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

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1           **PROOF OF CONCEPT OF AN ALTIMETER-BASED RIVER FORECASTING**  
2                           **SYSTEM FOR TRANSBOUNDARY FLOW INSIDE BANGLADESH**

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35

36 **Abstract**

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

57  
58 **Keywords:** Forecasting, satellite radar altimeter, Ganges, Brahmaputra, transboundary flow,  
59 JASON-2.

61 **1.0 INTRODUCTION**

62           Surface water does not flow according to political boundaries. It flows only according to  
63 the topographic limits and along gradients of the land surface. Yet more than 260 river systems  
64 of the world are subject to international political boundaries (Wolf et al., 1999). These basins are  
65 known as International River Basins (IRB) and they have transboundary rivers flowing from one  
66 nation to another within the basin before draining to a lake or an ocean. A total of 145 countries  
67 are geographically part of an IRB, which represents more than 40% of the Earth's land mass  
68 (Wolf et al., 1999).

69           Forecasting of transboundary flow in downstream nations of these IRBs however remains  
70 notoriously difficult due to the lack of basin-wide *in-situ* hydrologic measurements or its real-  
71 time sharing among nations. This difficulty is exacerbated by a combination of poor ground  
72 infrastructure and poor institutional capacity to manage water resources jointly among riparian  
73 nations (Bakker, 2009). Survey indicates that about 33 such downstream countries have more  
74 than 95% of their territory bounded within IRBs (Hossain and Katiyar, 2006; Hossain, 2007),  
75 making such countries heavily dependent on hydrologic data from not just within their borders  
76 but also beyond from upstream nations. While transboundary river flooding represents only 9.9%  
77 of all recorded flood events, they account for 32% of all casualties, almost 60% of affected  
78 individuals, and 14% of financial damage (Bakker, 2009). The disproportionate relationship  
79 between occurrence and impact of transboundary floods can often be traced to the lack of real-  
80 time communication between countries on rainfall and stream flow data that are essential for  
81 flood monitoring (Balthrop and Hossain, 2010).

82           Bangladesh, like several flood prone nations in IRBs around the world, represents one  
83 such classic example, where transboundary flow accounts for more than 90% of the surface

84 water during the Monsoon season, and its operational forecasting capability remains severely  
85 limited to only a 3 day lead based purely on persistence (Figure 1). Two specific issues make the  
86 extension of the lead time difficult: 1) because Bangladesh occupies only 7% of the total  
87 drainage area of the Ganges-Brahmaputra (GB) basins, 90% or more of the required spatial  
88 coverage of hydrologic data is controlled by the upstream nations of India and Nepal (Paudyal,  
89 2002); and 2) increasing human impoundment of rivers by nations upstream of Bangladesh  
90 makes conventional forecasting based on stand-alone hydrologic and atmospheric/climate  
91 models very difficult (see Figure 1 for location of dams) (Vorosmarty et al., 2009; Hossain et al.,  
92 2009; Siddique-E-Akbor et al., 2011).

93         Recent studies however have shown that a combination of satellite estimates of rainfall  
94 and modeling can forecast stream flow in Bangladesh (Nishat and Rahman, 2010; Moffit et al.,  
95 2011). Such studies collectively provide a very useful platform to address emerging challenges to  
96 forecasting dictated by the increasing impoundment of rivers upstream of flood-prone  
97 downstream nations. For example, as a low lying delta, Bangladesh is most vulnerable to  
98 unilateral human activity by the upstream nations, such as extraction, diversion and dam  
99 impoundment of river waters (Figure 1). Some pertinent examples are the Farakka barrage on the  
100 Ganges (commissioned in 1976), and the recently revived Indian River Linking Project (IRLP;  
101 Misra et al., 2007). Such diversions stand to make persistence-based or hydrologic model-based  
102 forecasting less effective without prior knowledge of the day-to-day flow regulation schedule  
103 from India. Other notable and man-made issues are the plans by the Chinese Government to  
104 impound the Brahmaputra River in Tibet (Evans and Delaney, 2011).

105         INSERT FIGURE 1 HERE

106 Thus, human intervention through extensive upstream flow regulation will likely be a  
107 critical factor in future that will control the downstream forecasting accuracy, no matter how  
108 well the forecasting system adequately represents the natural dynamics of atmospheric and  
109 terrestrial flows. However, if satellites could provide a proxy way of timely monitoring the  
110 upstream regulation of flow, such as estimating river level behind a dam or barrage, then the  
111 accuracy of a downstream forecasting system could be preserved at tactical timescales (days to  
112 weeks) of decision making. Using NASA/CNES TOPEX/POSEIDON (T/P) satellite altimetry  
113 measurements of water levels in India, Biancamaria et al. (2011) have demonstrated exactly this  
114 point. Their work has revealed that it is feasible to practically forecast water elevation anomalies  
115 (i.e., fluctuations) during the critical Monsoon season (June to September) near the Bangladesh  
116 border. The T/P-based forecasting scheme reported an RMSE of about 0.40 m (0.6–0.8 m) for  
117 lead times up to 5-days (10 days) without having to rely on any upstream *in-situ* (gauge) river  
118 level data. The need to extend forecasting lead time has a strong motivation from the standpoint  
119 of preventing loss of life and economic damages (ADPC, 2002; Bakker, 2006).

120 Satellite-based flood forecasting is also important for gauging the societal value of the  
121 planned future NASA/CNES satellite hydrology mission called the Surface Water and Ocean  
122 Topography (SWOT). The body of research over the past two decades on evaluating the  
123 feasibility of measuring discharge from space (e.g, Birkett et al., 2002; Frappart et al., 2005,  
124 2008; Lee et al., 2009, among others) has now culminated in the planned SWOT mission  
125 dedicated to space-based surface discharge measurements using the concept of water elevations  
126 and slope (Alsdorf et al., 2003). With a launch date timeframe around 2019, SWOT's nadir Ka-  
127 band altimeter and wide-swath interferometric altimetry has an aim to provide global sampling  
128 of surface water elevations to derive discharge and water storage change for rivers with widths

129 greater than 50 m, at an accuracy of a few centimeters when averaged over  $\sim 1 \text{ km}^2$  of river area  
130 (Alsdorf et al., 2007). In particular, for the humid tropics (the focus of our study), where most of  
131 the world's populous delta nations (in international river basins) are located, the planned 22-day  
132 (maximum) repeat sampling of SWOT will provide at least 2 observations in 3 weeks over these  
133 humid tropics (see <http://swot.jpl.nasa.gov>). An innovative aspect of SWOT will be the estimate  
134 of water surface elevation and slope from the 120 km wide-swath interferometric altimeter  
135 (known as KaRIn, Ka-band Radar Interferometer) to measure the hydraulic gradient line of river  
136 flow. Combined with an estimate of the river width and the inundated area of flow that will also  
137 be available, SWOT represents currently the only space mission planned exclusively for  
138 discharge estimation over land.

139         It is important at this stage to briefly review the state of the art of river discharge  
140 estimation from a remote sensing perspective. Discharge can be estimated by utilizing the one of  
141 commonly extractable physical variables from space-borne observables, such as, 1) water level  
142 (height) change by radar altimeters (e.g. Birkett et al., 2002; Kouarev et al., 2004; Papa et al.,  
143 2010; Biancamaria et al., 2011); 2) river width/inundated area by passive microwave (PMW)  
144 sensors (e.g. Brakenridge et al., 2005, 2007; Bjerklie et al., 2005; Temimi et al., 2011; Khan et  
145 al., 2011; see also: <http://floodobservatory.colorado.edu/IndexMapweb.htm>); and 3) slope of  
146 water level change (e.g. Alsdorf et al., 2007; LeFavour and Alsdorf, 2005; Jung et al., 2010;  
147 Woldemichael et al., 2010). The slope-based techniques have only been assessed against Shuttle  
148 Radar Topography Mission (SRTM) measurements of water elevations over a small sampling  
149 period of 11 days in the year 2000.

150         Our study is specifically focused on the river water level (i.e., height) based technique of  
151 discharge estimation using radar altimeters. For large river basin, such as the one studied here

152 (Ganges-Brahmaputra), there are sufficient altimeter ground tracks over major rivers and  
153 neighboring tributaries to collectively guarantee at least two samples per basin per day as an  
154 indication of flow. For example, for the Ganges-Brahmaputra basins, there are more than twenty  
155 JASON-2 ground tracks on the main stem rivers and neighboring tributaries. Second, the  
156 collective sampling of the constellation of nadir altimeters that can be expected to fly in the near  
157 future (JASON-2, AltiKa, JASON-3 and Sentinel-3) will considerably improve sampling further.  
158 We discuss the sampling issue later in the paper (sections 3 and 5). We believe that the  
159 synergistic use of all the techniques requires a thorough assessment of the individual methods.

160 This study extends the work of Biancamaria et al. (2011) and assesses the accuracy of a  
161 currently operational (as of June 2012) satellite altimeter - JASON-2 - for forecasting  
162 transboundary flow (i.e., river levels in this case) at locations further inside the downstream  
163 nation of Bangladesh. This is achieved by propagating forecasts derived from upstream (Indian)  
164 locations through a hydrodynamic river model. The goal of this study is to answer the question –  
165 *how practically useful is satellite altimeter for forecasting flows further inside Bangladesh for*  
166 *the public?* Detailed knowledge of the forecasting accuracy of a purely altimeter-based system  
167 can help guide the future development of more complex schemes involving data assimilation  
168 (Durand et al., 2008), statistical regression and persistence methods (Pingel et al., 2005), to  
169 extend further the forecast lead time.

170 The paper is organized as follows. Section 2 provides an overview of the study region  
171 (Bangladesh in the larger setting of the GB basins) and the forecasting domain. It also presents  
172 the hydrodynamic river model used for propagating the altimeter-based forecast further inside  
173 Bangladesh. Section 3 addresses the methodology. This comprises an overview of the JASON-2  
174 altimeter and the derivation of forecasts from Indian river locations. This section also describes



175 in detail how a daily streaming of 5-day forecast of river water level was created on the basis of  
176 the infrequent JASON-2 sampling over the GB basins. Finally, section 4 presents the results and  
177 discussions of study findings.

178

## 179 **2.0 FORECASTING DOMAIN AND HYDRODYNAMIC RIVER MODEL**

180 The domain for testing the forecasting accuracy of altimeter-based system was  
181 Bangladesh (Figure 2), which is the world's largest delta with extensive *in-situ* hydraulic and  
182 hydrologic data available to the authors through a Memorandum of Understanding (MOU)  
183 between the Institute of Water Modeling (IWM) of Bangladesh and Tennessee Technological  
184 University (TTU). As mentioned earlier, the lack of a data sharing treaty or basin-wide ground  
185 instrumentation in the GB basins means that flow data in transboundary regions is unavailable to  
186 Bangladesh at timescales of operational forecasting (daily) (Balthrop and Hossain, 2010). One of  
187 the rivers, the Ganges, is already impounded immediately upstream of the India-Bangladesh  
188 border (Figure 1), wherein the regulated nature of flow during the dry season limits the  
189 effectiveness of stand-alone hydrologic models to forecast flow downstream into Bangladesh.  
190 Inside Bangladesh, a dense drainage network comprising more than 300 rivers, make the delta  
191 one of the most riverine in the world (Figure 2).

192

193 INSERT FIGURE 2 HERE

194 Seventeen (17) locations on the Ganges, Brahmaputra river system, inside Bangladesh  
195 were chosen for testing of the forecasting accuracy of JASON-2 altimeter. These 17 locations are  
196 also the stations where the Flood Forecasting and Warning Center (FFWC) of the Bangladesh  
197 Government provide official forecasts of river level to the public at 3-day lead time during the

198 Monsoon season. We deliberately selected these 17 warning stations with the view to engineer  
199 (for FFWC and the people of Bangladesh) an operational forecasting system based on altimetry  
200 for real-time decision making in the near future. The internet (web-site at  
201 <http://www.ffwc.gov.bd>), cell-phone text messaging, and state-run media (TV and radio) are the  
202 three main delivery mechanisms by which the general public gets access to this official 3 day  
203 forecast. The stations “*Noonkhawa*” for the Brahmaputra river, “*Jangipur Barrage*” for the  
204 Ganges river and “*Amalshid*” for the Meghna river are the upstream-most locations of the  
205 current forecasting domain for Bangladesh. Hence, these locations represent the upstream  
206 boundary condition points for the hydrodynamic river model (discussed next), while for the  
207 downstream boundary condition point, the tidal station in the Meghna estuary (near the Bay of  
208 Bengal) is “*Daulatkhan*” (Figure 2).

209         The hydrodynamic river model used in this study was the HEC River Analysis Software  
210 (RAS), developed at the Hydrologic Engineering Center (HEC), of the U.S. Army Corps of  
211 Engineers. This hydrodynamic modeling software allows one-dimensional steady and unsteady  
212 flow river hydraulics calculations. In this study, the water surface profile computation module of  
213 HEC-RAS (version 4.0) was used to simulate the daily water level of the major rivers of  
214 Bangladesh shown in Figure 3. We used the model set up that was developed and verified by  
215 Siddique-E-Akbor et al. (2011), wherein HEC-RAS was used to compare the detection of river  
216 levels by satellite altimetry (ENVISAT in this case) against *in-situ* data or model-based  
217 simulations. For details on the model set up and simulation accuracy of nowcasting, the reader is  
218 referred to Siddique-E-Akbor et al. (2011). Herein, we provide only a very brief summary to help  
219 readers understand how altimeter-based forecasting skill was evaluated.

220 The HEC-RAS model was schematized at 226 river cross section locations on the major  
221 rivers of Bangladesh shown in Figure 2 (Siddique-E-Akbor et al., 2011). These river cross  
222 sections were obtained from IWM as part of its periodic field campaign to update river  
223 bathymetry of major rivers during the post-Monsoon season. River bathymetry requires frequent  
224 check through field surveys because of the shifting nature and extensive bank erosion of  
225 Bangladesh rivers. The spacing between river cross sections varied from 2.5 km to 10 km. This  
226 allowed the simulation of river level dynamics at close spacing and consequently resulted in 17  
227 locations that matched with FFWC forecast stations. Using chainage information from the  
228 bathymetry survey provided by the IWM, cross section data was entered in to the HEC-RAS  
229 schematization system.

230 INSERT FIGURE 3a HERE

231 Daily flow measurements (rated from river level observations) were used at the three  
232 most upstream entry points (for each river) in Bangladesh near the India-Bangladesh border  
233 (Figure 2). The rating curves for estimating discharge from river level had acceptable accuracy.  
234 For example, for the *Bahadurabad* station on the Brahmaputra river, the 10-year climatologic  
235 RMSE and mean error in estimating discharge from river level was found to be 2485 m<sup>3</sup>/s and 70  
236 m<sup>3</sup>/s, respectively (Figure 3a). In terms of percentage of climatologic mean flow (20,563 m<sup>3</sup>/s),  
237 the RMSE and mean error represent 12% and 0.3%, respectively. For the downstream boundary,  
238 HEC-RAS was forced with measured tidal river stage data at the most downstream point named  
239 *Daulatkhan* on the Lower Meghna river close to the Bay of Bengal (Figure 2). During  
240 forecasting, it is acceptable to use *in-situ* (or nowcast) water level data at the downstream-most  
241 boundary point (near the ocean) since that is the only type of information that an operational  
242 forecaster will have.

243 INSERT FIGURE 3B HERE

244 The simulation period for this study was 2008-2010. Figure 3b shows the calibration of  
245 the HEC-RAS model for the period using in-situ boundary condition data (at upstream and  
246 downstream points) for the period. Calibration was performed manually against *in-situ* river  
247 level measurements at sampled locations with the goal to minimize the RMSE of river level  
248 simulation by HEC-RAS. The primary parameter that was iterated for calibration was Manning's  
249 roughness coefficient for each river segment (e.g. Ganges, Brahmaputra and Meghna). Further  
250 details of calibration are provided in Siddique-E-Akbor et al. (2011). The simulated river level  
251 data at the 17 FFWC locations derived from the calibrated HEC-RAS model and forced with *in-*  
252 *situ* boundary data was therefore considered as '*nowcasting*' data. This was then treated as  
253 reference for testing the forecasting accuracy of JASON-2.

254 Before presenting the methodology used in forecasting, it is important to discuss the  
255 representativeness of the HEC-RAS as the hydrodynamic for water level simulations. Figure 3b  
256 shows that HEC-RAS systematically over-predicts the peaks with an increasing bias further  
257 downstream. One potential reason for this could be that the downstream water level boundary  
258 condition may be such that the model generates backwater and tidal effects further upstream that  
259 are not present in reality. Second, the HEC-RAS model, being essentially a 1-D model, may not  
260 be representing floodplain storage adequately for two key reasons: 1) the river cross sections  
261 may not extend sufficiently far across the floodplain; 2) the inherent limitations of the 1D  
262 representation of HEC-RAS to simulate 2-D lateral overbank flow (Prestininzi et al., 2011;  
263 Kalyanapu et al., 2011).

264

### 265 **3.0 METHODOLOGY**

266 The general methodology for testing the accuracy of the altimeter forecasting inside  
267 Bangladesh is presented below and also summarized as a schematic in Figure 4. First,  
268 quantitative relationships in the form of ‘rating curves’ were derived at various river locations in  
269 upstream India that matched with the JASON-2 altimeter ground tracks (also known as ‘virtual  
270 stations’). Conventional rating curves quantify the instantaneous relationship between estimated  
271 discharge and measured river level. To avoid confusion, we name the relationships between  
272 upstream river level anomalies and downstream river discharge as “Forecasting Rating Curves”  
273 (FRC) because of the primary use in forecasting. The various river locations that formed  
274 JASON-2 ground track are shown in Figure 5. Such FRCs were derived by establishing a  
275 graphical relationship between the instantaneous altimeter water level anomaly estimates (i.e.,  
276 anomaly relative to the calibration period, October 2008 – June 2009, in this case) at upstream  
277 locations on Indian rivers to the downstream *in-situ* discharge at the upstream-most boundary  
278 points of the forecasting domain of Bangladesh.

279 We used the nearest *in-situ* river level data pertaining to *Bahadurabad* (Brahmaputra  
280 river) and *Hardinge Bridge* (Ganges river), respectively, in accordance with the practice  
281 followed by Siddique-e-Akbor et al. (2011). As an example, Figure 6 shows the 6 day FRC (i.e.,  
282 for a lead of 6 days) derived for specific JASON-2 ground tracks over Indian locations of Ganges  
283 and Brahmaputra rivers. Development of the FRCs were guided by the previous work of  
284 Biancamaria et al. (2011) that investigated the relationships as a function of season (Monsoon,  
285 and dry season) and lags. Historical data spanning October 2008 – June 2009 was used to derive  
286 these FRCs at various lead times for all the JASON-2 ground track stations shown in Figure 5.

287 INSERT FIGURE 4 HERE

288 INSERT FIGURE 5 HERE

289 We used the JASON-2 Sensor Geophysical Data Record (SGDR, product version “T”)  
290 data set, which contains 20-Hz 104-sample radar waveforms, spanning from cycle 7 to 95  
291 (September 2008 – February 2011). Geophysical corrections (solid Earth and pole tides), and dry  
292 troposphere correction are applied. For these data, wet troposphere correction was calculated  
293 from the European Center for Medium Range Weather Forecasts (ECMWF) numerical weather  
294 prediction model, and an ionosphere correction derived from the Global Ionosphere Map (GIM)  
295 was also applied. Over non-ocean surfaces, various retracking methods have been developed to  
296 correct the deviation of the waveform leading edge from the nominal tracking gate (e.g., Martin  
297 et al., 1983; Wingham et al., 1986; Davis, 1997; Lee et al., 2008). JASON-2 data products  
298 contain retracked range measurements using the “ICE” retracker that is essentially a 30%  
299 threshold retracker using the mean power of the waveform calculated using the Offset Center of  
300 Gravity algorithm (*P. Thibaut, personal communication, 2010*). In this study, we adopted 50%  
301 threshold retracking which has been shown to perform well over inland water bodies for Jason-2  
302 waveforms (Lee et al., 2011).

303 In the next step (Figure 4), these FRCs were used to forecast 5-day ahead river discharge  
304 at the upstream-most boundary points of the HEC-RAS model setup. An independent validation  
305 (assessment) period of July 2009-December 2010 was chosen for assessing the forecast accuracy  
306 of JASON-2. For this period, instantaneous JASON-2 river level estimates at the upstream  
307 Indian river locations were used to derive the 5-day discharge forecast at *Hardinge Bridge* and  
308 *Bahadurabad* stations. Because JASON-2 revisit frequency at the same transboundary river  
309 ground track is never daily, a scheme was devised to allow daily computation of 5-day forecast  
310 of river levels at upstream boundary points of HEC-RAS set up using a combination of the most

311 recent altimeter scan, FRC and interpolation (if necessary). This is elaborated in detail in the  
312 paragraph below.

313           INSERT FIGURE 6 HERE

314           In this study, the idea was to compute a 5-day forecast in a pseudo “operational mode”  
315 using information only from the altimeter itself. The altimeter data spanning October 2008 –  
316 June 2009 was treated as ‘historical’ (calibration) data that the forecaster had access to for  
317 derivation of *a priori* FRCs. For each upstream JASON-2 virtual station (i.e, numbered ground  
318 tracks in Figure 5) on each river at Indian locations, an FRC for a given lead time was derived  
319 using the methodology used by Biancamaria et al. (2011). These FRCs correspond to a power  
320 law fit between upstream JASON-2 water level anomalies (lagged in time according to a specific  
321 lead time) and downstream *in-situ* discharge. This power law fit is actually derived by doing a  
322 linear fit of these two variables in the log space. An example of a 6-day lead time FRC is shown  
323 in Figure 6 (grey straight-fit lines). Such FRCs have been computed for lead times ranging from  
324 1 day to 20 days.

325           Using the period of July 2009 – December 2010 for independent testing of altimeter-  
326 based forecasting, 5-day forecast of river discharge for every day at the upstream-most point of  
327 Bangladesh domain were “routinely” derived assuming an operational environment as follows.  
328 During the validation ‘test’ period (July 2009 to December 2010), the aim was to compute for  
329 each day, noted D, the 5-day later forecast discharge, using a water level/discharge rating curve  
330 as shown on Figure 6, at *Bahadurabad* and *Hardinge Bridge* at the day of forecast, noted here as  
331  $D_f$  (i.e.,  $D_f=D+5$ ). To do so, the most recent JASON-2 observation in time from day D was  
332 selected for each upstream virtual station located in India. The date of the selected JASON-2  
333 observation is referred as  $D_{J2}$  in the rest of this section. Thus, there are  $D_f-D_{J2}=D+5-D_{J2}$  days

334 between the JASON-2 observation and the day of forecast. So the forecast is done using the  
335 JASON-2 water level anomaly and the pertinent FRC computed from historical data for a lead  
336 time equal to  $D_f - D_{J2}$ . For the Brahmaputra, JASON-2 virtual stations 053\_1 and 242\_1 have been  
337 considered (Figure 5). The FRCs at these locations had the lowest Root Mean Squared Error  
338 (RMSE) compared to in-situ measurements during the historical time period. On the Ganges,  
339 JASON-2 virtual stations 014\_1 and 155\_1 have been used (Figure 5). Whenever  $D_f - D_{J2}$   
340 exceeded 20 days (an unlikely scenario for JASON-2), the forecast was linearly interpolated  
341 from the two previous ones. This case did not occur during the July 2009 – December 2010 time  
342 span. Finally, it has been considered that JASON-2 measurements have at least 1-day latency,  
343 meaning that the minimum lead time is equal to 6 days (i.e.  $D_f - D_{J2} \geq 6$ ).

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

355 Once the 5 day ahead forecast of river discharge, pertaining to the upstream-most  
356 boundary point, was derived for each day of the independent assessment (validation) period (July



357 2009-Dec 2010) according to the methodology elaborated above, the HEC-RAS model was next  
358 run at the daily time step. For each day, the model was initialized with the corresponding 5-day  
359 forecast of river discharge at the upstream-most boundary points for Brahmaputra and Ganges  
360 rivers. For the downstream most boundary point, *in-situ* river level data at *Daulatkhan* was used  
361 ‘as is’ due to practical limitations (see last paragraph of section 2). Also, for the upstream  
362 boundary point on Meghna river – *Amalshid*- (Figure 2) *in-situ* water level data was used. The  
363 justifications for using *in-situ* river level data for the Meghna river are as follows: 1) there are no  
364 suitable JASON-2 ground track for Meghna river in Indian locations (Figure 5); 2) Meghna river  
365 contributes only an insignificant portion (~3.5%) of total transboundary flow (about 1,777 km<sup>3</sup>  
366 per year) into Bangladesh. The simulation of river levels inside Bangladesh in this manner at the  
367 17 FFWC station locations (Figure 2) were then considered as the ‘5-day forecast’ for the  
368 specific date of the model run and compared with the ‘5-day later’ nowcast already shown in  
369 Figure 3b.

370

#### 371 **4.0 RESULTS AND DISCUSSION**

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

380           INSERT FIGURE 7 HERE

381           For a quantitative assessment of the accuracy of forecasting using JASON-2 altimeter  
382 data at upstream Indian river locations, the following assessment metrics has been derived: 1)  
383 mean error, 2) Root Mean Squared Error (RMSE), 3) Correlation and 4) Mean Absolute Error.  
384 Here ‘error’ is defined as the scalar difference between the JASON-2-based “5-day forecast” and  
385 the “5-day later” nowcast based on only in-situ boundary condition data. Furthermore, we  
386 assessed the skill for two distinct seasons: Monsoon season (July–September) and Dry season  
387 (October-June). Finally, we analyzed accuracy as a function of distinct river segments of the  
388 forecasting domain. Herein, there were 6 distinct river segments (or stretches): Ganges,  
389 Brahmaputra, Padma, Surma, Upper Meghna and Lower Meghna. These river segments are  
390 shown in distinct color in Figure 2. The purpose of breaking down the analysis per each river  
391 segment was to identify how the accuracy degraded as a function of flow distance downstream  
392 and river morphology. Figure 8 shows the 5-day forecast hydrographs of river levels at 6  
393 locations (at the various river segments shown in Figure 2). In comparison to the now cast  
394 hydrographs, the 5-day forecasts appear quite acceptable in following the trends and capturing  
395 the peak events. In fact, when compared to *in-situ* river level data at the two gauging stations  
396 (Bahadurabad and Hardinge Bridge), the 5-day forecasting agrees a little more closely than the  
397 now cast. The systematic overestimation of the HEC-RAS model appears to cancel out  
398 somewhat the systematic underestimation of the forecasting approach to yield a relatively more  
399 unbiased solution.

400           INSERT TABLE 1 HERE, INSERT FIGURE 8 HERE

401           Table 1, Figures 9 and 10, summarize the performance of the JASON-2-based 5-day  
402 forecast at the 17 FFWC locations and also as a function of season and for the various river

403 segments. Results show that JASON-2 forecasts retain good accuracy (relative to now cast) at 5-  
404 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  
405 in estimating the river level. However, there is a consistent underestimation (negative mean bias)  
406 in forecasting of river levels. The forecasting accuracy of JASON-2 is generally found to be  
407 higher during the dry season compared to the Monsoon season. This can be a useful finding for  
408 water resources management at seasonal timescales for addressing problems such as droughts or  
409 saline water intrusion from the Bay of Bengal. A possible reason for higher accuracy (compared  
410 to now cast and wet season) during dry season can be attributed to the extensive irrigation and  
411 diversion by India that leads to highly steady but reduced flow into Bangladesh, thus making  
412 forecasting more accurate.

413 INSERT FIGURE 9 and 10 HERE

414 Except for the Brahmaputra river reach, the forecasting accuracy seemed relatively  
415 preserved as a function of downstream flow distance. An additional reason to keep in mind is  
416 that the stage variation used to estimate discharge can be less correlated for large rivers as the  
417 bank slopes decreases and the river cross-sectional area expands. A point to note is that the skill  
418 for the river segments of Surma, Upper and Lower Meghna river (Figure 8) is not representative  
419 of the true forecasting potential of JASON-2, since these rivers pertain to the Meghna river basin  
420 (the smallest of the three basins) and used *in-situ* discharge data as the upstream-most boundary  
421 condition point in the forecasting domain. Figures 11a and 11b depicts an overall graphical  
422 summary of forecasting skill of JASON-2 as a function of downstream flow distance for each  
423 river segment and for the two seasons.

424 INSERT FIGURE 11 HERE

425

426 As indicated before, the satellite altimeter JASON-2 data are obtained using the 50%  
427 threshold radar waveform retracker, which has shown to have good performance for inland water  
428 (Lee et al., 2009, 2011). However, there has not been an elaborate *in situ* calibration of JASON-2  
429 conducted to reveal whether a range bias exists. It has been shown that for example, large bias  
430 could concur in river basins, e.g., the Amazon, for ENVISAT radar altimeter (Calmant et al.,  
431 2013), due primarily to terrains surrounding the river and possibly also meteorological  
432 conditions. An uncorrected altimeter bias would have degraded the forecasting accuracy for this  
433 study.

434 A follow-up question that emerges regarding the proof-of-concept forecasting approach  
435 using JASON-2 satellite data is *what is the true accuracy (skill) of forecasting given that*  
436 *nowcasting has inherent uncertainty?* Armed with encouraging results for our proof-of-concept  
437 study shown previously, we next embarked on a real-time, truly operational and independent  
438 assessment of JASON-2 forecasting against observed water level measurements (where  
439 available). As part of a US Department of State (Fulbright) project awarded to the first author,  
440 the flood forecasting staff of IWM were trained over a 4 month period to independently learn,  
441 apply and troubleshoot the JASON-2 forecasting scheme in a real-time (day to day) environment.  
442 Once the training was complete, the staff then carried out a real-time operational forecasting of  
443 JASON-2 during a 20-day period spanning Aug 1, 2012 to Aug 20, 2012. Each day of this 20-  
444 day period, the 5-day water level forecast at the upstream boundary condition locations of the  
445 HEC RAS domain was generated from JASON-2 data available at the shortest latency (called  
446 Interim Geophysical Data Records- IGDR). The HEC RAS set up used a 10-day spin-up  
447 (hindcast) to remove the effect of initial conditions. Thus, in total, HEC RAS was ran each day

448 for a period of 15 days (10-day hindcast and 5-day forecast) to generate the corresponding  
449 forecast water levels further inside Bangladesh.

450 Comparison against observed water levels at 3 river stations (Bahadurabad, Sirajganj on  
451 the Brahmaputra river and Hardinge Bridge on the Ganges river) revealed an average error of  
452 forecast ranging from  $-0.4$  m to  $0.4$  m and an RMSE ranging from  $0.2$  m to  $0.7$  m. Table 2  
453 provides a statistical summary of the assessment of the JASON-2 forecast against observed water  
454 levels at these 3 locations. As an example for one location (*Sirajganj* on Brahmaputra river),  
455 Figure 12 shows the comparison of the forecast water level against observed water levels at  
456 various lead times during the period of Aug 1 2012 to Aug 20 2012. In general, we clearly see  
457 that our choice of using nowcasting as the reference to establish proof-of-concept operational  
458 feasibility of JASON-2 scheme was not unfounded. In fact, the skill of forecasts at the 5 day lead  
459 time is now found to be more accurate against observed water level measurements. Overall, our  
460 study shows that satellite altimeters can indeed be an efficient and practical tool for building a  
461 robust forecasting system for transboundary flow for the developing world.

462

## 463 **5.0 CONCLUSION AND PERSPECTIVES**

464 This study provides a proof of concept of how an operational system can be implemented  
465 on the basis of satellite altimetry and the fundamentally intractable limitations of insufficient  
466 measurements and the transboundary nature of flood forecasting pose in developing nations.  
467 Generally, it is promising to observe that satellite altimeters (including JASON-2) are indeed  
468 quite capable of forecasting transboundary flow inside downstream nations at 5 (or higher) day  
469 lead time without complex data assimilation, time-series analysis and climate-based forecasting  
470 tools. This inherently implies that when such altimeter based transboundary flow forecasting

471 schemes are combined with current state of the art methods involving statistical regression or  
472 climate (such as Webster et al., 2010), the potential for extending the lead time, as well as  
473 handling unscheduled issues with regulation of flow by upstream nations, can be tremendous.  
474 The more important question is however on operational sustainability. The current suite of  
475 concurrently flying altimeters such as JASON-1, JASON-2, ENVISAT (this mission ended in  
476 May 2012), CryoSat-2 and SARAL/AltiKa are essentially science-discovery missions with a  
477 finite life span of 5-7 years and not tailored for operational needs of an agency (such as NOAA  
478 GOES or Landsat of the USGS). *Thus, how can such an altimeter-base forecasting system be*  
479 *made operationally sustainable in the long-term with near-real time data availability to the*  
480 *public?*

481         We contend that although the answer to the above question has not been identified yet by  
482 the scientific community, it is only through concept demonstration and operational feasibility  
483 studies, such as ours, that nations will step forward as invested stakeholders and plan to launch  
484 more operational satellite altimetry missions. Data products from JASON-1/-2 are largely  
485 available in almost near-real time, either by efforts of respective cognizant space agencies, or via  
486 efforts by scientific investigators. It is worthwhile to note that after the JASON-2 and Envisat  
487 altimeters, JASON-3 scheduled to be launched in 2014, and AltiKa mission has been launched in  
488 2013, following the 10-day and 35-day repeat orbits of JASON-2 and Envisat, respectively. In  
489 addition, ESA's Sentinel-3 (2-satellite constellation) will be launched in 2013. NASA/CNES'  
490 Surface Water and Ocean Topography (SWOT) wide-swath radar interferometric altimetry  
491 mission is also scheduled for launch in 2019. Of these planned altimetry missions, JASON-3 and  
492 Sentinel-3 are actually designated operational missions, dedicated to providing near-real time  
493 data to the general public. Thus, there will be abundant satellite altimetry missions, scientific and

494 operational missions, well into the foreseeable future. With such a prolonged window of data  
495 continuity and minimum latency, nations that need a more ‘sovereign’ approach to forecasting  
496 their incoming transboundary flow, may now have the unique opportunity to create something  
497 truly operational for serving their society with longer lead times for adaptation.

498

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631 **8.0 TABLES**

632 **Table 1.** Error analysis of JASON-2-based 5 day forecast using nowcast as reference. Chainage  
 633 is measured as distance upstream from the downstream-most point of a river segment. MAE –  
 634 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	<i>Bahadurabad</i>	-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

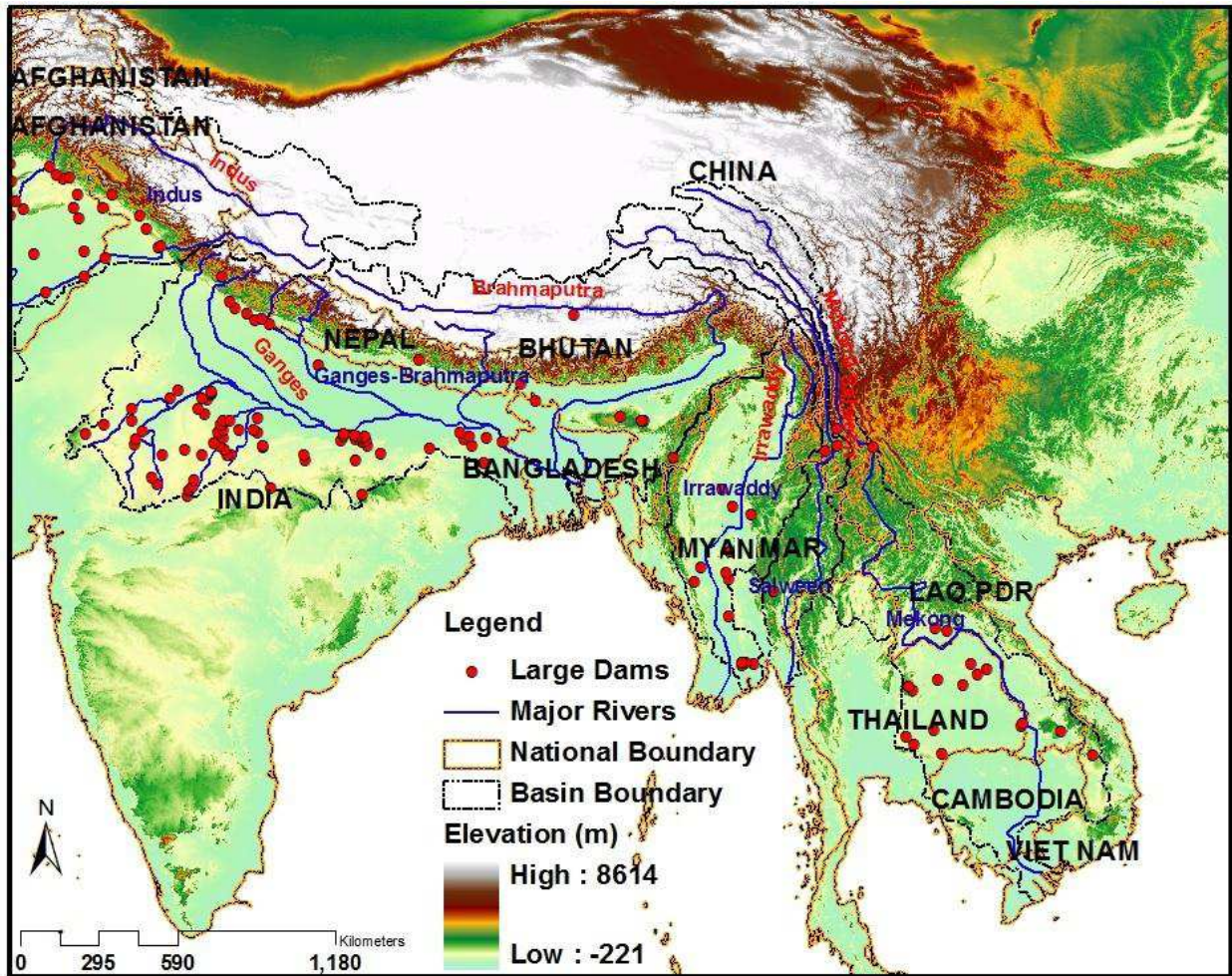
635

636

637 **Table 2.** Independent assessment of JASON-2 5 flood forecasting at 3 river locations (see Figure  
638 2 for location) against observed water level (relative to local datum) in a real-time and  
639 operational framework during Aug 1 to Aug 20, 2012.  
640

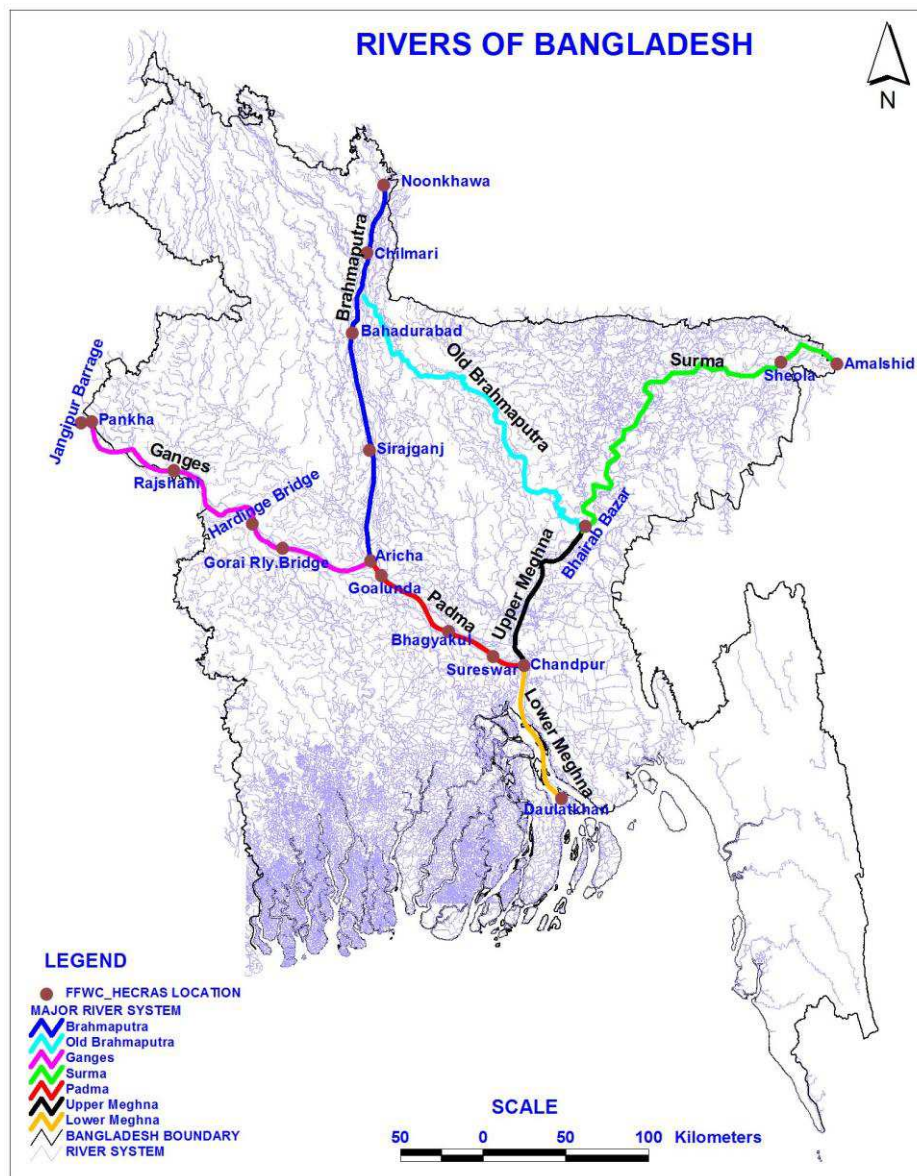
Lead (day)	Correlation	Mean Error (m)	RMSE (m)
	<i>Sirajganj</i>		
1	0.990	0.419	0.660
2	0.993	0.380	0.690
3	0.980	0.358	0.721
4	0.960	0.330	0.789
5	0.949	0.387	0.803
	<i>Hardinge Br.</i>		
1	0.939	-0.396	0.105
2	0.787	-0.411	0.130
3	0.578	-0.431	0.217
4	0.305	-0.460	0.340
5	0.020	-0.434	0.467
	<i>Bahadurabad</i>		
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

641



643  
 644 **Figure 1.** Bangladesh as the low lying downstream-most nation of the Ganges-Brahmaputra  
 645 basins. Red circles denote location of large dams or barrages that divert or regulate flow in the  
 646 basins. The information on dams was obtained from the GranD dam database available at  
 647 <http://www.gwsp.org/85.html>

648

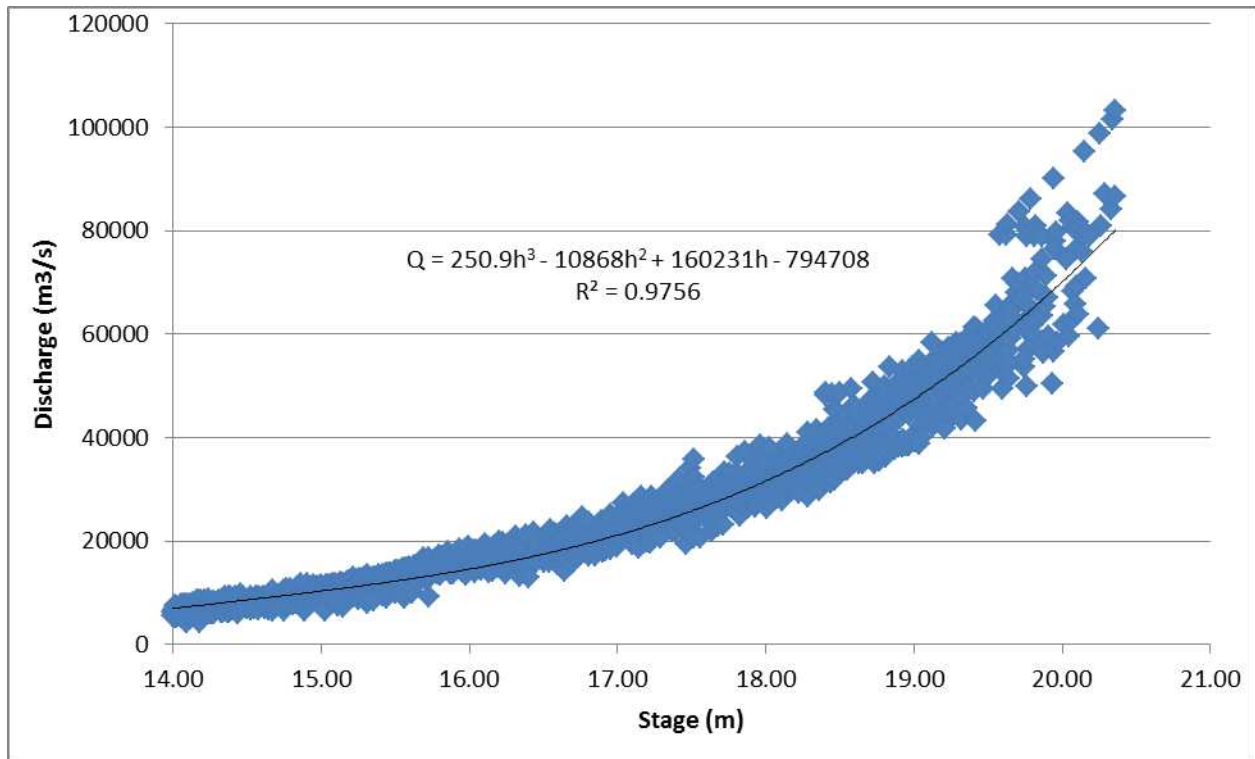


650

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

657

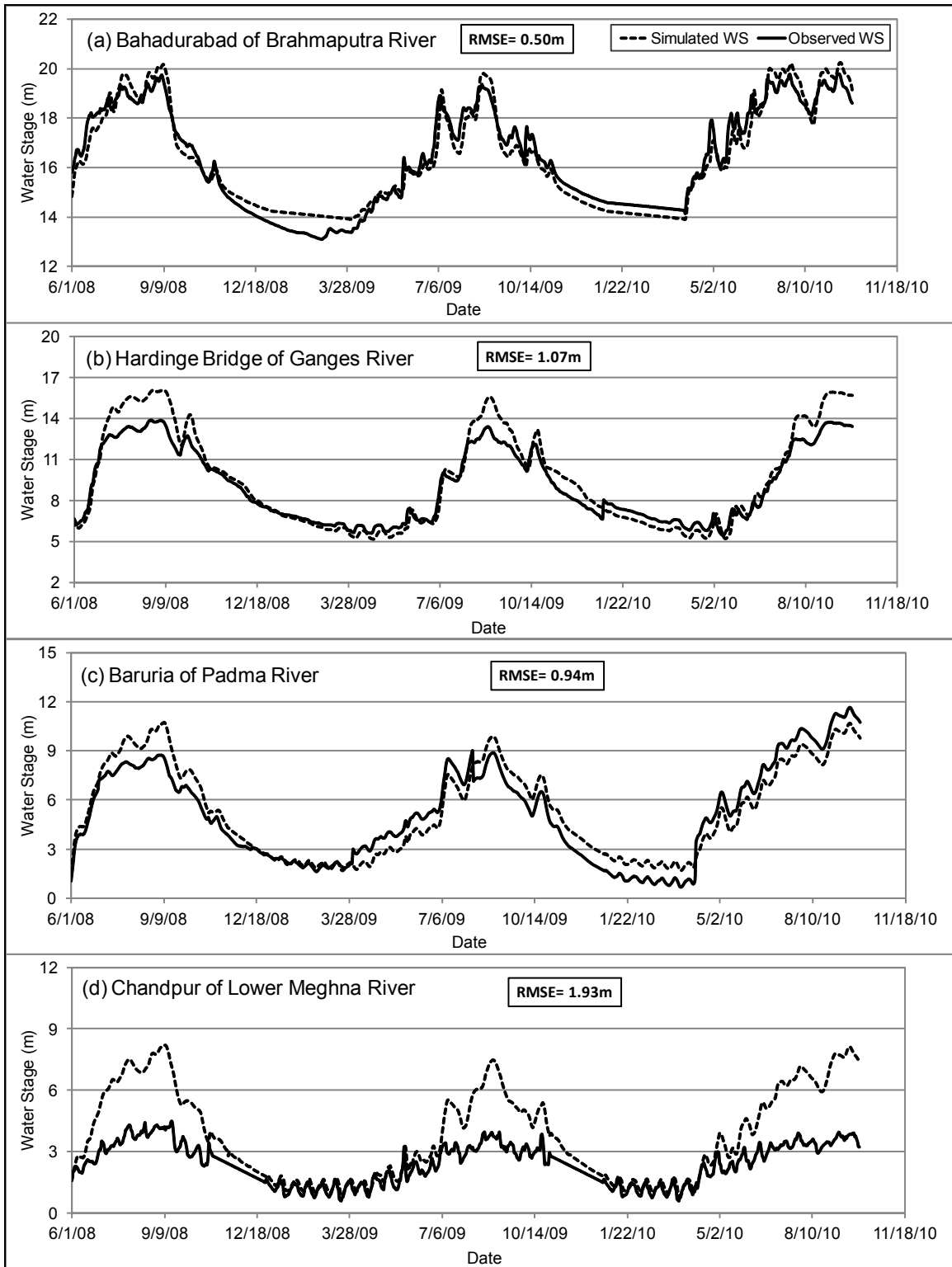




658  
659

660 **Figure 3a.** Discharge-versus- river level (or stage) rating curve for the *Bahadurabad* station on  
661 the Brahmaputra river with the associated uncertainty (RMSE: 2485 m<sup>3</sup>/s and Mean Absolute  
662 Error=70 m<sup>3</sup>/s).

663



664

665 **Figure 3b.** Plot of HEC-RAS simulated and observed (gauged) water stage data (at four  
 666 locations – see Figure 2) for the period of June, 2008 to October, 2010 in now casting mode.

667

## 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).

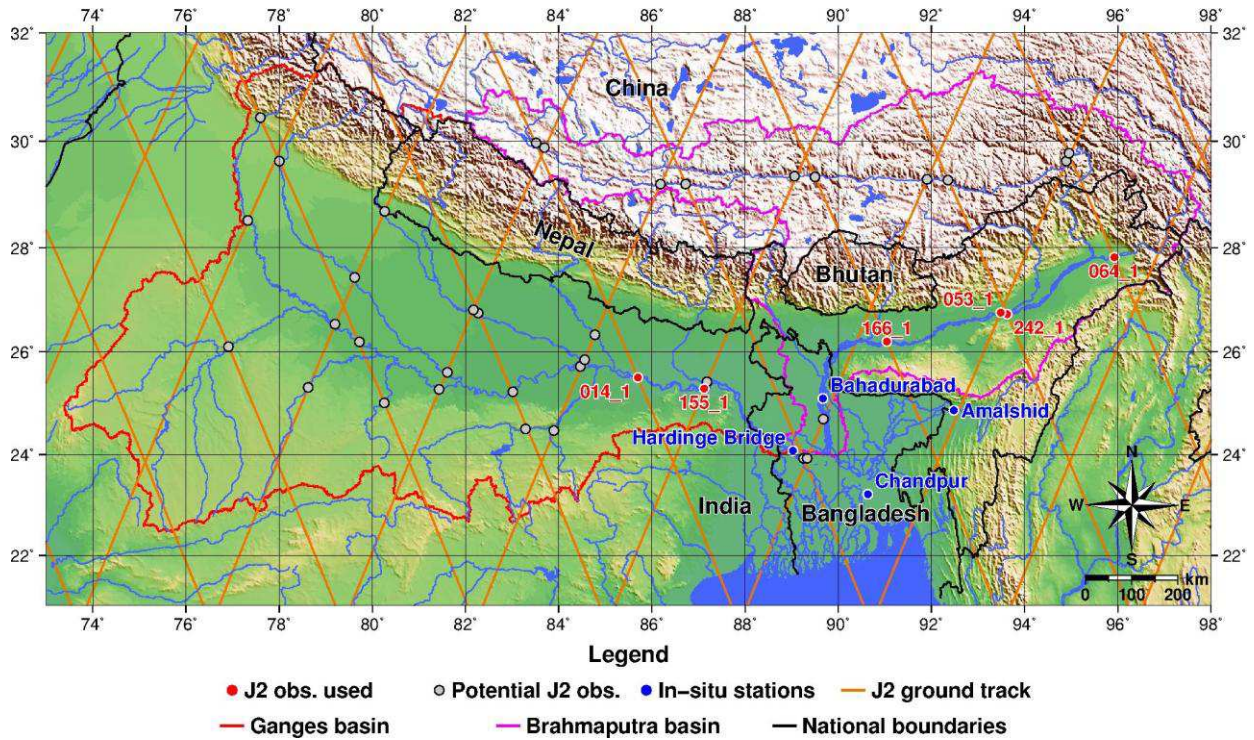
### Estimation of 5-day forecast of River Discharge at Upstream boundary point of Model domain

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

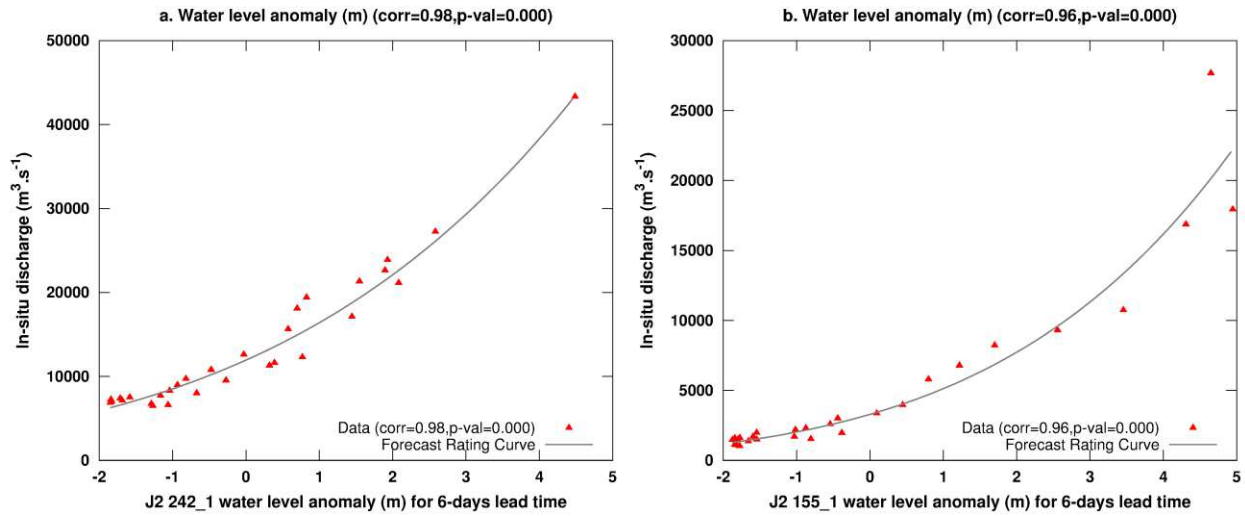
HEC-RAS model is initialized each day with the 5-day forecast of river discharge at the upstream-most boundary points and then model runs performed at daily time step. For downstream most boundary point, in-situ river level data at *Daulatkhan* is used. The simulation of river levels in this manner at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

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

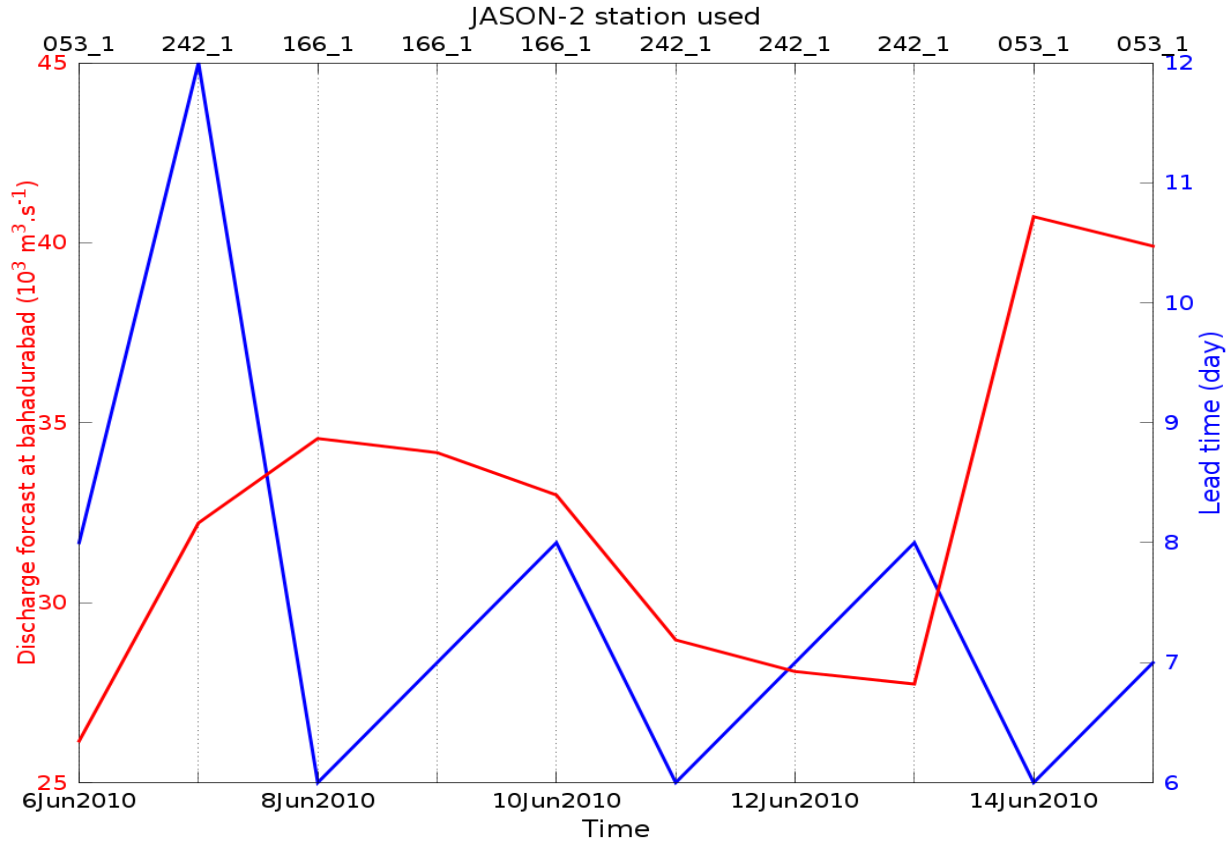


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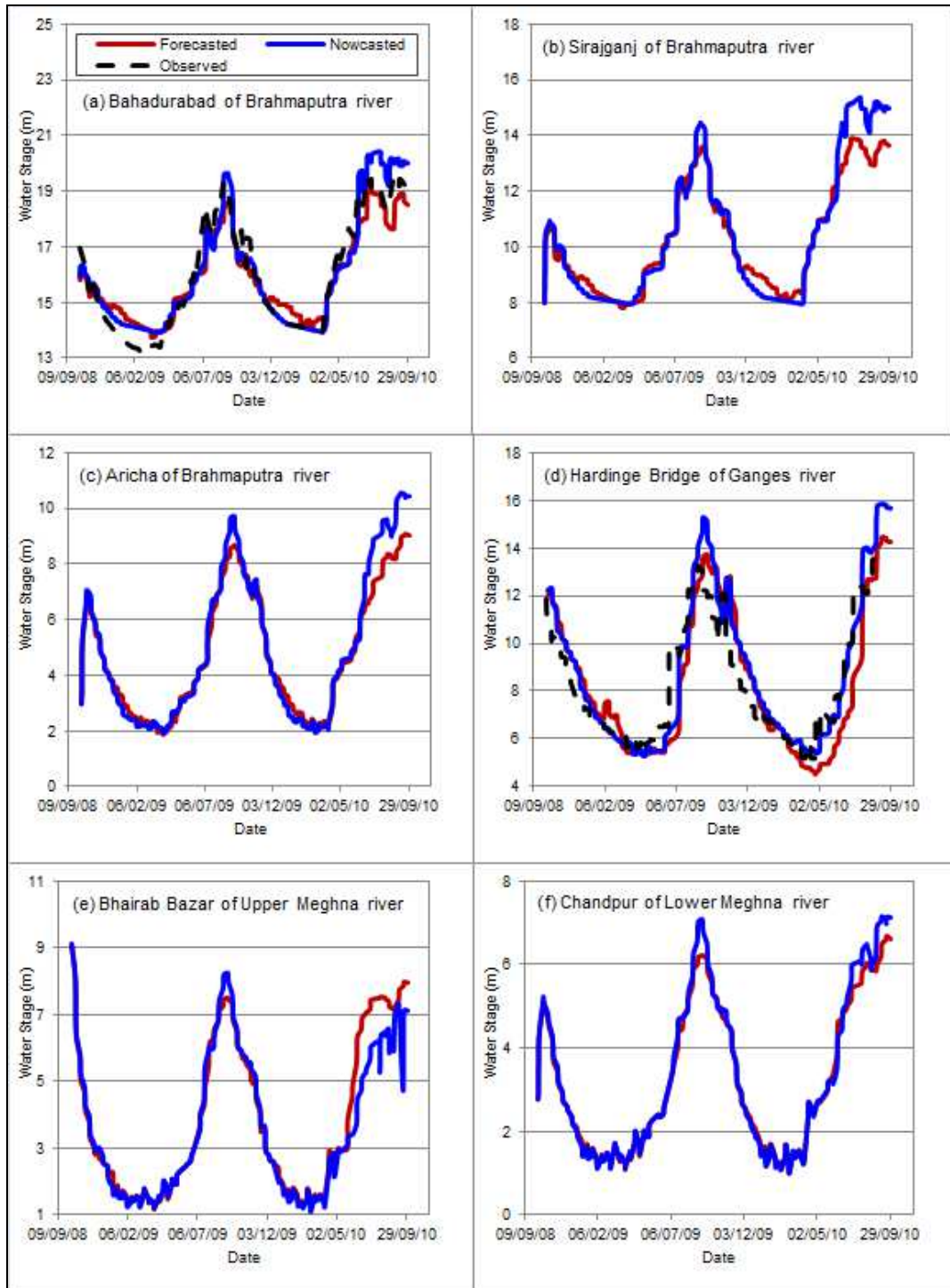
**Figure 5.** Ground tracks or virtual stations of JASON-2 (J2) altimeter over the GB basin shown in orange lines and circles, respectively. The locations where the track crosses a river and used for deriving forecasting rating curves is shown with a circle and station number. Circles without a station 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.



704  
 705 **Figure 6.** Example of 6-day forecasting rating curves (FRC) for JASON-2 at ground track  
 706 (virtual station) location 242\_1 (Brahmaputra river – Figure 2) for *Bahadurabad* station (left  
 707 panel) and 155\_1 (Ganges river –Figure 2) for *Hardinge Bridge* station (right panel). These  
 708 rating curves are derived on the basis of historical data during the calibration period (October  
 709 2008 – June 2009).  
 710



711  
 712 **Figure 7.** Example of 5-day forecasted water level (red curve) at *Bahadurabad* on the  
 713 Brahmaputra River (left y-axis) between 6 June 2010 and 15 June 2010 versus time (bottom x-  
 714 axis). The blue curve corresponds to the lead time (right y-axis) of the JASON-2 FRC used to  
 715 compute the forecasted water level. The top x-axis corresponds to the name of the JASON-2  
 716 virtual station of the pertinent FRC used for each day.  
 717



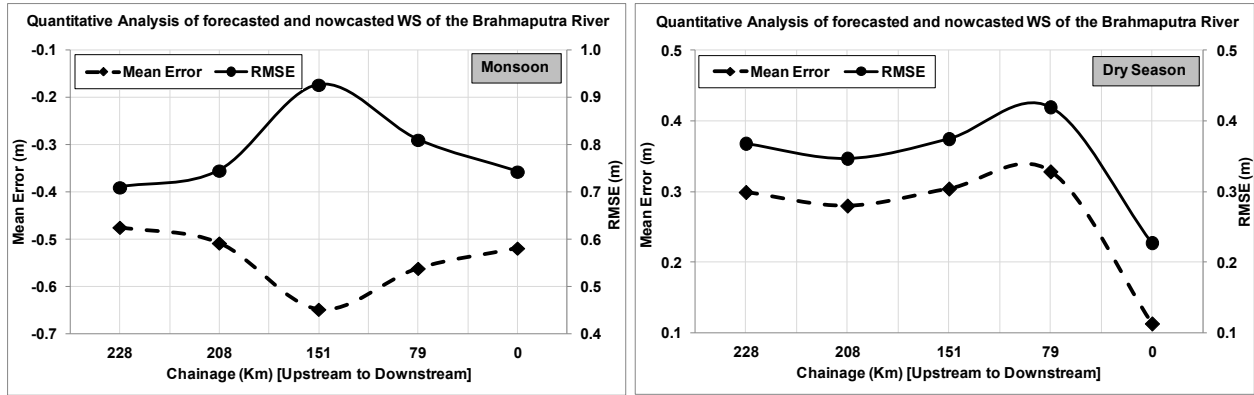
718

719 **Figure 8.** Forecast (5 day) and Nowcast water level hydrographs at six river stations during the validation

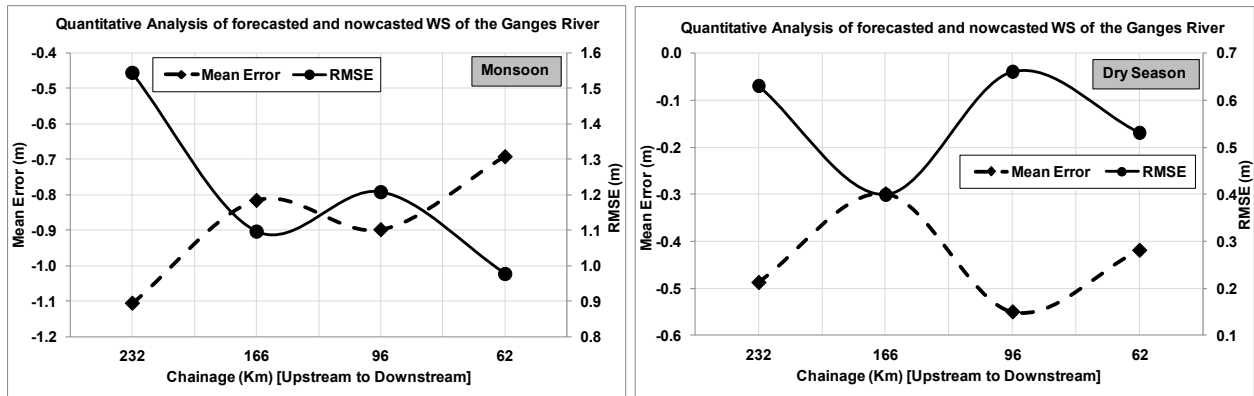
720 period of July 22, 2009 to September 30, 2010. Observed water level data are available only for

721 Bahadurabad and Hardinge Bridge stations. For location of the stations, refer to Figure 2 and Table 1.

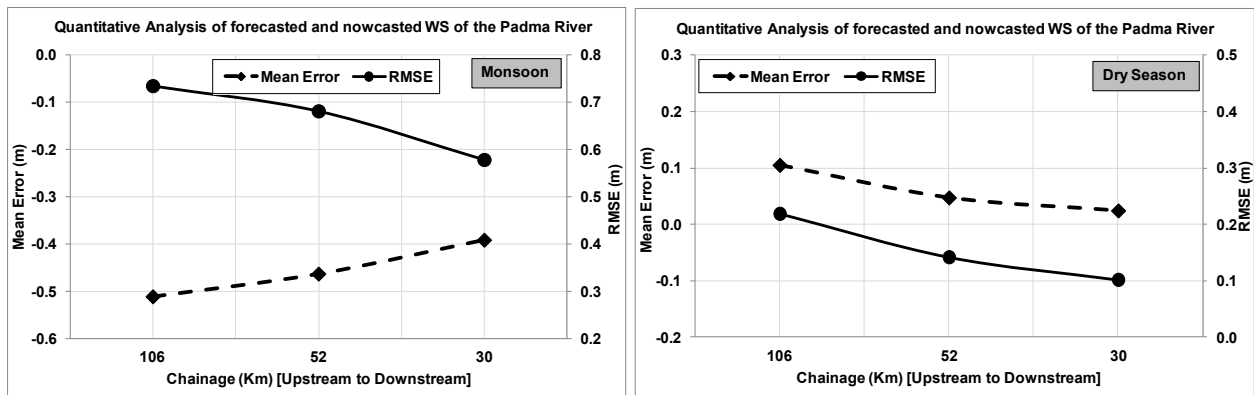
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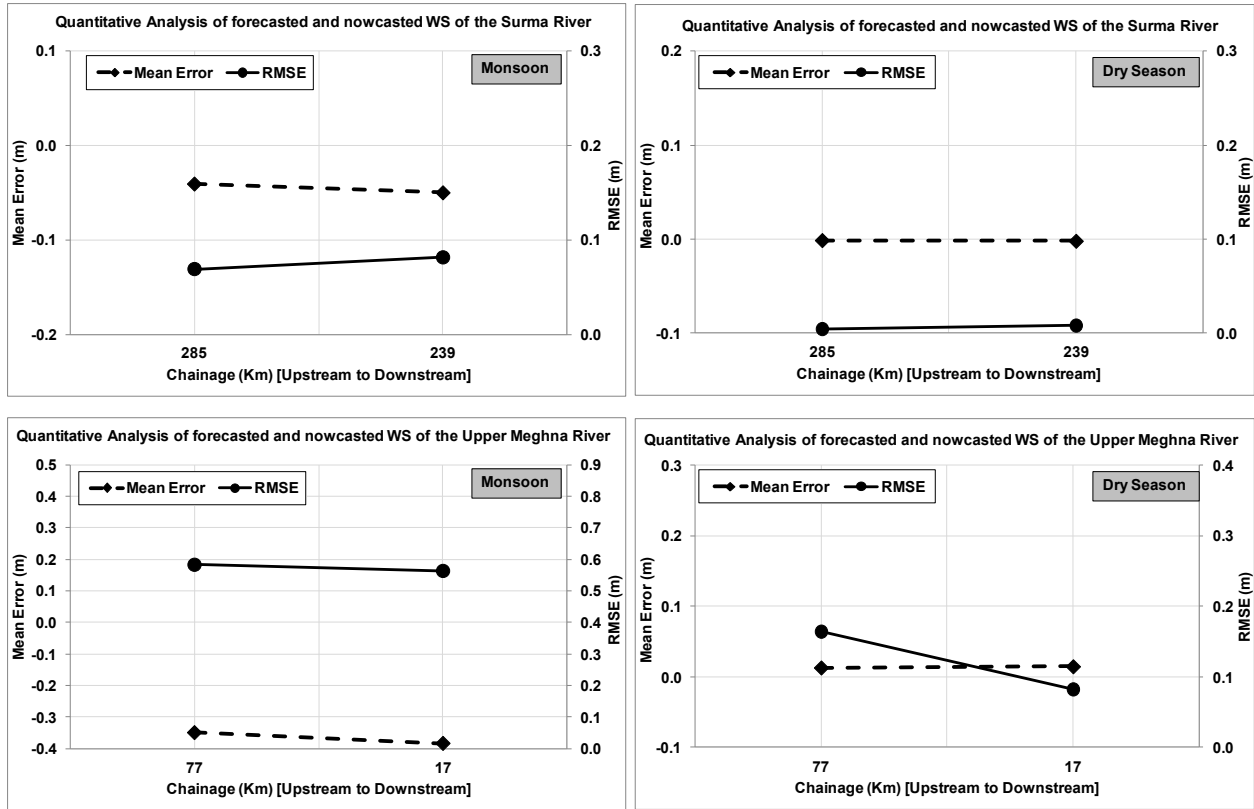


725 **Figure 9.** Accuracy assessment as a function of season (left panel-Monsoon; right panel – Dry  
 726 season), river segments and flow distance downstream (chainage) (x-axis). Upper panels –  
 727 Brahmaputra river; Middle panels – Ganges River; Lower panels – Padma River.

728



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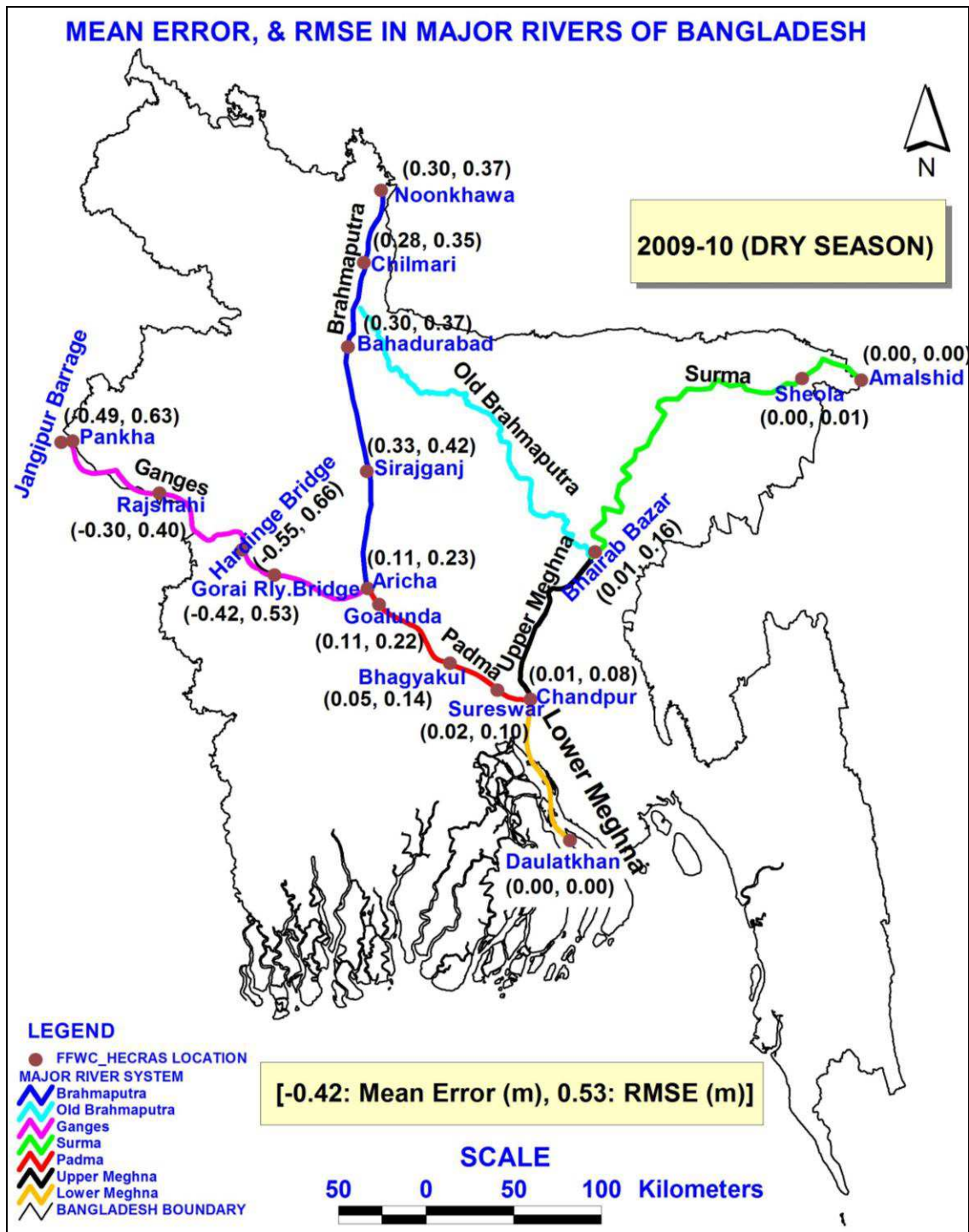


730

731 **Figure 10.** Accuracy assessment as a function of season (left panel-Monsoon; right panel – Dry  
732 season), river segments and flow distance downstream (chainage) (x-axis). Upper panels –  
733 Surma river; Lower panels – Lower-Meghna river.

734

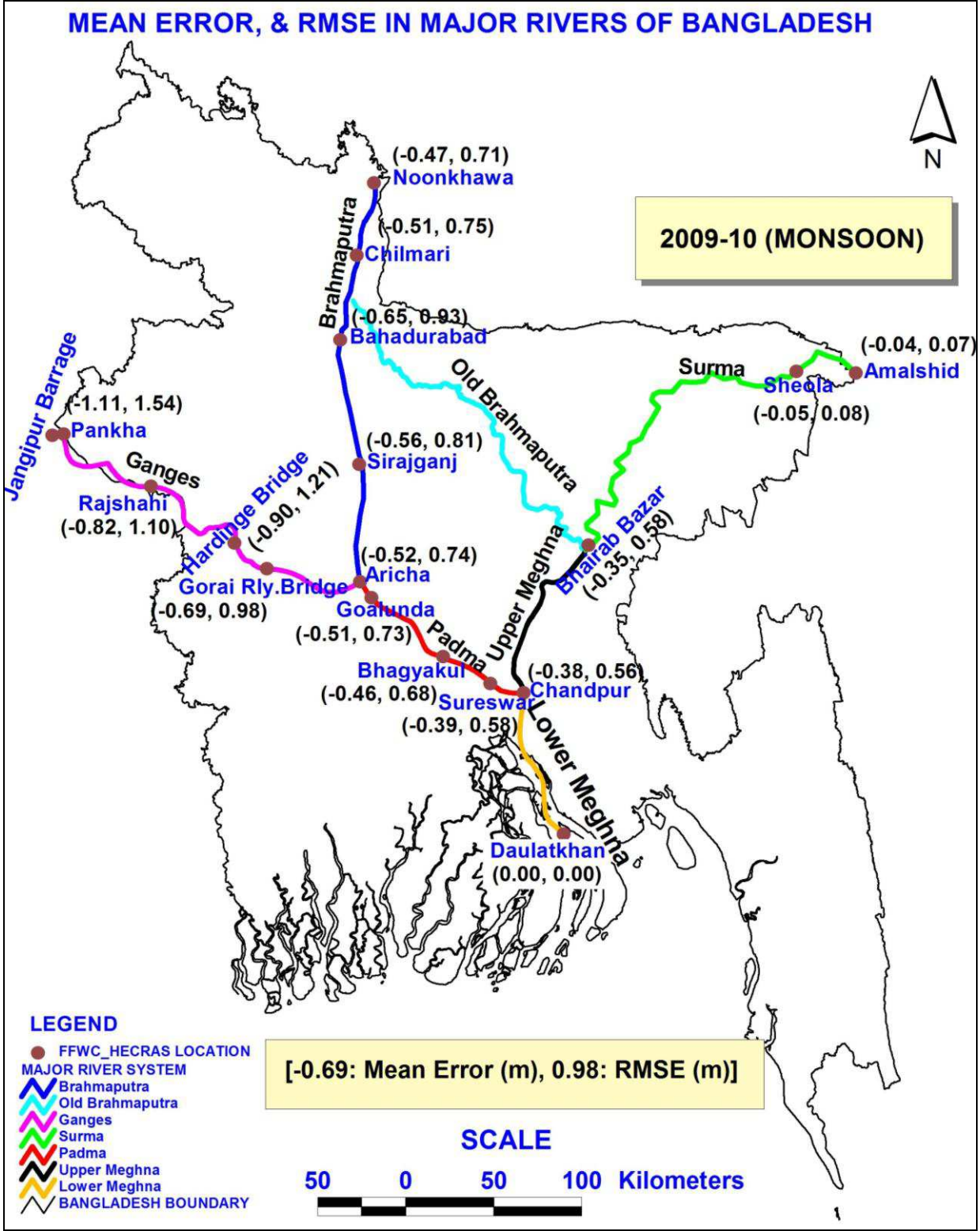
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737

738 **Figure 11a.** Accuracy of JASON-2 based 5-day forecast in terms of mean error and RMSE of  
 739 river level at the 17 FFWC river stations inside Bangladesh during dry season.

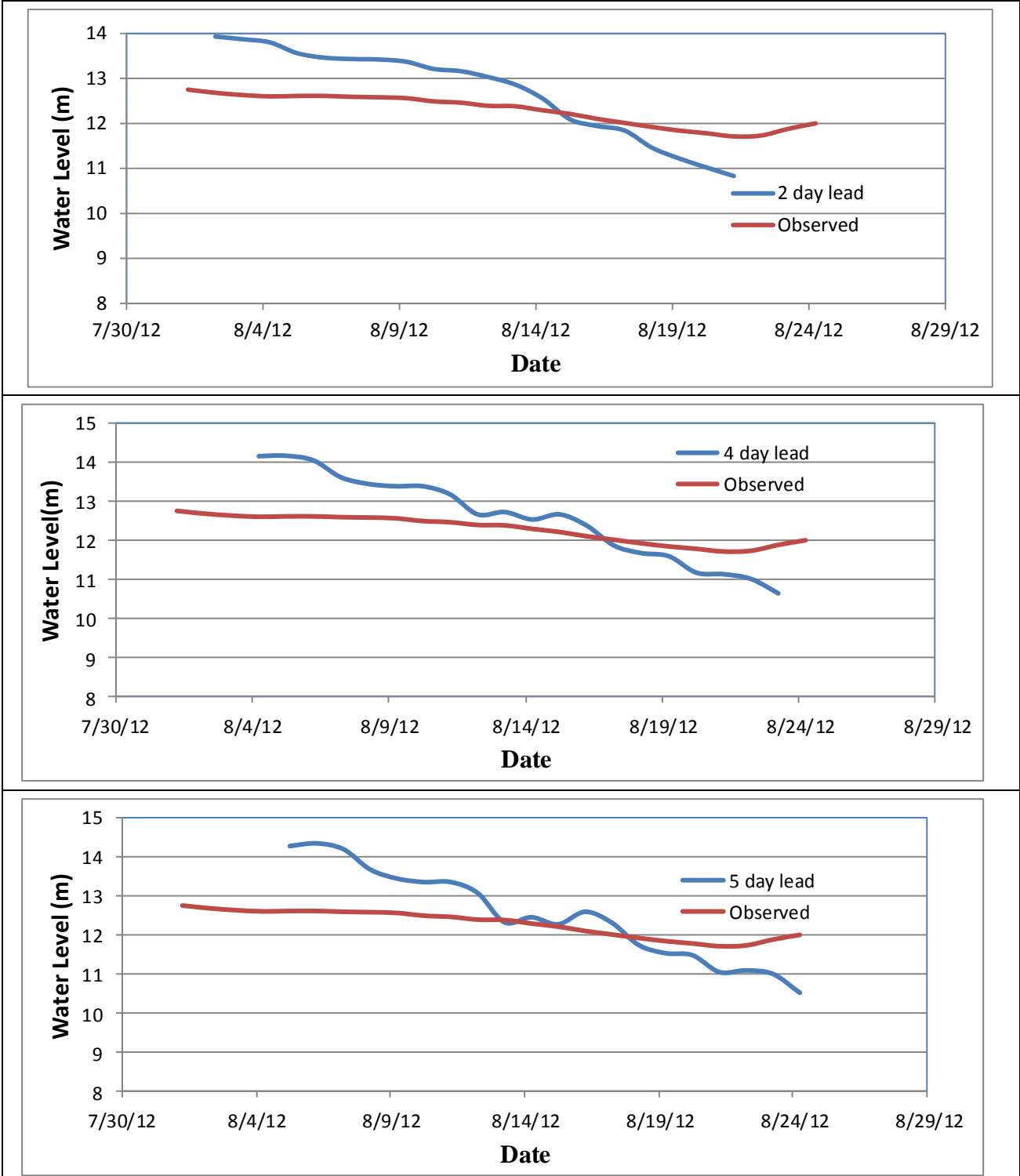
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741

742 **Figure 11b.** Accuracy of JASON-2 based 5-day forecast in terms of mean error and RMSE of

743 river level at the 17 FFWC river stations inside Bangladesh during Monsoon season.



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

