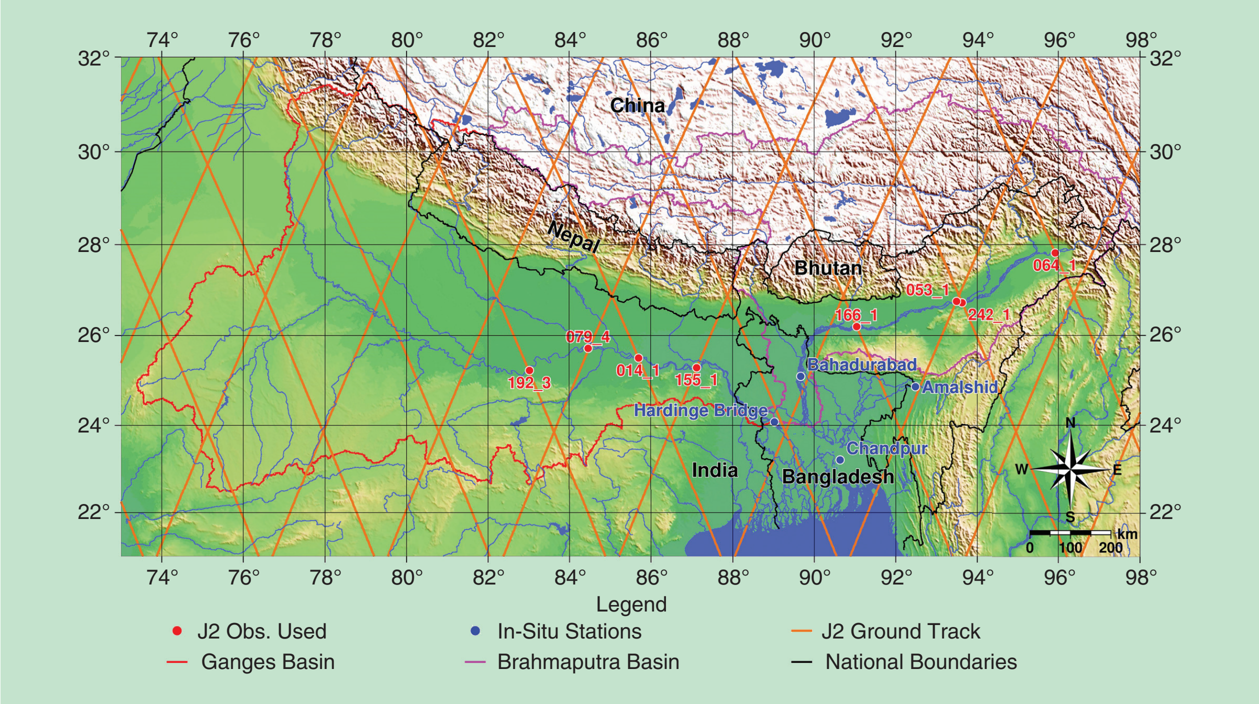


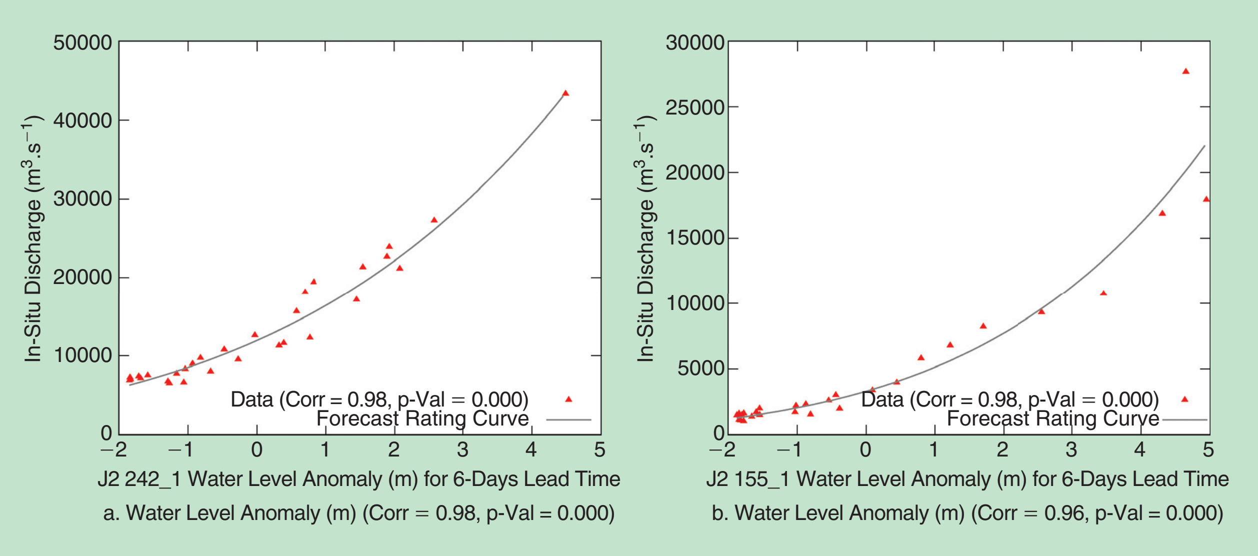
FIGURE 2. Ground tracks or virtual stations of JASON-2 (J2) altimeter over the GB basin shown in yellow lines. The locations where the track crosses a river and used for deriving forecasting rating curves is shown with a circle and station number (magenta—Brahmaputra basin; blue—Ganges basin). Reproduced from *Hossain et al., (2013b)*.

(i.e., Bahadurabad and Hardinge Bridge in Figure 2) for the day of forecast, noted here as Df (i.e., Df=D+X). To do so, the most recent JASON-2 satellite observation in time from day D was selected for each upstream virtual station located in India (Figure 2). The date of the selected JASON-2 observation is referred as DJ2. Thus, there are Df−DJ2=D+X−DJ2 days between the JASON-2 observation and the day of forecast. The corresponding FRC for DJ2=D+X−DJ2 was used to generate the X-day forecast for each day of operational forecasting. Finally, the forecast water level at upstream boundary location at X day was propagated through HEC-RAS model to generate the X day forecast of water level at the 17 flood warning locations.

A point to note is that the system relies on a collection of JASON-2 stations upstream on Ganges (4 virtual stations) and on Brahmaputra (3 virtual stations) for high frequency satellite measurements. JASON-2 typically overpasses a single virtual station every 10 days, which clearly is not enough for flood forecasting at 8 day lead times. A collection of clustered JASON-2 stations ensures a higher frequency of sampling and data availability from upstream locations. For downstream boundary condition, the location selected is as close to the Bay of Bengal as possible with strong tidal effects that can be idealized. The boundary water level for the downstream point of the model boundary is then mathematically modeled as a sinusoidal function or based on climatology. Results reported in *Hossain et al. (2013)* show that JASON-2 based flood forecasting system can retain good fidelity at 5 days of lead time in the 'pseudo' operational mode with an average RMSE (relative to now casting) ranging from 0.5 m to 1.5 m and a mean bias (underestimation) of 0.25 m to 1.25 m in river level estimation. Hereafter, a point to note is that the forecasting accuracy pertains to the cumulative effect of various forecasting components comprising JASON-2, the forecast methodology and the hydrodynamic model used rather than just the altimeter measurement technique.

3. HOW PROMISING IS OPERATIONAL DELIVERY OF OPERATIONAL FORECASTS FOR REAL-TIME DECISION MAKING?

The purpose of this paper is to answer the question—*Can a Radar Altimetry Satellite Deliver on the Promise of an Operational and Real-Time Transboundary Flood Forecasting System For Floodprone Bangladesh?* The previous works (as research) outlined in *Biancamaria et al. (2011)* and *Hossain et al., (2013a, b)* collectively provide proof that the JASON-2 forecasting can work in the pseudo-operational mode if implemented. However, these works do not provide direct and verifiable evidence if the system *has* indeed worked for real-time decision making given the ground realities of the limited infrastructure and human resources capacity available in Bangladesh. Furthermore, *the previous works also do not provide a rigorous assessment of the forecast skill of the system in real-time against independently observed water level data and against the FFWC-issued traditional 3-day forecasts of flooding.* The contribution of this article is in demonstrating that the JASON-2 altimeter based flood forecasting concept is operationally



a. Water Level Anomaly (m) (Corr = 0.98, p-Val = 0.000)

b. Water Level Anomaly (m) (Corr = 0.96, p-Val = 0.000)

FIGURE 3. Example of 6-day forecasting rating curves (FRC) for JASON-2 at ground track (virtual station) location 242_1 (Brahmaputra river–Figure 2) for *Bahadurabad* station (left panel) and 155_1 (Ganges river–Figure 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). Taken after *Hossain et al., (2013b)*.

feasible and can yield skillful forecasts in near real-time. A long-term goal of our work is to provide complete ownership of the altimeter-based forecasting scheme to the stakeholder agencies of the South Asian region as well as other flood-prone downstream nations in other places outlined in *Hossain and Katiyar (2006)* (e.g., such as FFWC in Bangladesh; Center Water Commission- CWC in India; and Water and Power Development Authority—WAPDA in Pakistan).

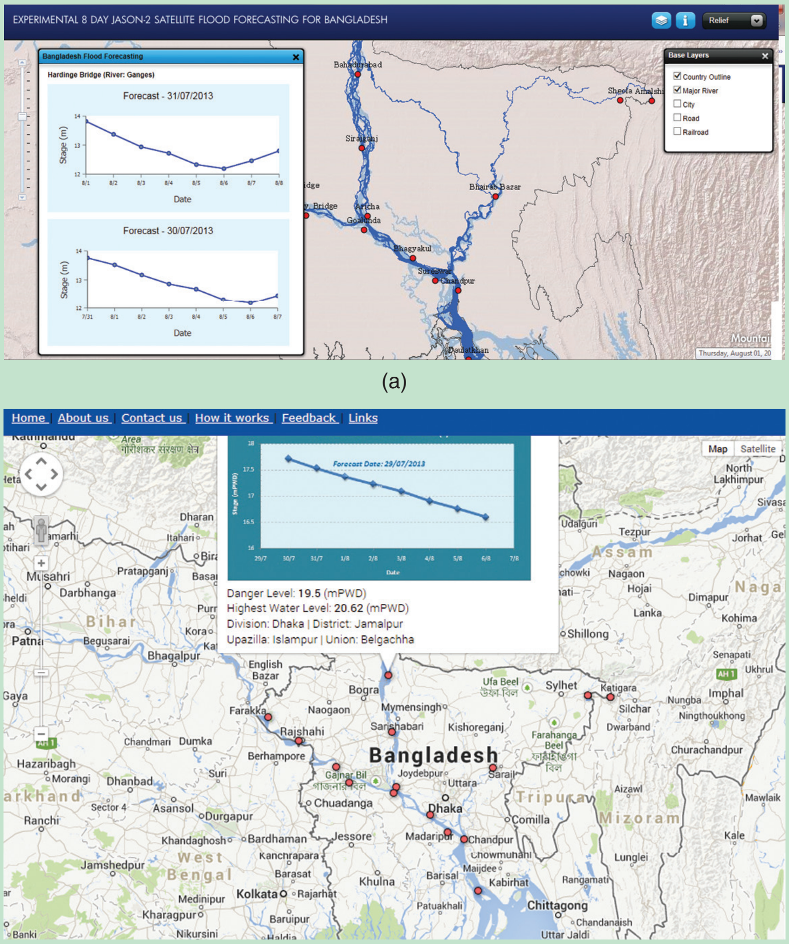
If achieving large-scale buy-in for the satellite altimeter-based system is the key goal, we realized that further work would be needed to: a) train the necessary workforce of the flood forecasting agency (the Institute of Water Modeling-IWM, in this case; http://www.iwmbd.org); b) customize the JASON-2 system within the software and hardware constraints of the existing infrastructure in Bangladesh (such as, internet availability for accessing near-real-time data, computers and data storage); c) create an environment where the flood forecasting agency could independently generate and own routine flood forecasts during the Monsoon season without any external incubation or technical support; and finally, d) make forecasts publicly available in real-time to maximize decision making for the public of Bangladesh.

In an attempt to shore up resources for answering the question posed, *Hossain et al. (2014)* had already reported on the necessity of applying a series of seven steps to transition a research finding to the ultimate operational reality with full ownership for the stakeholder. Herein, we briefly outline these steps below that we had followed:

- **STEP ONE:** Do the Research on Theoretical Feasibility on a Visible Research Publication Forum.
- **STEP TWO:** Disseminate Widely the Theoretical Feasibility to Potential Stakeholder Agencies through a 2-Way Public Education Process. Generate Interest.
- **STEP THREE:** Respond to Skepticism of the Proposed Scheme in an Engaging Way; Do Not Lose Stakeholder Interest by Talking More than Listening.
- **STEP FOUR:** Get Commitment from the Stakeholder Agency to Prototype and Test the Satellite Forecasting System; Start with the Simplest of Ideas.
- **STEP FIVE:** Begin Hands-on Training of Stakeholder Agency Staff for Implementing the Prototype System. Patiently Hand-hold the staff and Teach them Ground up the Basics of the System in an Active-Learning Environment.
- **STEP SIX:** Allocate Supporting Resources to Address Unexpected Hurdles during Launch of the Prototype System.
- **STEP SEVEN:** When Launching the Prototype, Ensure Complete Ownership and Independent Operation.

CALLOUT CALLOUT.

Through a 2-way education/hands-on training workshop conducted during early 2013 at the stakeholder premises (of IWM), we adapted further the design structure of the JASON-2 forecasting system (reported in *Hossain et al.*, 2013b) that would work seamlessly in the operating conditions of the agency. For example, we quickly realized that we would need to work with existing hydrologic-hydrodynamic models of IWM and find ways to ingest the satellite altimetry data accordingly. Suggesting a new model was not an option as that would increase the overhead costs. We also learned that if a proposed new scheme is likely to add to further strain



Danger Level: 19.5 (mPWD)
Highest Water Level: 20.62 (mPWD)
Division: Dhaka | District: Jamalpur
Upazilla: Islampur | Union: Belgachha

(a)

(b)

FIGURE 4. (a) The web portal displaying the dynamic flood forecasts on a web-GIS interface at IWM website. (b) The web portal displaying the dynamic flood forecasting back up (mirror) services on a web-GIS interface at ICIMOD website.

on time, effort and computational resources of the agency, that scheme is less likely to be institutionally embraced without incubation. Thus, all new modeling schemes and data extraction tools we developed further were based on free software tools that were highly popular, easily available, user-friendly (GUI-driven) and with a demonstrated track record of user-friendliness. Lastly, we realized that staff had limited operational skill to handle the unique data format of JASON-2 satellite data. Thus, an intermediate toolbox for format conversion had to be tailored at short notice. Details of these adaptation features are outlined in *Hossain et al. (2013)*.

CALLOUT CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT. CALLOUT.

Once the JASON-2 flood forecasting prototype was customized with the required tailor-made design modifications, we began the process of implementing the system in a real-time mode with the goal of independent management by the staff of IWM. Beginning from June 1, 2013, JASON-2 data began to be downloaded, extracted and then processed routinely for generating 8 day forecasts of river levels at entry points of Bangladesh rivers. These forecasts were then used to initialize the HEC hydrodynamic model that the IWM staff had been trained on. The entire process was independently managed and executed end-to-end by IWM staff. Interested readers are referred to experience the culmination of this application by visiting two dynamic web portals: a) IWM web portal at http://apps.iwmbd.com/satfor shown in Figure 4a; and b) ICIMOD backup web portal at http://apps.geoportal.icimod.org/BDFloodForecasting shown in Figure 4b.

4. ASSESSMENT OF THE PROMISE FOR REAL-TIME DECISION-MAKING

The full-scale operational launch was maintained entirely by IWM staff during the period of June 1 2013 until September 9, 2013 (100 days). This 100 day period essentially covered the Monsoon flood season where the water levels in the rivers of Bangladesh gradually rise by an order of magnitude (during June-July), overflow into the floodplains (during July-Aug) and recede to the low pre-Monsoon levels (during Aug-Sept). In addition, this period also includes the marked inter-seasonal variability dictated by local-scale rainfall events, terrain conditions and transboundary human impacts (such as the opening of an upstream Ganges river barrage known at *Farakkha Barrage* in India). For each of the 100 days, the corresponding observed water level, as reported by FFWC in its official forecast website (www.ffwc.gov.bd) along with the official 3 day forecast at each of these 17 stations were also recorded for a post-Monsoon assessment of forecast skill.

Figure 5 demonstrates the comparison of water level hydrographs for 8 days and 3 days lead time with observed water levels (for the forecast dates). The comparison is presented for two river stations (one each for Ganges and Brahmaputra rivers). An assessment of the Root Mean Squared

FIGURE 5. Observed and forecast water level hydrographs for 8 days (left panels) and 3 days (right panels) lead time. The upper panels are for a river station on the Ganges River (Hardinge Bridge), while the lower panels are for a river station on the Brahmaputra River (Bahadurabad).

Error (RMSE) and correlation of forecast of JASON-2 system as a function of lead time (from 1 day to 8 days) was also performed for the warning stations with the most complete record of observed data. In addition, the danger level, defined as the water elevation beyond which large-scale inundation of homesteads or cropland begin, was noted for computing the Signal-to-Noise Ratio (SNR) of the forecast. For example, if a station with id#1 had a danger level of 24 meters (relative to the river bed) and a forecast RMSE at X day of 2 meters, then the SNR for lead time of X days would be 24/2=12 (considered very high). On the other hand, a station with a danger level of 8 meters (relative to the river bed) and a reported RMSE of 2 meters, would yield a SNR of 8/2=4 (considered very low). Herein, we consider arbitrarily an SNR exceeding 10 (one order of magnitude) as having the necessary decision making utility in real-time for adaptation against anticipated flood inundation.

Figure 6 shows a sample plot for RMSE and correlation as a function of forecast lead time at three FFWC warning stations. Careful inspection of such plots at all other warning stations reveals the following skill features of the JASON-2 flood forecasting system (Table 1):

1) The minimum correlation at the 8 days lead time is always higher than 0.70.
2) Correlation for most of the warning stations range between 0.95 to 0.80 during the 1 to 8 days lead time range.
3) RMSE of forecast typically ranges between 0.75m to 1.5m.
4) RMSE of forecast at the 8 days lead time do not exceed 2m for upstream and mid-stream rivers inside Bangladesh with a reported danger level that is an order higher (such as the stations of Pankha, Hardinge Bridge, Gorai Railway Bridge, Chilmari, Serajganj, Bahadurabad, Amalshid, Sheola). Thus, upstream and mid-stream regions of the rivers of Brahmaputra, Ganges and Surma inside Bangladesh yield acceptable SNR ranging from 10 to 20.
5) RMSE of forecast at the 8 day lead time exceeds 2m for the downstream rivers with a reported danger level that is not an order higher (such as Aricha, Chandpur, Bhairab Bazaar). Thus, downstream regions of the rivers of Brahmaputra, Ganges and Meghna near the estuary with the Bay of Bengal yield the lowest (and unacceptable) SNR ranging from 3 to 6. The main reason for the low SNR can be attributed to the downstream boundary condition of water level in the Meghna estuary not being captured accurately for the HEC-RAS model. Thus, the uncertainty in the tidal fluctuations propagates further upstream to contaminate the skill of the forecast at these FFWC warning stations).

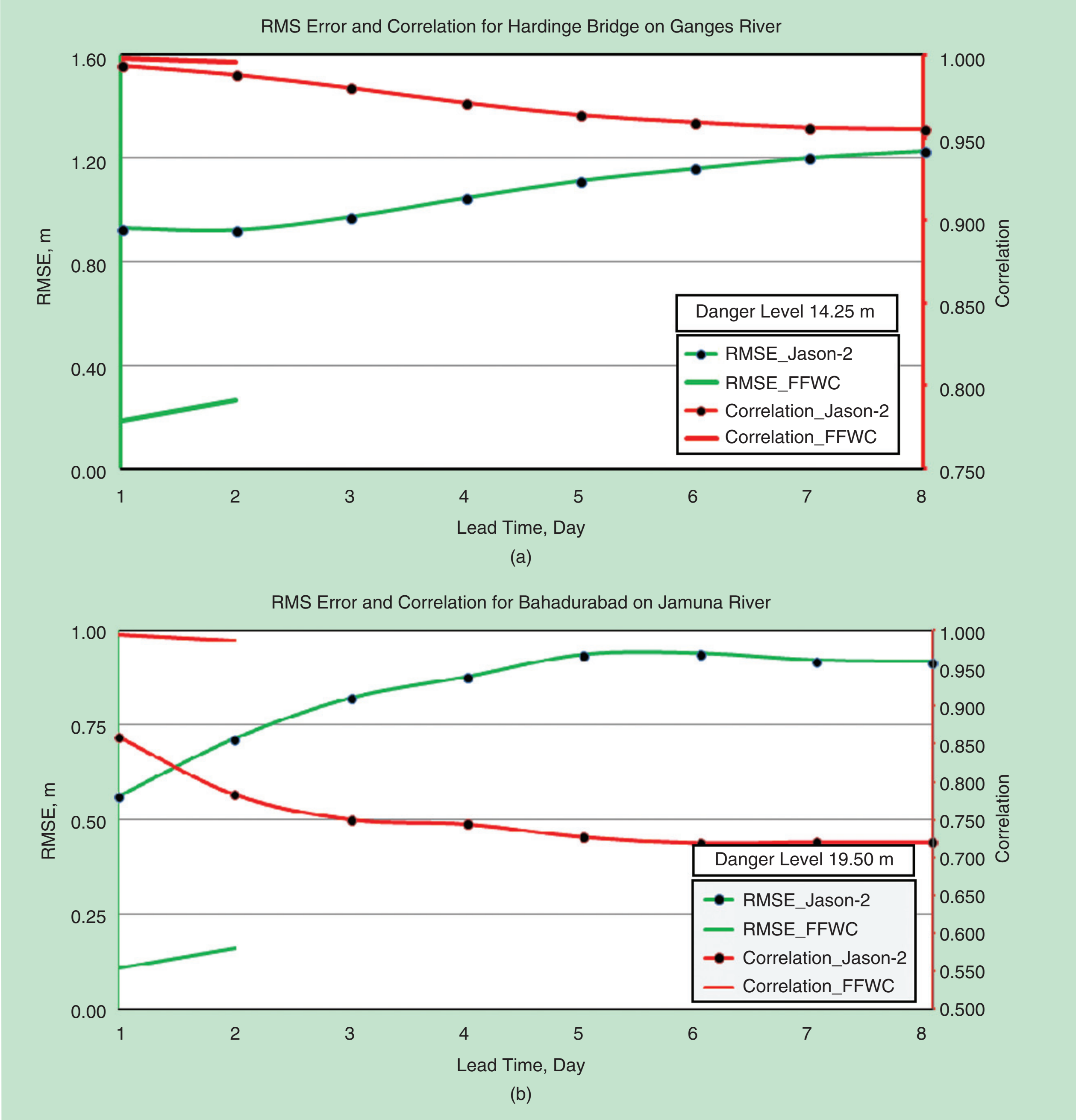


FIGURE 6. Assessment of JASON-2 forecasting skill for warning stations Hardinge Bridge (a) and Bahadurabad (b). For location of the stations, refer to Figure 1. The lines without dark circles refer to the Govt's official 3 day forecast. The 3rd day was often times not reported in www.ffwc.gov.bd.

6) For all FFWC-generated forecast, the lead time reported officially never exceeded 2 days during the 100 day assessment period (as opposed to the 3 days that is commonly known) [Note: The reason for this is unknown to us]. The FFWC RMSE is lower than the JASON-2 RMSE at the 2 days lead time. However, this is not unexpected as the current FFWC system combines persistence with extensive human intervention and applies complex hydrologic and atmospheric models for forecasting boundary flow conditions. On the other hand, the JASON-2 system is entirely hydrodynamic model-based (non-persistence based) and automated (with no routine human intervention for quality check).

5. CONCLUSION

To the best of our knowledge, the rigorous assessment of flood forecast skill up to 8 days of lead time for a real-time and independently managed (by a stakeholder agency) satellite altimeter-based system is perhaps the first of its kind reported in literature. Such an assessment provides a consistent and verifiably affirmative response to the question we posed earlier—*Can a Radar Altimetry*

TABLE 1. SUMMARY OF FORECAST SKILL OF JASON-2 FLOOD FORECASTING SYSTEM AT FFWC WARNING STATIONS. THE MAXIMUM AND MINIMUM FOR CORRELATION AND RMSE PERTAIN TO THE 1 DAY TO 8 DAY LEAD TIMES.

JASON-2 FORECAST SKILL AT 1 TO 8 DAY LEAD TIMES					
STATION ID NAME OR RIVER			**STATION ID NAME OR RIVER**		
PANKHA	**RMSE**	**CORRELATION**	**BHAGAKUL**	**RMSE**	**CORRELATION**
Maximum	1.872	0.980	Maximum	2.111	0.973
Minimum	1.740	0.932	Minimum	1.746	0.816
HARDINGE BRIDGE			**AMALSHID**		
Maximum	1.228	0.994	Maximum	1.061	0.920
Minimum	0.920	0.955	Minimum	0.981	0.888
GORAI RAILWAY BRIDGE			**SHEOLA**		
Maximum	1.122	0.996	Maximum	2.036	0.937
Minimum	0.683	0.951	Minimum	1.552	0.907
NOONKHAWA			**BHAIRAB BAZAR**		
Maximum	0.952	0.855	Maximum	2.521	0.884
Minimum	0.626	0.760	Minimum	2.070	0.642
CHILMARI			**CHANDPUR**		
Maximum	1.209	0.882	Maximum	3.190	0.793
Minimum	0.879	0.769	Minimum	2.954	0.642
BAHADURABAD			**DOULATKHAN**		
Maximum	0.939	0.860	Maximum	1.891	0.478
Minimum	0.562	0.720	Minimum	1.569	−0.391
SERAJGANJ			**GOALAND**		
Maximum	1.252	0.915	Maximum	1.513	0.983
Minimum	0.699	0.708	Minimum	1.000	0.855

Satellite Deliver on the Promise of an Operational and Real-Time Transboundary Flood Forecasting System for Floodprone Bangladesh? When a satellite-based system consistently generates high SNR (and low RMSE below 1 m) even at the 8 days lead time at most flood warning locations, there remains little doubt about the tremendous potential that satellite altimeters have for the other 33 downstream nations currently deprived of upstream flow data in real-time. In addition, such a satellite system is also poised to serve the entire inhabitants or the larger river basin rather than only the downstream regions if the concept of upstream versus downstream forecast rating curves is re-applied. We note that our achievement of a 100 day successful JASON-2 flood forecasting run, for the first time in history, would not have been possible without the numerous staff, national and international agencies, unselfish support and dedication from various quarters over the period of 4 years since the dream of empowering a developing nation was born in 2006 (*Hossain and Katiyar, 2006*).

It is worthwhile to note that after the phasing out of JASON-2 in the near future, JASON-3 is scheduled to be launched in 2015. The Indo-French satellite altimeter mission, named SARAL has also been launched in 2013. In addition, European Space Agency's (ESA) Sentinel-3 (2-satellite constellation) will be launched in 2015. Finally, the proposed Surface Water and Ocean Topography (SWOT) wide-swath radar interferometric altimetry mission (see http://swot.jpl.nasa.gov) is also scheduled for launch in 2020. 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 at short latency. Thus, a new era of abundant water elevation data from satellite altimetry missions awaits us in the foreseeable future. With such a prolonged window of data continuity and minimum latency, developing 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 flood adaptation.

CALLOUT CALLOUT.

ACKNOWLEDGMENTS

The first author acknowledges the gracious support provided by the US Department of State (Fulbright Program) for capacity building of Bangladesh flood forecasting infrastructure. Additional support from NASA Physical Oceanography program (NN13AD97G) and NASA SERVIR program (NNX12AM85AG) is also acknowledged. The authors are also grateful to the generous support received from the Institute of Water Modeling (IWM) in Bangladesh for access to quality controlled discharge and river level data as part of a 5-year MOU between TTU and IWM.

AUTHOR INFORMATION

Faisal Hossain *received his Ph.D. from The University of Connecticut in 2004. Prior to that, he had earned his M.S. and B.S. from The National University of Singapore and Indian Institute of Technology, Varanasi, respectively. He is currently an Associate Professor in the Department of Civil and Environmental Engineering where he received one of highest awards of University—the Caplenor Research Award in 2012. His research interests comprise hydrologic remote sensing, uncertainty modeling of water cycle variables, human modification of extreme hydro-climatology, sustainable water resources engineering, space-borne transboundary water resources management, engineering education and public outreach. He is also the recipient of awards such as NASA Earth System Science Fellowship (2002), Outstanding PhD Thesis Award (2005), NASA New Investigator Award (2008), American Society of Engineering Education (ASEE) Outstanding Research Award (2009), National Association of Environmental Professionals Education Excellence Award (2010), US Fulbright Faculty Award (2012), G.O.L.D. (Graduate Of the Last Decade) award from University of Connecticut (2012) and American Geophysical Union (AGU) Charles Falkenberg Award. He has published over 85 peer-reviewed journal articles, authored an undergraduate-level textbook, edited two book volumes and contributed eight book chapters. His recent research on human modification of extreme events by artificial reservoirs has been featured by public media such as the BBC, National Geographic, New Scientist, Newsweek, Fox News, MSNBC, Wired.com and German Public Radio. He served as associate editor of Journal of American Water Resources Association from 2006–2010. Currently he serves as an associate editor for Journal of Hydrometeorology and lead editor for the water volume of Elsevier Sciences 5 volume reference series on "Climate Vulnerability: Understanding and Addressing Threats to Essential Resources."*

CALLOUT CALLOUT.

6. REFERENCES

[1] C. M. Birkett, "The contribution of TOPEX/POSEIDON to the global monitoring of climatically sensitive lakes," *J. Geophys. Res.*, vol. 100, no. C12, pp. 25179–25204, 1995.

[2] M. H. N. Bakker, "Transboundary river floods and institutional capacity," *J. Amer. Water Resour. Assoc.*, vol. 45, no. 3, pp. 553–566, 2009.

[3] C. Balthrop and F. Hossain, "A review of state of the art on treaties in relation to management of transboundary flooding in international river basins and the global precipitation measurement mission," *Water Policy*, 2010.

[4] F. A. Hirpa, T. Hopson, T. De Groeve, G. R. Brakenridge, M. Gebremichael, and P. J. Restrepo, "Upstream satellite remote sensing for river discharge prediction: Application to major rivers in South Asia," *Remote Sens. Environ.*, 2012.

[5] T. M. Hopson and P. J. Webster, "A 1–10 day ensemble forecasting scheme for the major river basins of Bangladesh: Forecasting severe floods of 2003–2007," *J. Hydrometeorol.*, vol. 11, no. 3, pp. 618–640, 2010.

[6] F. Hossain, C. K. Shum, F. J. Turk, S. Biancamaria, H. Lee, A. Limaye, L. C. Mazumder, M. Hossain, S. Shah-Newaz, T. Ahmed, W. Yigzaw, and A. H. M. Siddique-E-Akbor, "A guide for crossing the valley of death: Lessons learned from making a satellite based flood forecasting system operational and independently owned by a stakeholder agency," *Bull. Amer. Meteorol. Soc.*, 2014.

[7] F. Hossain, A. H. M. Siddique-E-Akbor, L. C. Mazumder, S. M. ShahNewaz, S. Biancamaria, H. Lee, and C. K. Shum, "Proof of concept of an operational altimeter-based forecasting system for transboundary flow," *IEEE J. Select. Topics Appl. Remote Sens.*, vol. 7, no. 2, pp. 587–601, 2013.

[8] F. Hossain and N. Katiyar, "Improving flood forecasting in international river basins," *EOS Trans. Amer. Geophys. Union*, vol. 87, no. 5, pp. 49–50, 2006.

[9] F. Hossain, "Satellites as the panacea to transboundary 380 limitations to longer range flood forecasting?" *Water Int.*, vol. 32, no. 3, pp. 376–379, 2007.

[10] N. Katiyar and F. Hossain, "An open-book watershed model for prototyping space-borne flood monitoring systems in international river basins," *Environ. Model. Softw.*, vol. 22, no. 12, pp. 1720–1731, 2007.

[11] C. B. Moffit, F. Hossain, R. F. Adler, K. Yilmaz, and H. Pierce, "Validation of TRMM flood detection system over Bangladesh," *Int. J. Appl. Earth Observ. Geoinform.*, vol. 13, pp. 165–177, 2010.

[12] B. Nishat and S. M. Rahman, "Water resources modeling of the Ganges-Brahmaputra-Meghna river basins using satellite remote sensing data," *J. Amer. Water Resour. Assoc.*, vol. 45, no. 6, pp. 1313–1327, 2009.

[13] G. N. Paudyal, "Forecasting and warning of water-related disaster in a complex hydraulic setting: The case of Bangladesh," *Hydrologic. Sci. J.*, vol. 47, no. S1, pp. S5–S18, 2002.

[14] G. Schumann, P. D. Bates, M. S. Horritt, P. Matgen, and F. Pappenberger, "Progress in integration of remote sensing–derived flood extent and stage data and hydraulic models," *Rev. Geophys.*, vol. 47, no. 4, Article RG4001, 2009.

[15] A. H. Siddique-E-Akbor, F. Hossain, H. Lee, and C. K. Shum, "Inter-comparison study of water level estimates derived from hydrodynamic-hydrologic model and satellite altimetry for a complex deltaic environment," *Remote Sens. Environ.*, vol. 115, no. 6, pp. 1522–1531, 2011.

[16] P. J. Webster, J. Jian, T. M. Hopson, C. D. Hoyos, P. Agudelo, H-R. Chang, J. A. Curry, R. L. Grossman, T. N. Palmer, and A. R. Subbiah, "Extended-range probabilistic forecasts of Ganges and Brahmaputra floods in Bangladesh," *Bull. Amer. Meteor. Soc.*, vol. 91, no. 11, pp. 1493–1514, 2010.

GRS