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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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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 m³/s and 70
236 m³/s, respectively (Figure 3a). In terms of percentage of climatologic mean flow (20,563 m³/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 8th, 2010 was
347 obtained from virtual station 242_1 on June 5th (D_{J2}), 2010 (Figure 5). Thus, for forecasting river
348 discharge for June 13th, 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 6th, 2010 to June 15th, 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 km³
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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- 630

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

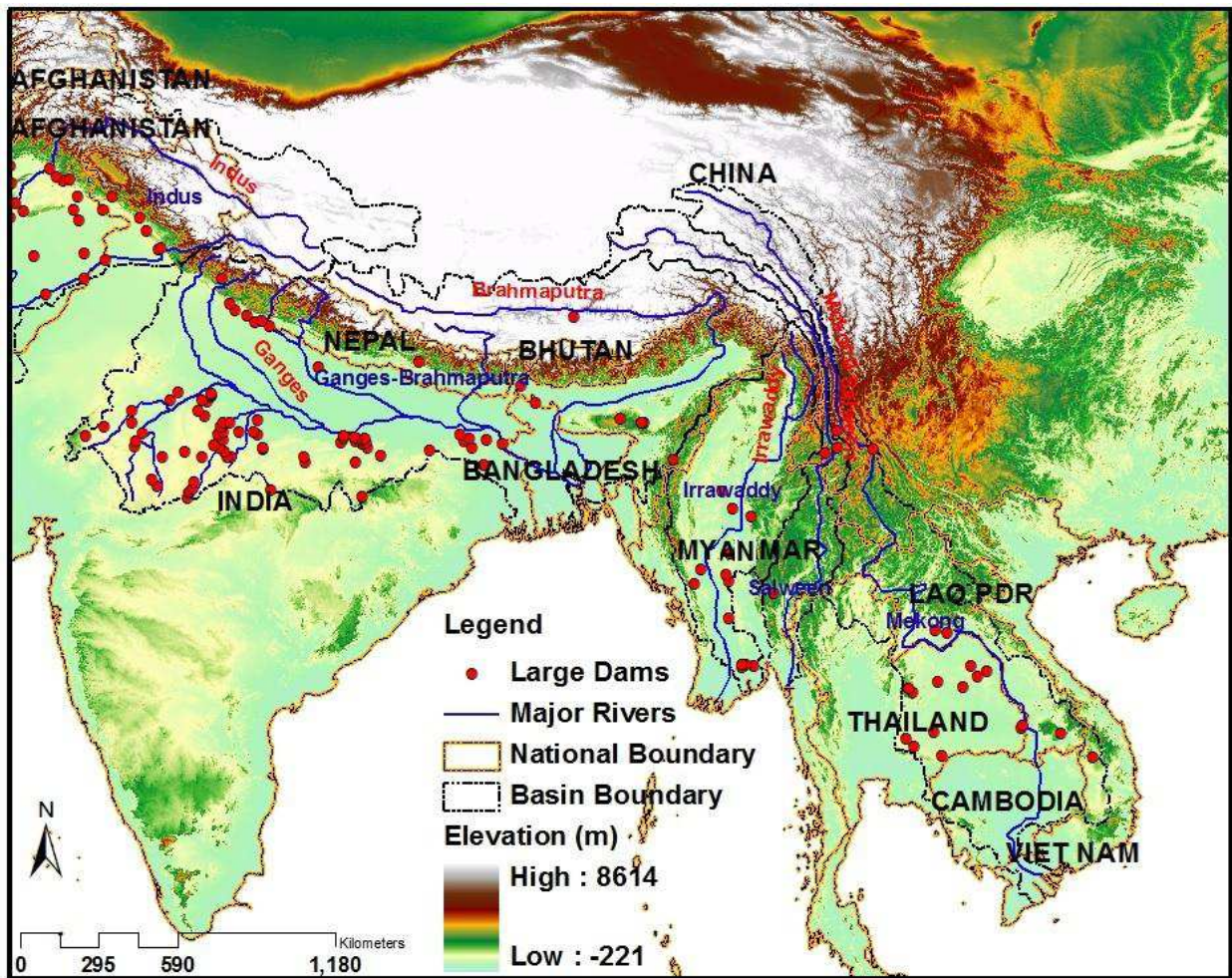
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636

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

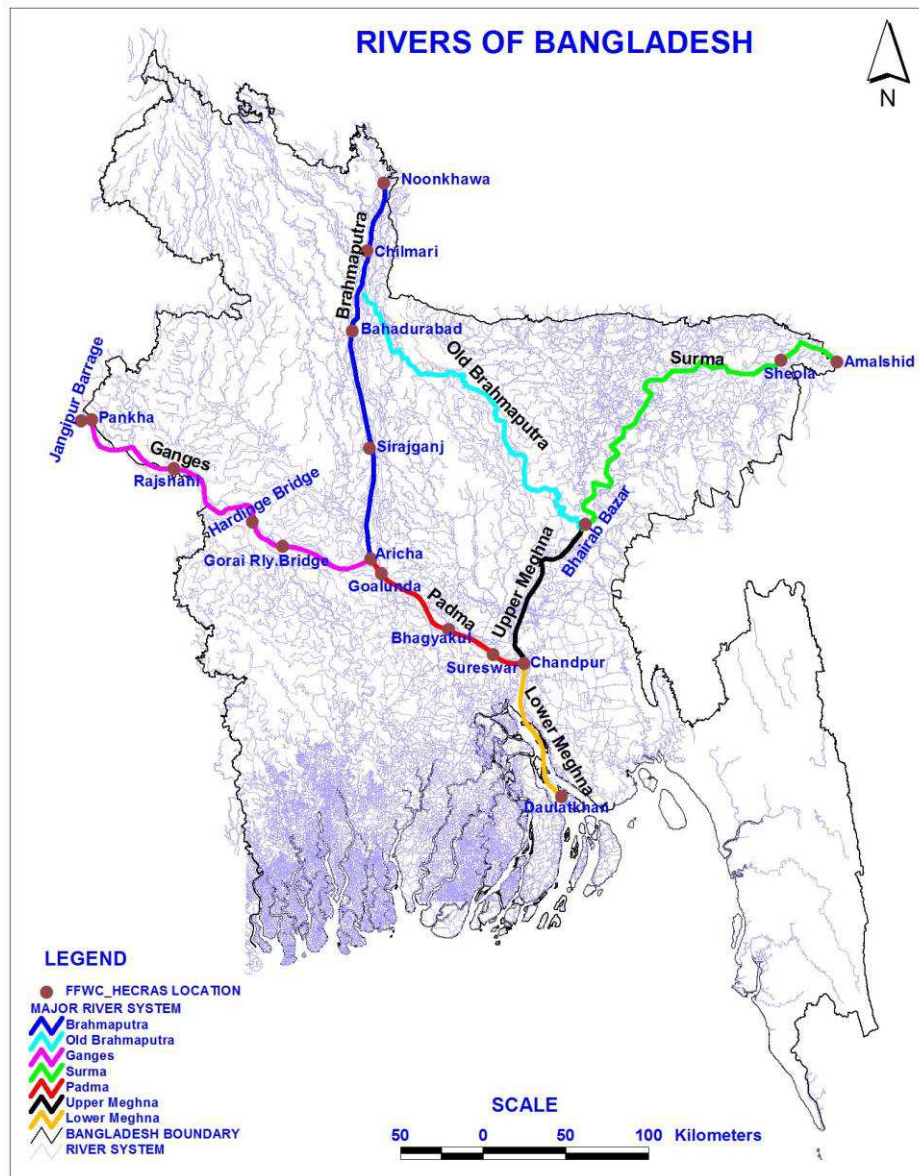
Lead (day)	Correlation	Mean Error (m)	RMSE (m)
	<i>Sirajganj</i>		
1	0.990	0.419	0.660
2	0.993	0.380	0.690
3	0.980	0.358	0.721
4	0.960	0.330	0.789
5	0.949	0.387	0.803
	<i>Hardinge Br.</i>		
1	0.939	-0.396	0.105
2	0.787	-0.411	0.130
3	0.578	-0.431	0.217
4	0.305	-0.460	0.340
5	0.020	-0.434	0.467
	<i>Bahadurabad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

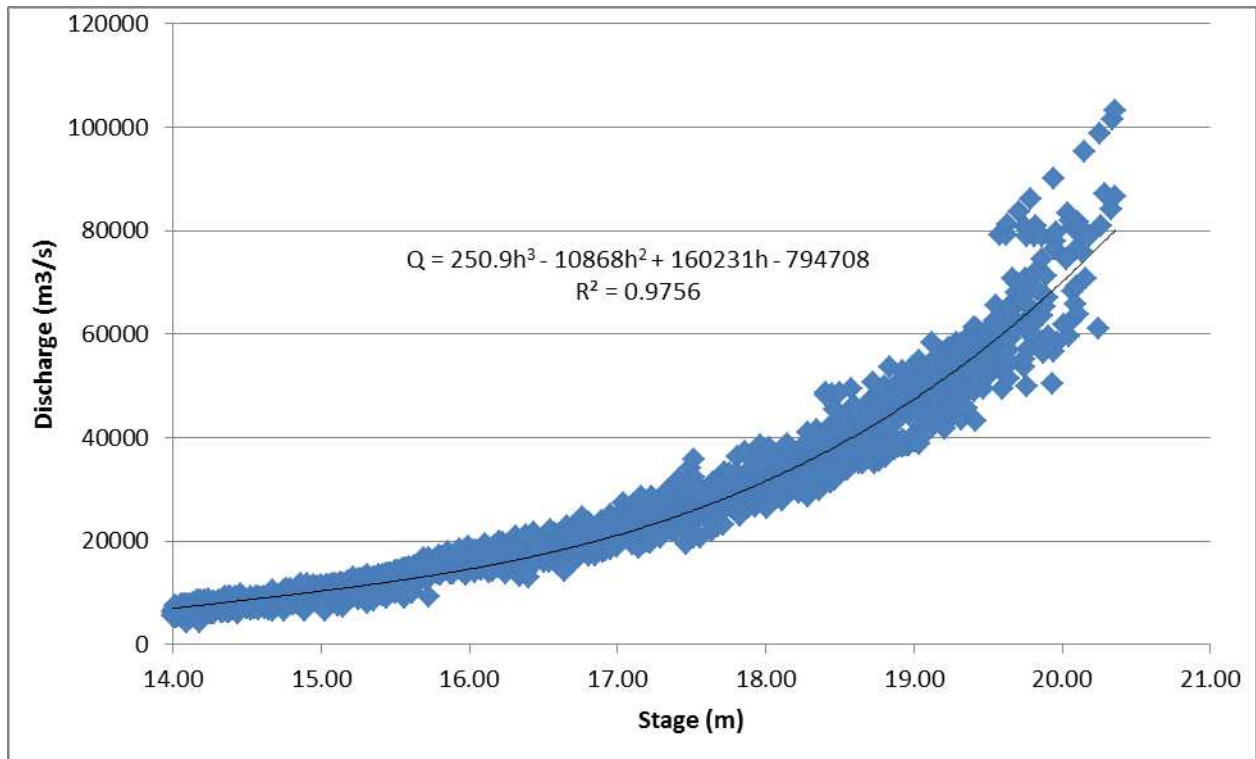
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650

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.

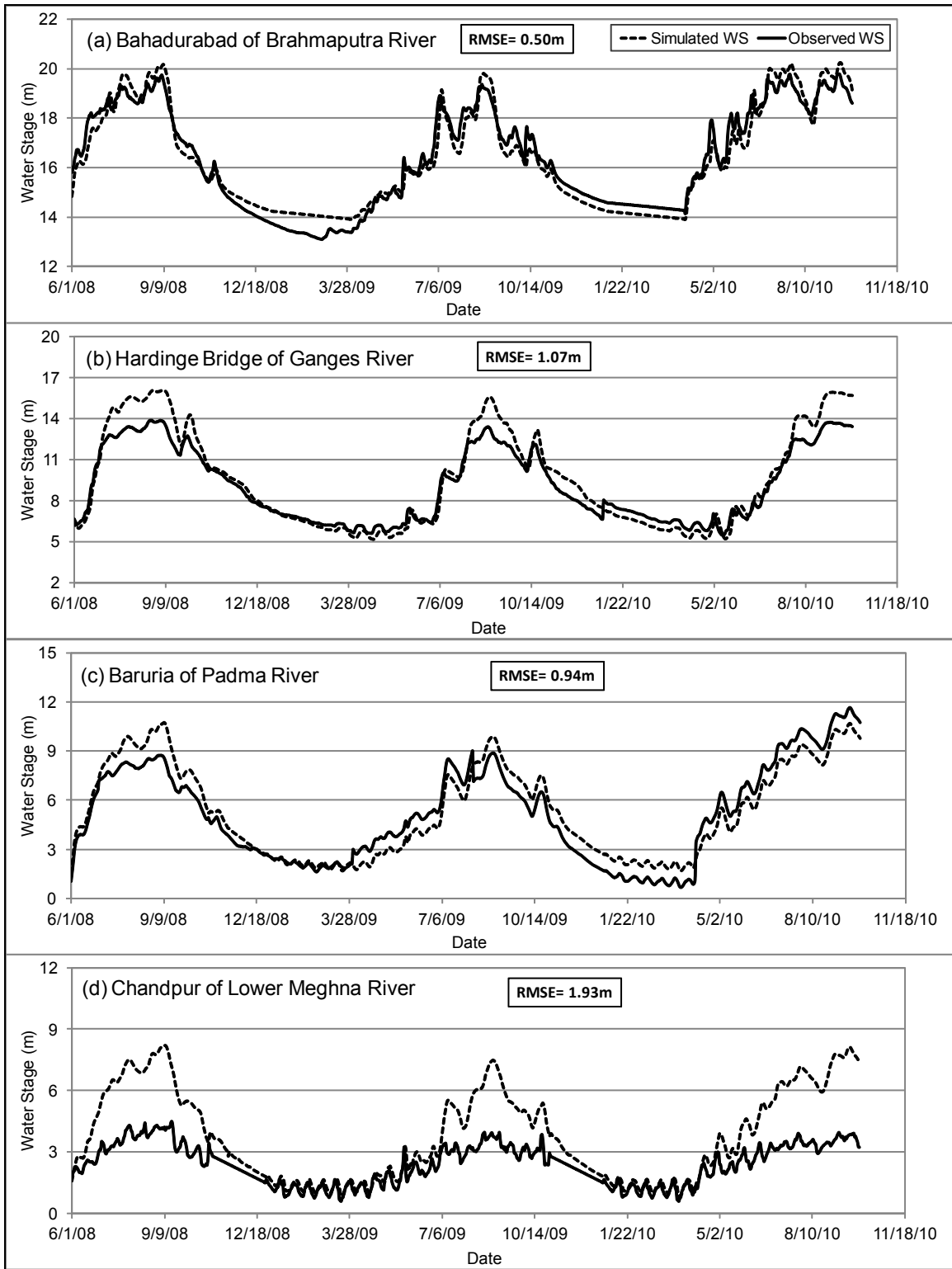
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659

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 m³/s and Mean Absolute
662 Error=70 m³/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).

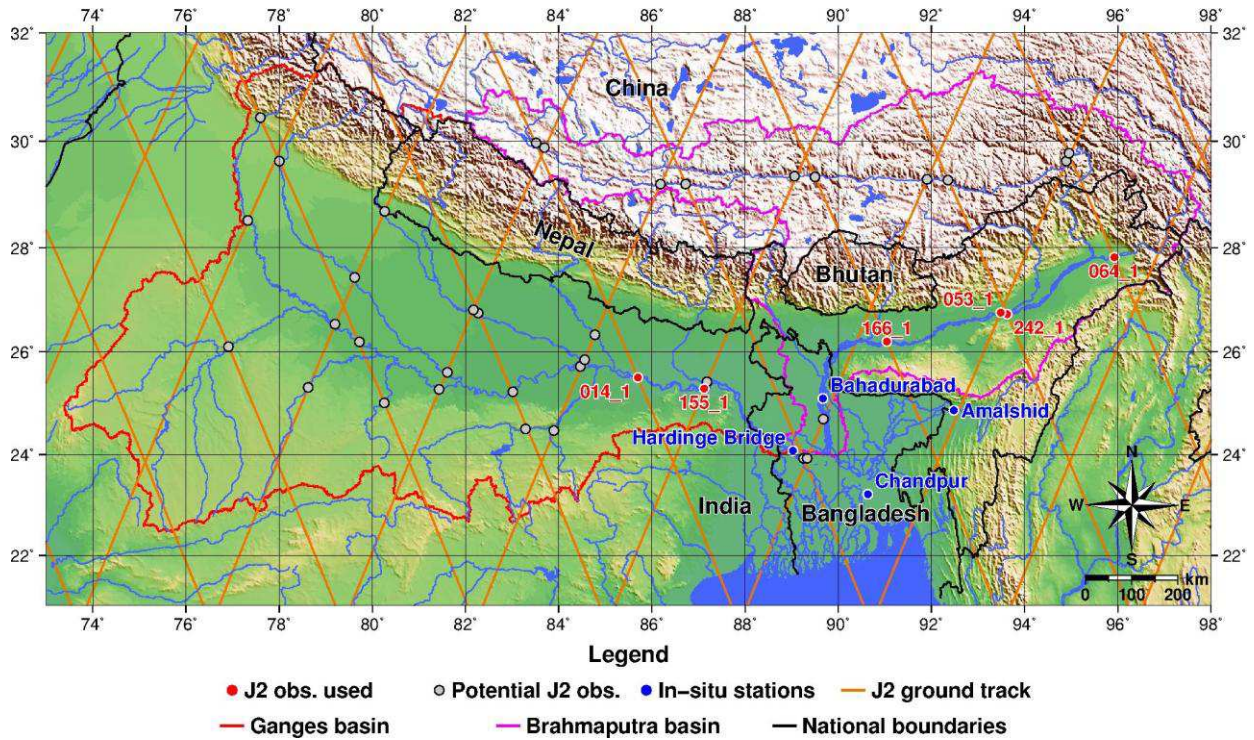
Estimation of 5-day forecast of River Discharge at Upstream boundary point of Model domain

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

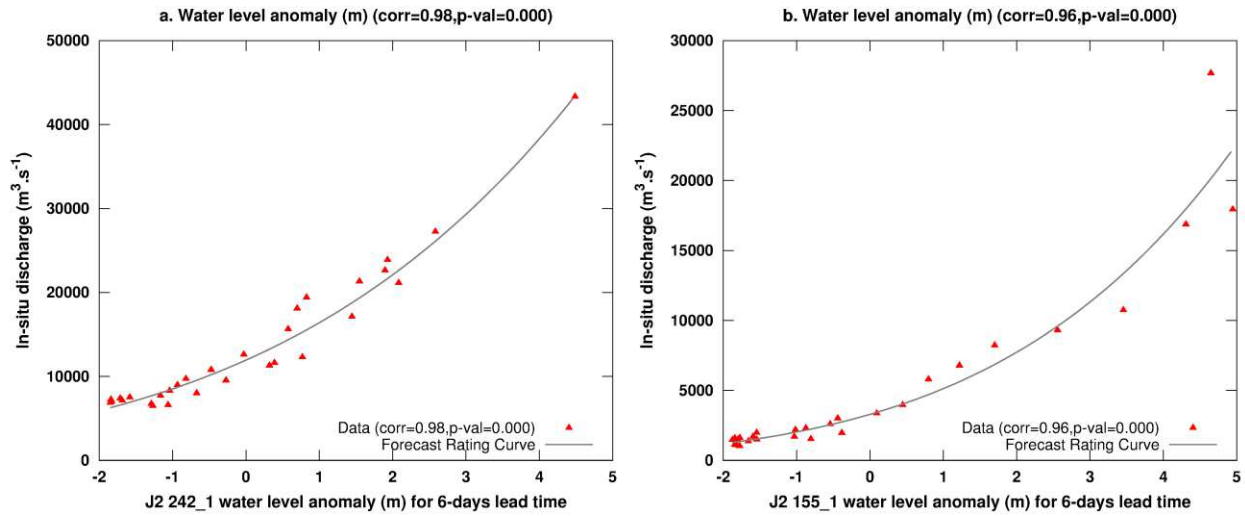
HEC-RAS model is initialized each day with the 5-day forecast of river discharge at the upstream-most boundary points and then model runs performed at daily time step. For downstream most boundary point, in-situ river level data at *Daulatkhan* is used. The simulation of river levels in this manner at 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.



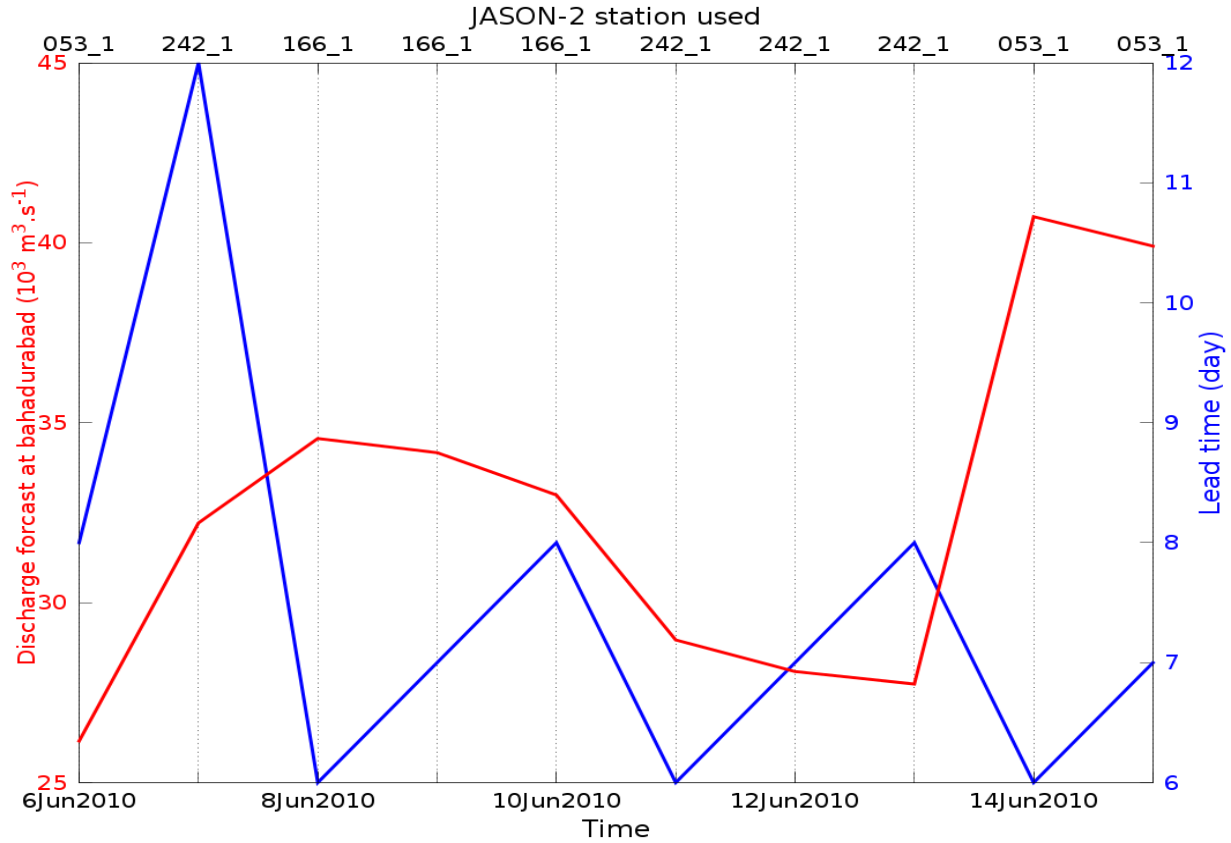
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Figure 5. Ground tracks or virtual stations of JASON-2 (J2) altimeter over the GB basin shown in orange lines and circles, respectively. The locations where the track crosses a river and used for deriving forecasting rating curves is shown with a circle 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.

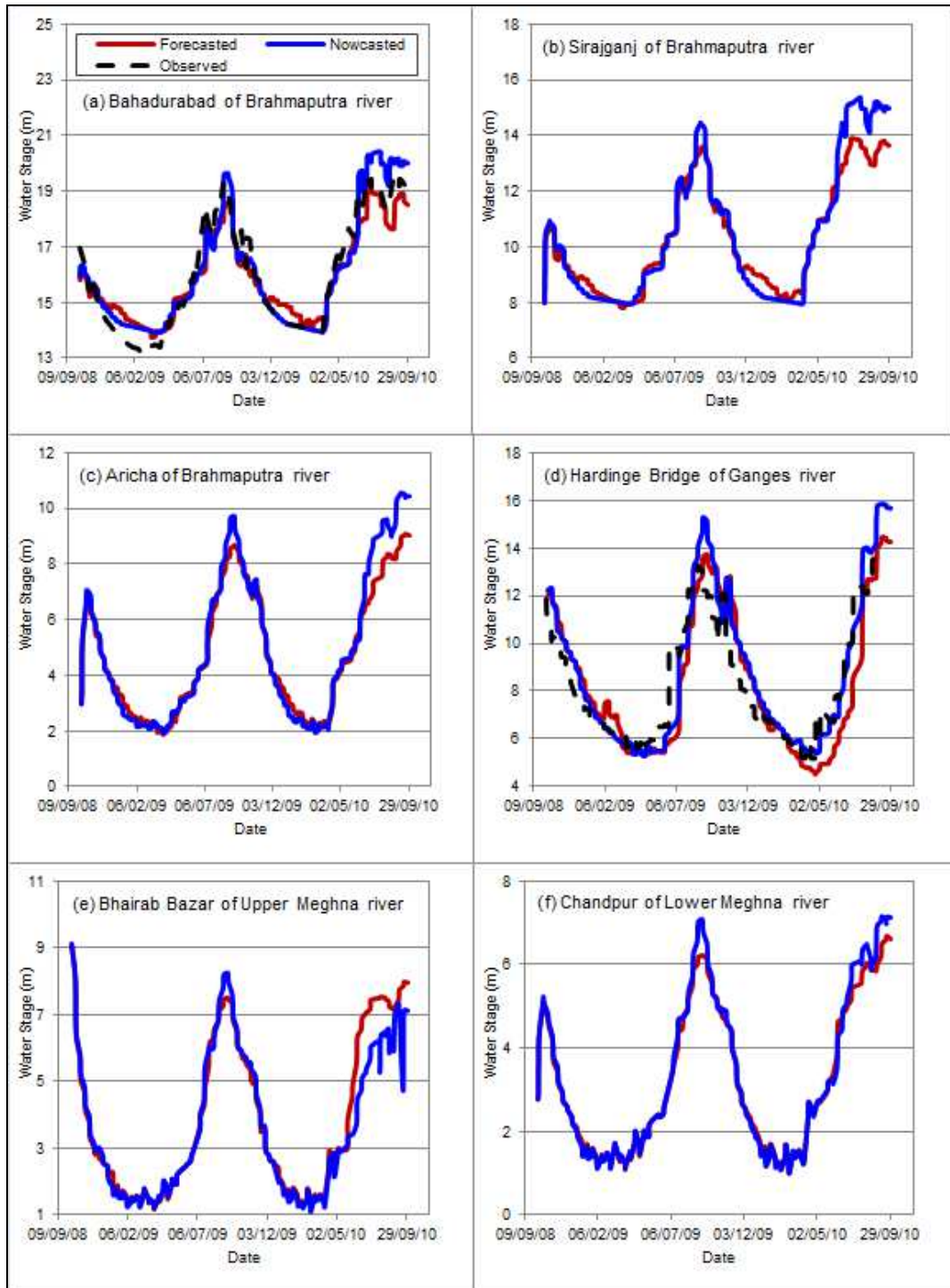


704
 705 **Figure 6.** Example of 6-day forecasting rating curves (FRC) for JASON-2 at ground track
 706 (virtual station) location 242_1 (Brahmaputra river – Figure 2) for *Bahadurabad* station (left
 707 panel) and 155_1 (Ganges river –Figure 2) for *Hardinge Bridge* station (right panel). These
 708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

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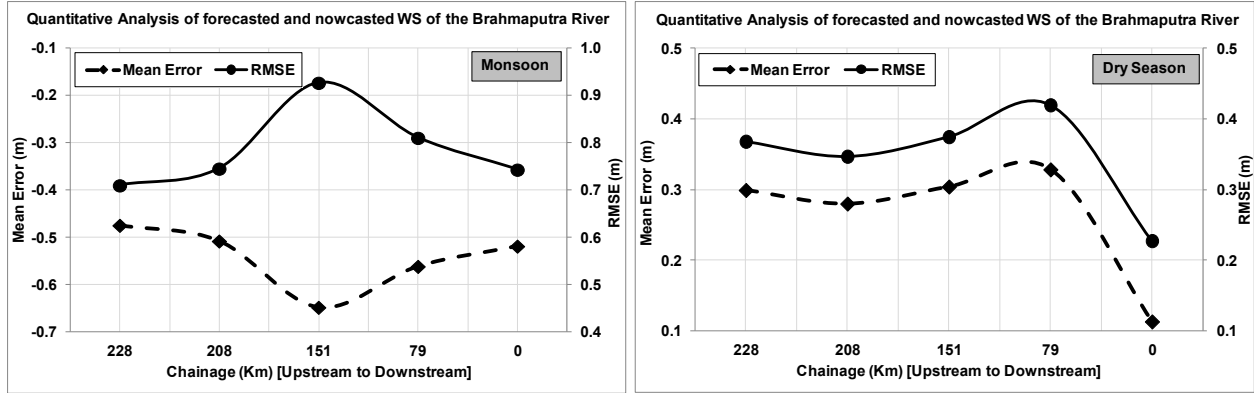
711
 712 **Figure 7.** Example of 5-day forecasted water level (red curve) at *Bahadurabad* on the
 713 Brahmaputra River (left y-axis) between 6 June 2010 and 15 June 2010 versus time (bottom x-
 714 axis). The blue curve corresponds to the lead time (right y-axis) of the JASON-2 FRC used to
 715 compute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



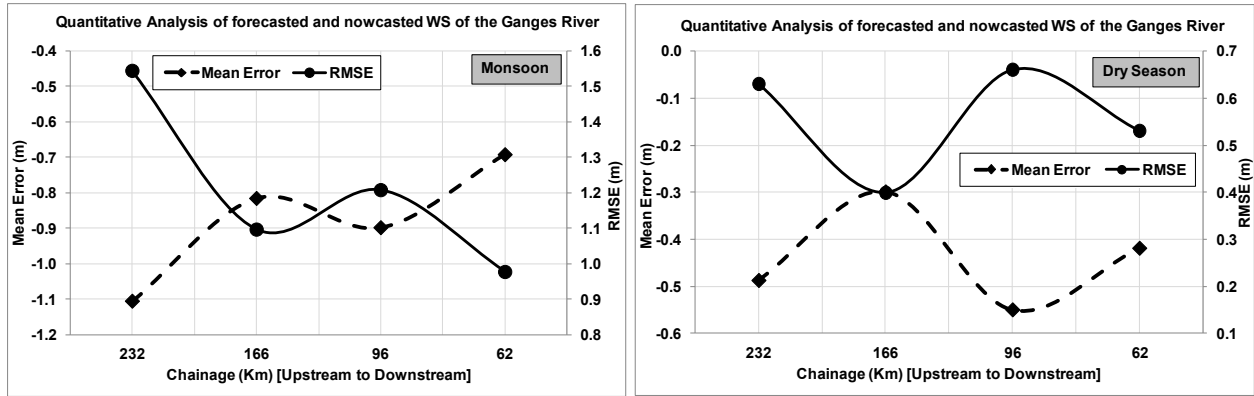
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719 **Figure 8.** Forecast (5 day) and Nowcast water level hydrographs at six river stations during the validation
 720 period of July 22, 2009 to September 30, 2010. Observed water level data are available only for
 721 Bahadurabad and Hardinge Bridge stations. For location of the stations, refer to Figure 2 and Table 1.

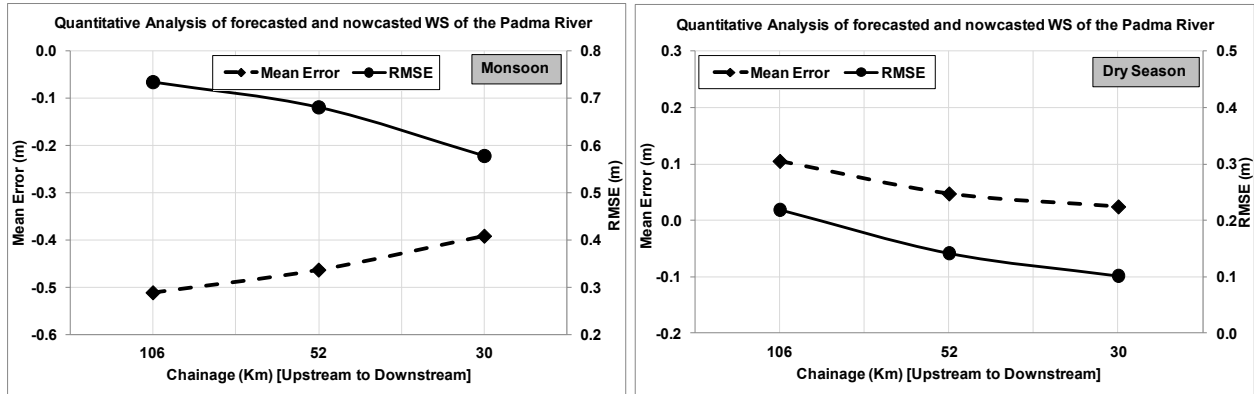
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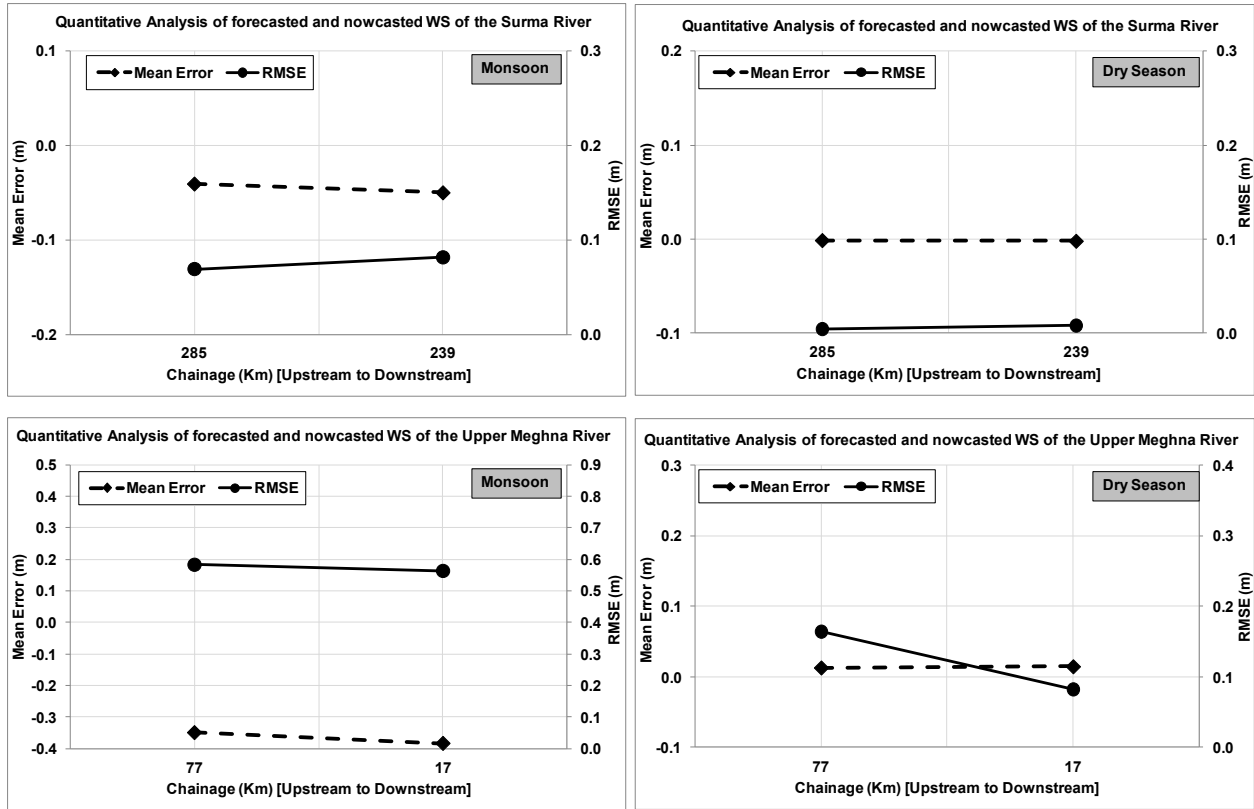
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725 **Figure 9.** Accuracy assessment as a function of season (left panel-Monsoon; right panel – Dry
 726 season), river segments and flow distance downstream (chainage) (x-axis). Upper panels –
 727 Brahmaputra river; Middle panels – Ganges River;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

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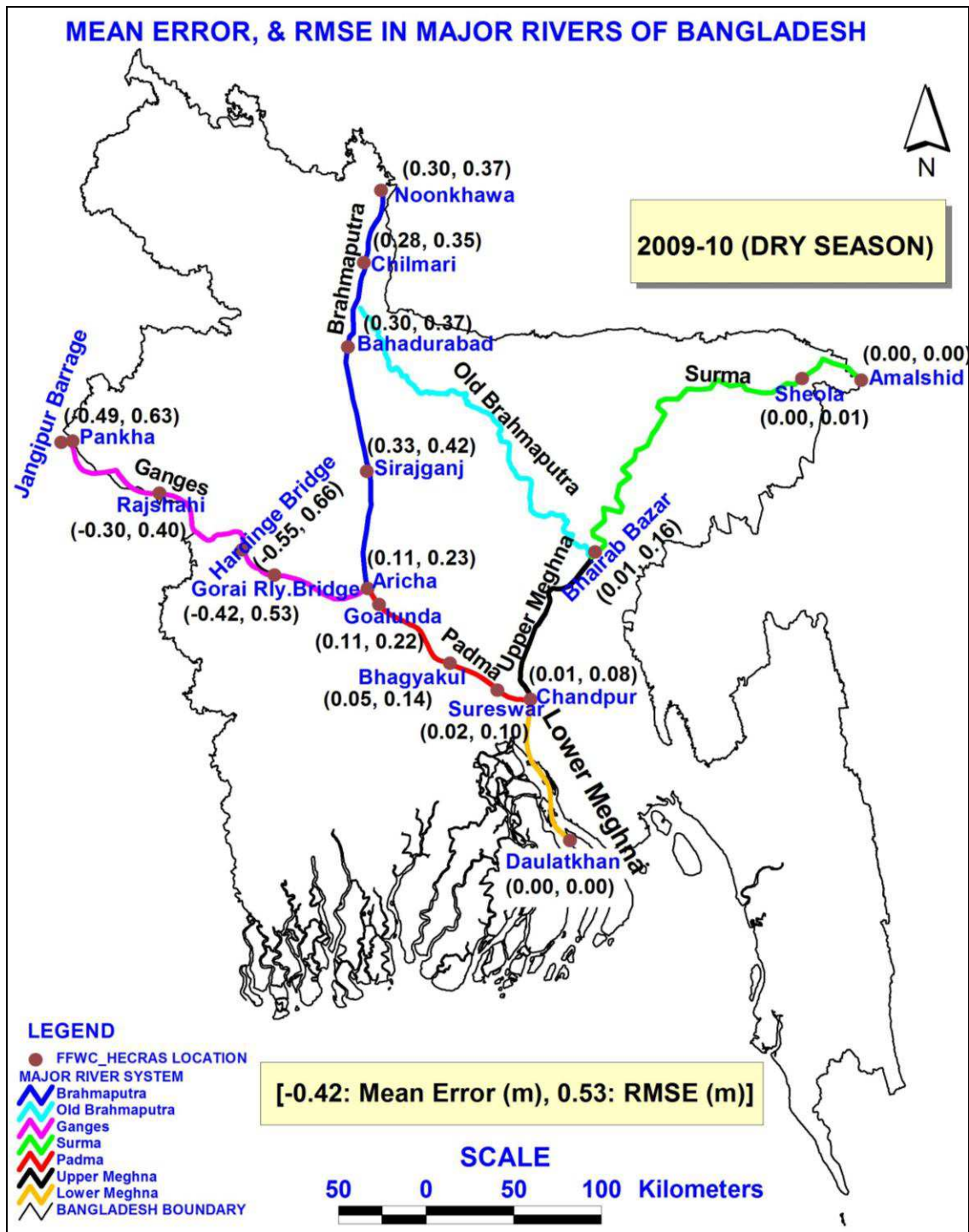


730

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

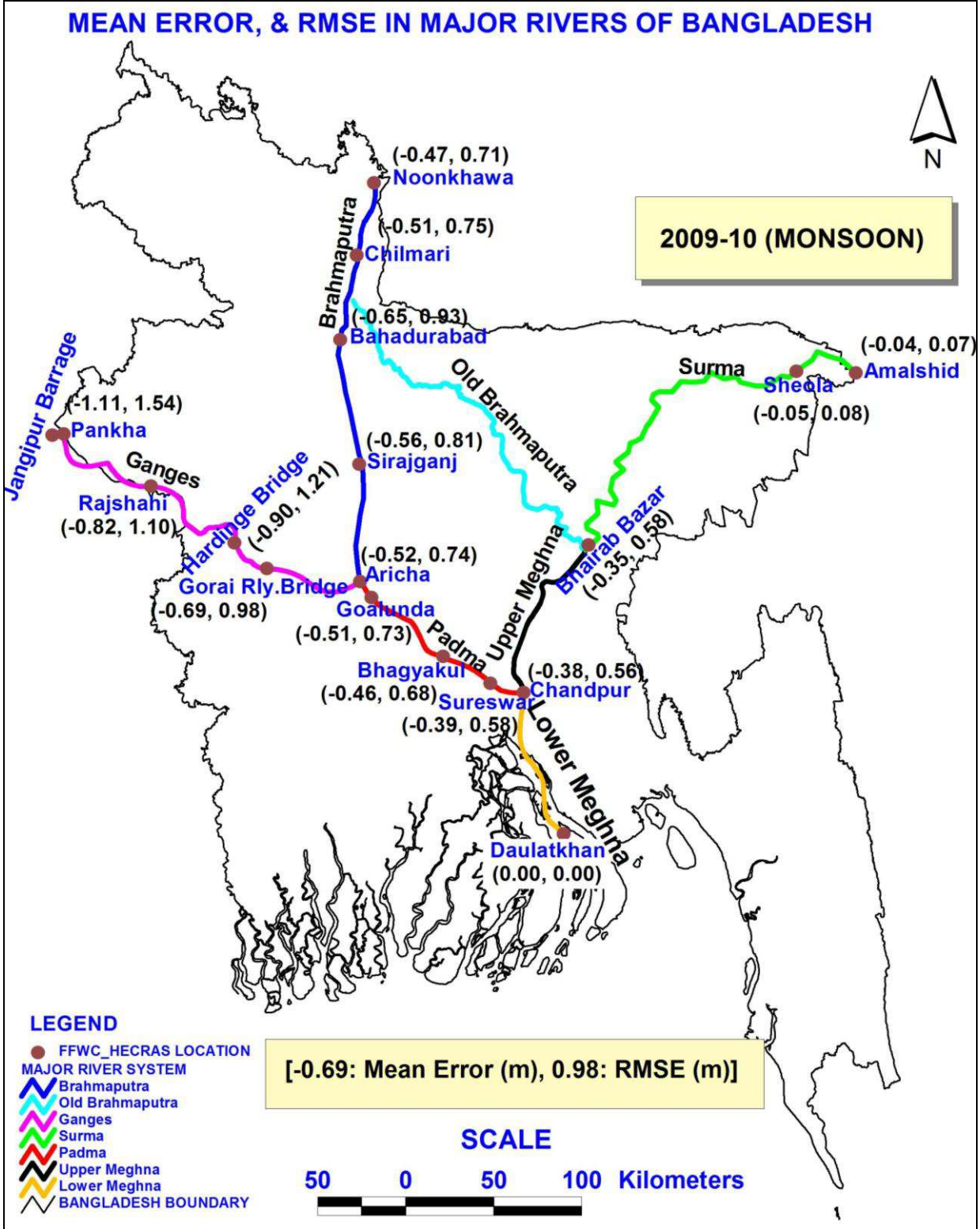
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737

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.

740



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.

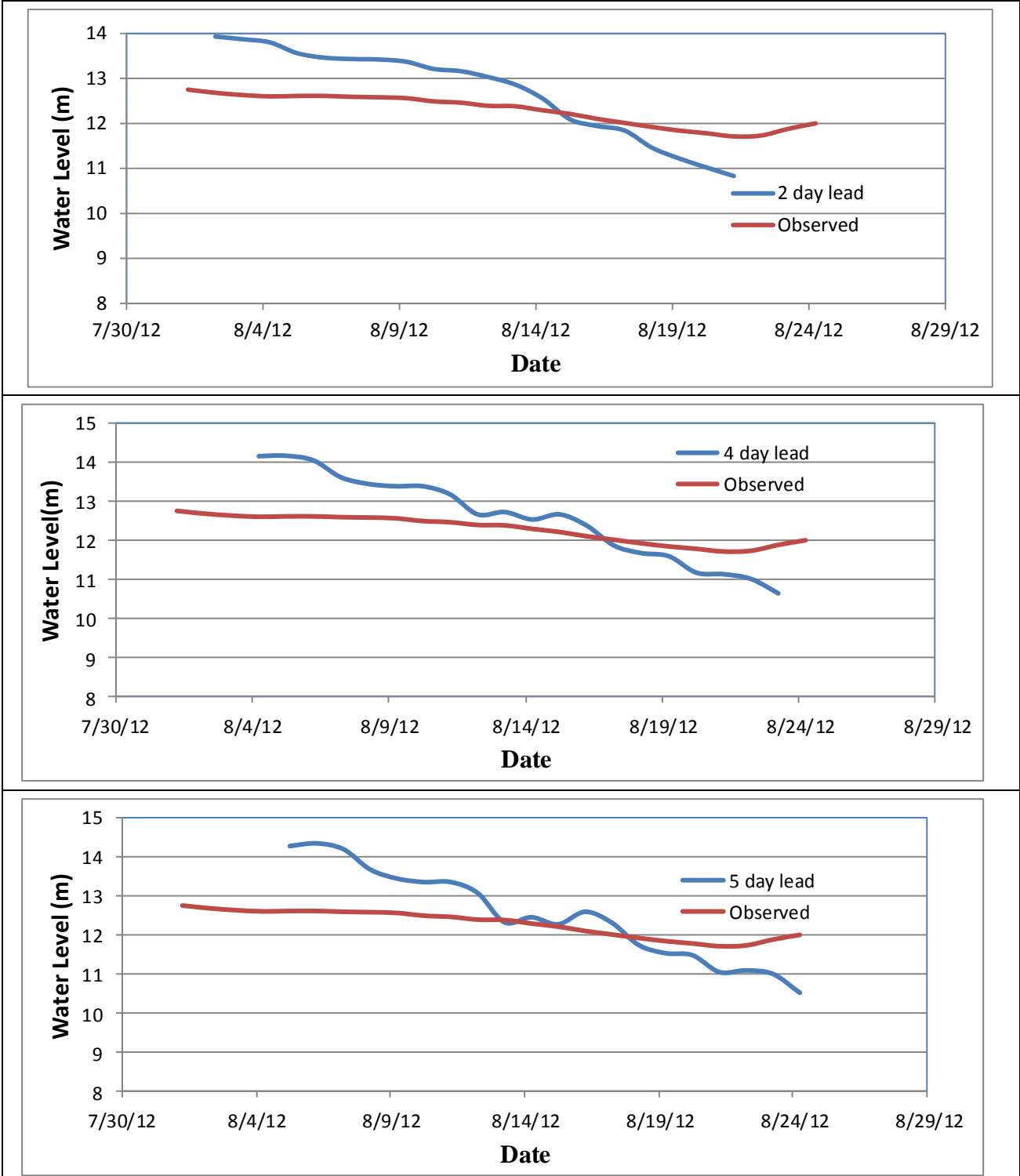


Figure 12. Assessment of JASON-2 5 day flood forecasting at Sirajganj (see Figure 2 for location) on Brahmaputra river against observed water level (relative to local datum) in a real-time and operational framework during Aug 1 to Aug 20, 2012. The forecasts were generated entirely and independently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

