Research Project on Developing Flash Flood Early Warning System, Capacity Building and Knowledge Management for the Haor Region of Bangladesh

FLASH FLOOD FORECAST EVALUATION REPORT

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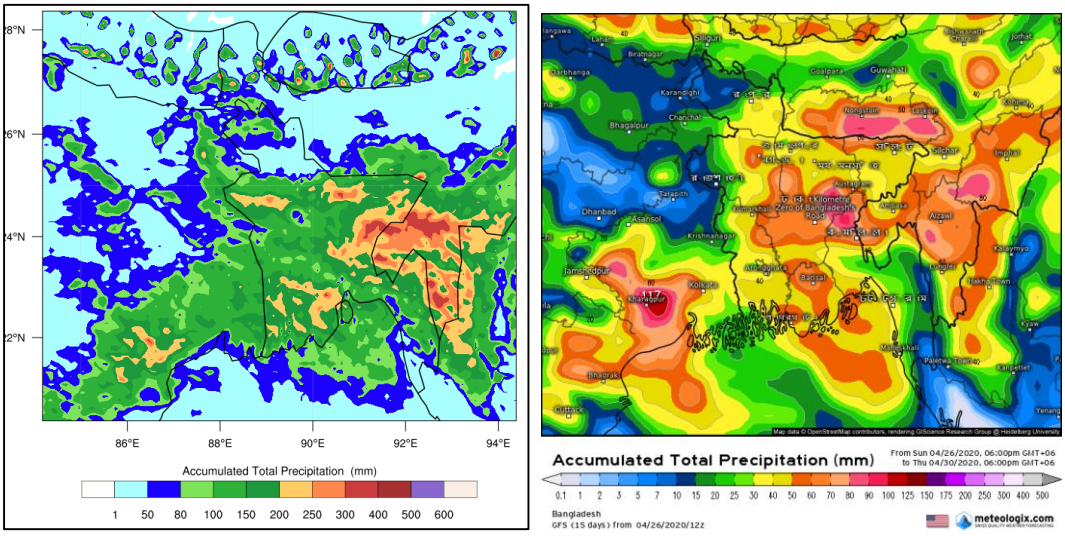

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ABBREVIATIONS AND ACRONYMS

BMD	Bangladesh Meteorological Department
BUET	Bangladesh University and Engineering and Technology
BWDB	Bangladesh Water Development Board
CALIP	Climate Adaptation and Livelihood Protection
DDM	Department of Disaster Management
DEM	Digital elevation model
DL	Danger Level
FFFS	Flash Flood Forecasting System
FFWC	Flood Forecasting and Warning Center
FNL	Final Analysis data
GFS	Global Forecast System
GPM	Global Precipitation Measurement
HEC-HMS	Hydrologic Modeling System
HEC-RAS	Hydrologic Engineering Centers River Analysis System

IFAD	International Fund for Agricultural Development
IMD	India Meteorological Department
IWFM	Institute of Water and Flood Management
LGED	Local Government Engineering Department
NARX	Nonlinear Autoregressive Network with Exogenous inputs
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NE	North East
NSE	Nash-Sutcliffe efficiency
PBIAS	Percentage Bias
RHWL	Record High Water Level
TRMM	Tropical Rainfall Measuring Mission
WRF	Weather Research and Forecasting Model

EXECUTIVE SUMMARY

IWMF, BUET has carried out flash flood forecasting for the rivers in the northeast haor areas of Bangladesh. This report provides a brief summary of the evaluation of the model performance of forecasting of river stages for the 26 forecast stations of BWDB. Open source based modeling system has been developed under the HILIP/CALIP project of LGED funded by IFAD which includes four essential components: (1) weather forecasting model (WRF) to forecast rainfall over the upper Meghna basin, (2) hydrological modeling using HEC-HMS to generate boundary flow of the transboundary rivers to derive the hydrodynamic model, (3) hydraulic routing using one dimensional model, HEC-RAS, (4) integrated graphical interface, Delft-FEWS to prepare forecast and providing early warnings. These open source based integrated flash flood forecasting system known as IFFEWS has been simulated during the pre-monsoon seasons of this year. WRF model is simulated at the super computer of NCAR, USA with a horizontal resolution of 9km and forced by NCEP GFS global model forecasts generated at 25km resolution. Due to covid19 pandemic IWFM, BUET server was closed under the nation was lockdown and we are thankful to NCAR for providing online access to simulate model in Cheyenne supercomputer. Both HEC-HMS and HEC-RAS models are well-calibrated using the observation hydro-meteorological data and details of this calibration and validation are available in the last annual report for 2018-2019 and quarterly progress report September-December 2019. This report presents an evaluation of model performance in near real-time flash flood forecasting for the period of April 17-May 6, 2020 (20 days) in the pre-monsoon season. Although the model shows satisfactory performances in the majority of the stations (20 stations out of 26) for the 24-hr lead time, forecast errors are growing with the increase in lead time. Several issues are identified for generating the forecast errors such as 1) errors in rainfall forecasts, 2) lack of observations of discharge in the hydrodynamic model boundary, 3) lack of observations of rainfall in the upper catchment areas outside Bangladesh, 4) lack of high resolution bathymetry and topographic data etc.

Considering the experiences of the flash flood forecast of this pre-monsoon seasons, we would like to recommend the following-

1) As ECMWF rainfall forecast is generally regarded as more accurate than GFS, we should purchase subscript of this forecast products for the upcoming season.
2) It is necessary to update the model using the latest bathymetry data every year.
3) Moulavibazar Radar data should be collected from BMD which can use on data assimilation
4) Real time observations of water level and discharge using automated gauge is necessary.
5) Machine learning tools like ANN could be applied for correcting bias of forecast.

1. Introduction

To save the crops by harvesting before the occurrence of flash flood, a proper early warning system is an important need. The Meghna Basin, located in the north-east region of Bangladesh at the foothills of Meghalaya and Assam of India is a bowl shaped basin with low lands (haor areas) and mostly hilly catchment areas. Sudden heavy rainfall in these hills during the pre-monsoon season rushes down in a very short time, about 6 hours, and floods the low-lands. A hydrodynamic model can be used to route the water at the foot of the hill through the complex system of rivers in the north-east region, to estimate the river surface profile and get an early indication of water level and hence flash flood. This knowledge can be used to generate an early warning system for flash flood.

IWFM, BUET has carried out forecasting of flash floods for the northeast haor region during the pre-monsoon season of 2020. Integrated Flash Flood Forecasting and Warning System (IFEWS) was developed by coupling a number of open source based models and tools under the CALIP/HILIP project of LGED funded by IFAD. Forecasting of water levels in the 26 forecast stations of BWDB started since the middle of April based on the extended meteorological forecasts of possible event of heavy rainfall during the last week of April from BMD and NOAA as shown in Figure 1.

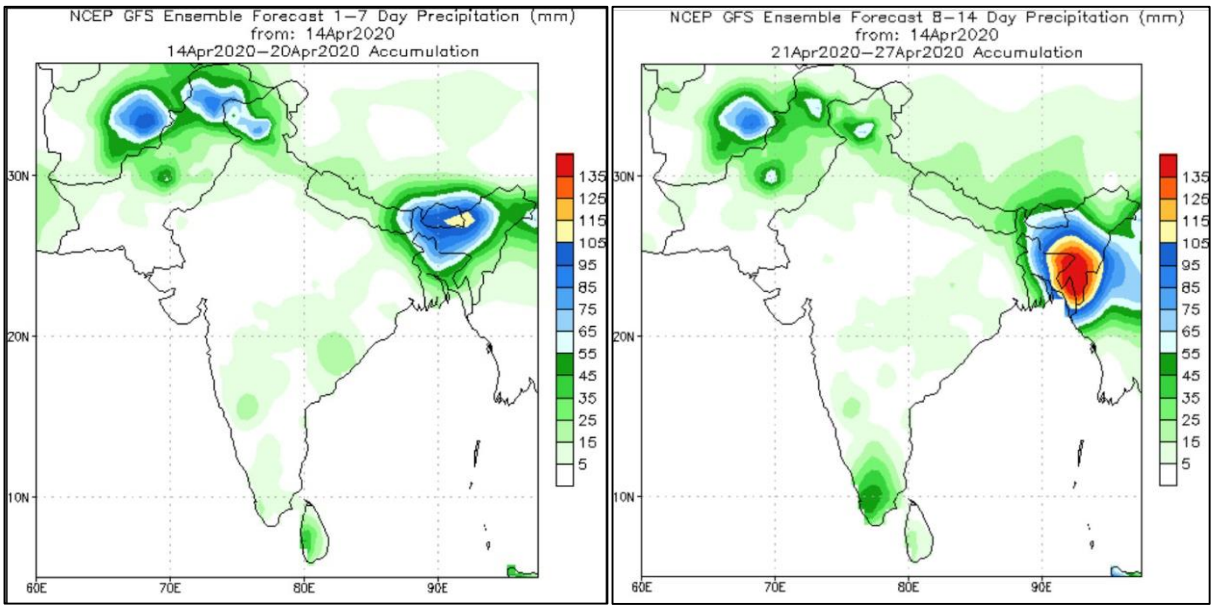


Figure 1: Heavy rainfall forecasts from NCEP GFS model week of 14-20 April 9, 2020 (left) and 21-27 April, 2020 (right).

2. Hydrodynamic modeling for flash flood forecasting

The Hydrodynamic model using HEC-RAS 1-d module to simulate water level and predict the flashflood. The aim is to predict water level based on input flow data and analyze flood level using measured cross-section and streamflow data of the river network. The model has generated water levels at various sections which can be used by the forecast stations for early warning of flashflood and be disseminated to the concerned so that appropriate actions can be taken to minimize the loss and damages due to flash flood.

A total of 26 forecast station on which the forecast is prepared based on the hydrodynamic model is shown in Figure 2. Water level forecast for the 10-day lead time for these 26 forecast stations on April 27, 2020 are shown in Appendix B.

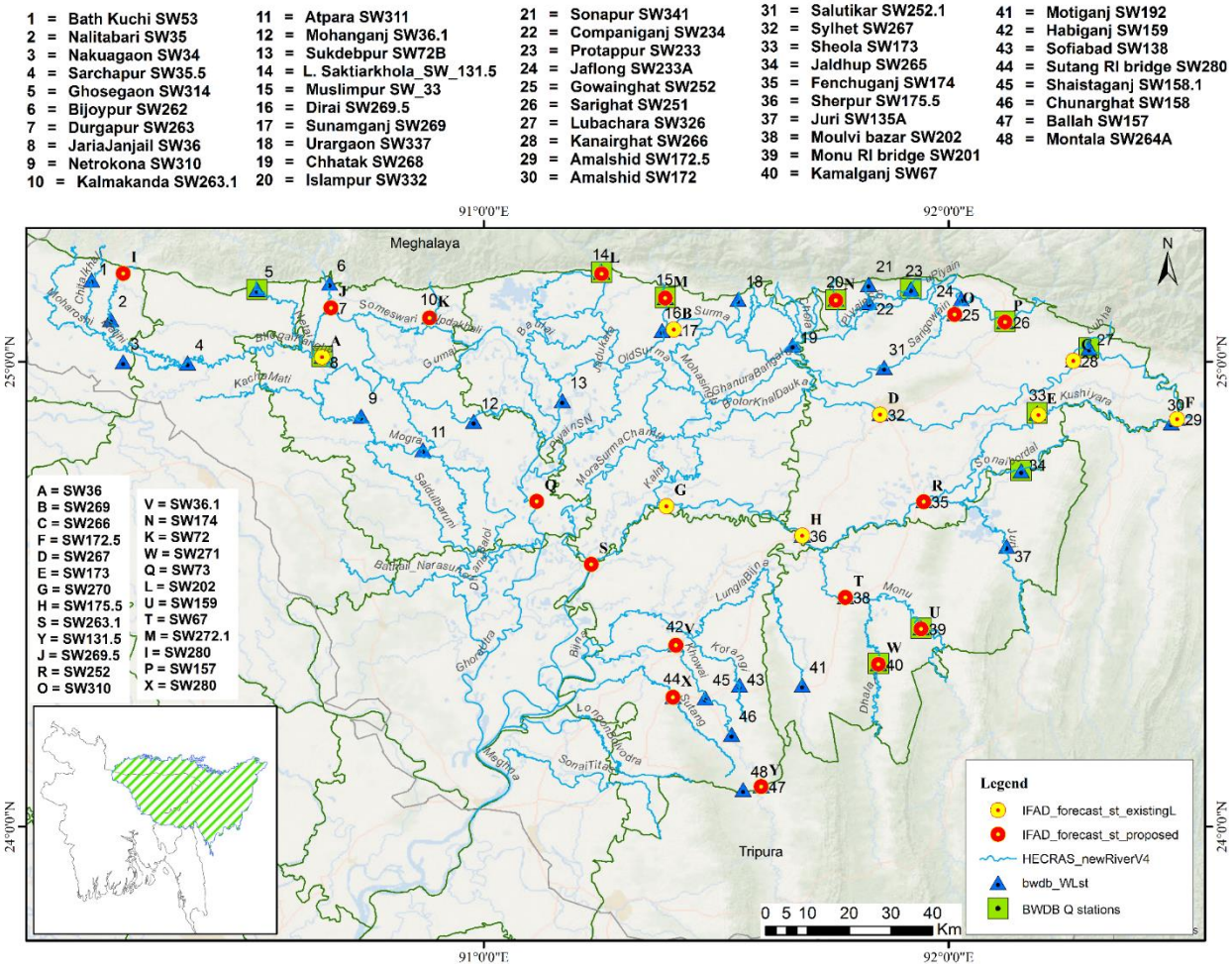


Figure 2: The Meghna basin, river system and water level forecast station.

3. Stage Forecast Evaluation Criteria

Four statistical criteria were used to assess the performance of the HEC-RAS model as shown in the Table 1. Coefficient of determination (**R^2**) describes the proportion of the variance in measured data explained by the model. R^2 ranges from 0 to 1, with higher values indicating less error variance, and typically values greater than 0.5 are considered acceptable. The Nash-Sutcliffe efficiency (**NSE**) is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance. NSE indicates NSE ranges between $-\infty$ and 1.0 (1 inclusive), with NSE as 1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values <0.0 indicates that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance. **RSR** standard-sizes RMSE using the observations standard deviation, and it combines both an error index**.** RSR is calculated as the ratio of the RMSE and standard deviation of measured data. Table 2 present the model evaluation criteria for stage forecasting.

Table 1: Statistical parameters for performance evaluations of stage forecast.

Indicator	Value of the Indicator		Range
	Negative	Positive	
PBIAS (Percentage Bias)	Model over-estimation	model under-estimation	0 to ∞
NSE (Nash-Sutcliff Efficiency)	Mean observation value is a better predictor	The observed data is distributed?	−∞ to 1
RSR (RMSE-observations Standard Deviation Ratio)	Cannot be negative	A higher value than 0.5 indicates that data itself can predict itself better than the model can	0 to ∞
$\boldsymbol{R^2}$ (coefficient of determination)	Model and observed data may or may not agree with each other/ their relation is opposite	The model and observed data may or may not agree with each other and their relation is direct	0 to 1

Table 2: Criteria for evaluating model performance using statistical parameters.

Parameter	Very good range	Good range	Acceptable range	Minimally Acceptable range	Unsatisfactory range
R^2	0.9 –1.0	0.8 – 0.9	0.7 – 0.8	0.5-0.7	<0.5
NSE	0.75 - 1	0.65 – 0.75	0.5 – 0.65	0.3-0.5	<0.5
RSR	0 – 0.5	0.5 – 0.6	0.6 – 0.7	0.7-1.0	>1.0
PBIAS	<±10	+10 – ±15	+15 – ±25	+25 – +35	>+35

4. Evaluation of model performance

Stage forecasts of the hydrodynamic model with a lead time of at 24-hr, 48-hr and 72-hr are compared with the observations. It can be found that model performs satisfactory (20 stations out of 26) for forecasting flash flood occurrence during the pre-monsoon period for the majority of the stations. However, with the increase in forecast lead time, an increasing number of unsatisfactory results are found. Stations located in Bangladesh near the border between Bangladesh and India showed more inaccuracy than the stations located far from the border. Evaluation of model performance for 24-hour, 48-hour, 72-hour lead time is presented in Table 3, 4 and 5 respectively. Time series plot of observed and forecasted water level at 24-hr, 48-hr and 72-hr for all the 26 forecast stations are plotted since May 17, 2020, as shown in Appendix A. Major causes of the forecast errors is discussed in the following section. A set of recommendations is suggested to improve model performance. However, given the complexity of the Meghna basin and vastness of the project, forecasts provided by the HEC-RAS model are satisfactory.

Table 3: Evaluation of model performance for 24-hour lead time.

Sl	River	Station	R2	Remarks	NSE	Remarks	RSR	Remarks	PBIAS	Remarks	RMSE
1	Someswari	Kalmakanda	0.24	Unsatisfactory	-0.50	Unsatisfactory	1.19	Unsatisfactory	17.26	Acceptable	0.60
2	Sarigowain	Gowainghat	0.91	Very Good	0.74	Good	0.50	Very Good	11.39	Good	0.39
3	Dhalagang	Islampur	0.52	Min. Acceptable	-9.47	Unsatisfactory	3.15	Unsatisfactory	5.80	Very Good	0.41
4	Jhalukhali	Muslimpur	0.98	Very Good	0.71	Acceptable	0.53	Good	10.49	Good	0.20
5	Sutang	SultanRlyBridge	0.75	Acceptable	0.50	Acceptable	0.69	Acceptable	6.06	Very Good	0.60
6	Dhanu	Khaliajuri	0.99	Very Good	0.59	Acceptable	0.62	Acceptable	11.41	Good	0.21
7	Manu	MonuRlyBridge	0.37	Unsatisfactory	-1.22	Unsatisfactory	1.45	Unsatisfactory	3.11	Very Good	0.52
8	Khowai	Ballah	0.53	Min. Acceptable	-1.17	Unsatisfactory	1.43	Unsatisfactory	0.72	Very Good	0.19
9	Khowai	Habiganj	0.31	Unsatisfactory	-0.31	Unsatisfactory	1.11	Unsatisfactory	4.45	Very Good	0.31
10	Manu	MouloviBazar	0.33	Unsatisfactory	-1.04	Unsatisfactory	1.39	Unsatisfactory	7.64	Very Good	0.57
11	Dhalai	Kamalganj	0.41	Unsatisfactory	-1.79	Unsatisfactory	1.63	Unsatisfactory	2.35	Very Good	0.67
12	Kushiyara	Fenchuganj	0.95	Very Good	0.84	Very Good	0.38	Very Good	5.21	Very Good	0.19
13	Kushiyara	Sheola	0.91	Very Good	0.83	Very Good	0.40	Very Good	5.03	Very Good	0.22
14	Kushiyara	Amalshid	0.87	Good	0.52	Acceptable	0.67	Acceptable	1.92	Very Good	0.17
15	Surma	Kanarghat	0.87	Good	0.46	Min. Acceptable	0.72	Min. Acceptable	3.66	Very Good	0.18
16	Surma	Sylhet	0.98	Very Good	0.76	Very Good	0.48	Very Good	9.82	Very Good	0.21
17	Sarigowain	Sarighat	0.64	Min. Acceptable	-0.21	Unsatisfactory	1.07	Unsatisfactory	8.88	Very Good	0.46
18	Kushiyara	Sherpur	0.91	Very Good	0.78	Very Good	0.45	Very Good	8.92	Very Good	0.22
19	Kalni	Markuli	0.93	Very Good	0.82	Very Good	0.42	Very Good	7.59	Very Good	0.18
20	Surma	Sunamganj	0.98	Very Good	0.70	Good	0.53	Good	10.58	Good	0.20
21	Titas	B_Baria	0.66	Min. Acceptable	-1.05	Unsatisfactory	1.40	Unsatisfactory	15.79	Acceptable	0.27
22	Jadukatha	Lourergorh	0.40	Unsatisfactory	-1.61	Unsatisfactory	1.57	Unsatisfactory	6.83	Very Good	0.28
23	Someswari	Durgapur	0.52	Min. Acceptable	-0.04	Unsatisfactory	0.99	Min. Acceptable	1.73	Very Good	0.19
24	Bhugai	Nakuagaon	0.54	Min. Acceptable	0.10	Unsatisfactory	0.92	Min. Acceptable	0.39	Very Good	0.13
25	Kangsha	Jarijanjail	0.93	Very Good	0.76	Very Good	0.48	Very Good	3.77	Very Good	0.30
26	Kalni	Azmiriganj	0.93	Very Good	0.81	Very Good	0.42	Very Good	9.55	Very Good	0.20

Table 4: Evaluation of model performance for 48-hour lead time.

Sl	River	Station	R2	Remarks	NSE	Remarks	RSR	Remarks	PBIAS	Remarks	RMSE
1	Someswari	Kalmakanda	-0.19	Unsatisfactory	-0.72	Unsatisfactory	1.85	Unsatisfactory	24.01	Min. Acceptable	0.64
2	Sarigowain	Gowainghat	0.60	Min. Acceptable	0.28	Unsatisfactory	1.08	Unsatisfactory	17.51	Acceptable	0.74
3	Dhalagang	Islampur	0.33	Unsatisfactory	0.09	Unsatisfactory	4.47	Unsatisfactory	7.35	Very Good	0.49
4	Jhalukhali	Muslimpur	0.95	Very Good	0.52	Acceptable	1.06	Unsatisfactory	17.88	Acceptable	0.35
5	Sutang	SultanRlyBridge	0.47	Unsatisfactory	-0.15	Unsatisfactory	1.00	Min. Acceptable	9.97	Very Good	0.88
6	Dhanu	Khaliajuri	0.97	Very Good	0.47	Unsatisfactory	1.28	Unsatisfactory	19.76	Acceptable	0.37
7	Manu	MonuRlyBridge	0.08	Unsatisfactory	-0.33	Unsatisfactory	1.72	Unsatisfactory	3.56	Very Good	0.61
8	Khowai	Ballah	0.13	Unsatisfactory	-0.26	Unsatisfactory	1.66	Unsatisfactory	1.00	Very Good	0.24
9	Khowai	Habiganj	-0.13	Unsatisfactory	-0.49	Unsatisfactory	1.98	Unsatisfactory	7.59	Very Good	0.54
10	Manu	MouloviBazar	-0.19	Unsatisfactory	-0.93	Unsatisfactory	1.70	Unsatisfactory	8.53	Very Good	0.70
11	Dhalai	Kamalganj	-0.09	Unsatisfactory	-0.41	Unsatisfactory	2.07	Unsatisfactory	3.22	Very Good	0.83
12	Kushiyara	Fenchuganj	0.90	Very Good	0.74	Good	0.72	Min. Acceptable	8.03	Very Good	0.30
13	Kushiyara	Sheola	0.84	Good	0.65	Good	0.58	Very Good	7.60	Very Good	0.33
14	Kushiyara	Amalshid	0.57	Min. Acceptable	0.14	Unsatisfactory	0.97	Min. Acceptable	3.25	Very Good	0.29
15	Surma	Kanarghat	0.74	Acceptable	0.25	Unsatisfactory	1.14	Unsatisfactory	6.95	Very Good	0.32
16	Surma	Sylhet	0.96	Very Good	0.54	Acceptable	0.87	Min. Acceptable	17.59	Acceptable	0.38
17	Sarigowain	Sarighat	0.27	Unsatisfactory	-0.12	Unsatisfactory	1.59	Unsatisfactory	11.99	Good	0.61
18	Kushiyara	Sherpur	0.86	Good	0.69	Good	0.73	Min. Acceptable	12.40	Good	0.30
19	Kalni	Markuli	0.89	Good	0.68	Good	0.70	Min. Acceptable	11.34	Good	0.27
20	Surma	Sunamganj	0.95	Very Good	0.53	Acceptable	1.06	Unsatisfactory	17.97	Acceptable	0.35
21	Titas	B_Baria	0.66	Min. Acceptable	0.39	Min. Acceptable	1.74	Unsatisfactory	19.10	Acceptable	0.33
22	Jadukatha	Lourergorh	0.39	Unsatisfactory	0.03	Unsatisfactory	2.08	Unsatisfactory	8.42	Very Good	0.35
23	Someswari	Durgapur	0.12	Unsatisfactory	-0.69	Unsatisfactory	1.32	Unsatisfactory	2.29	Very Good	0.25
24	Bhugai	Nakuagaon	0.22	Unsatisfactory	-0.58	Unsatisfactory	1.21	Unsatisfactory	0.63	Very Good	0.17
25	Kangsha	Jarijanjail	0.81	Good	0.60	Acceptable	0.81	Min. Acceptable	5.87	Very Good	0.48
26	Kalni	Azmiriganj	0.89	Good	0.70	Good	0.70	Min. Acceptable	13.61	Good	0.30

Table 5: Evaluation of model performance for 72-hour lead time.

Sl	River	Station	R2	Remarks	NSE	Remarks	RSR	Remarks	PBIAS	Remarks	RMSE
1	Someswari	Kalmakanda	-0.11	Unsatisfactory	-0.40	Unsatisfactory	2.09	Unsatisfactory	26.06	Min. Acceptable	0.68
2	Sarigowain	Gowainghat	0.25	Unsatisfactory	-0.08	Unsatisfactory	1.63	Unsatisfactory	23.50	Acceptable	0.94
3	Dhalagang	Islampur	0.13	Unsatisfactory	0.01	Unsatisfactory	4.33	Unsatisfactory	7.18	Very Good	0.47
4	Jhalukhali	Muslimpur	0.91	Very Good	0.36	Acceptable	1.55	Unsatisfactory	22.77	Acceptable	0.47
5	Sutang	SultanRlyBridge	0.31	Unsatisfactory	-0.47	Unsatisfactory	1.15	Unsatisfactory	12.50	Good	0.99
6	Dhanu	Khaliajuri	0.93	Very Good	0.30	Min. Acceptable	1.92	Unsatisfactory	25.41	Min. Acceptable	0.51
7	Manu	MonuRlyBridge	-0.20	Unsatisfactory	-0.32	Unsatisfactory	2.64	Unsatisfactory	5.71	Very Good	0.94
8	Khowai	Ballah	-0.32	Unsatisfactory	-0.81	Unsatisfactory	2.05	Unsatisfactory	1.26	Very Good	0.29
9	Khowai	Habiganj	-0.14	Unsatisfactory	-0.38	Unsatisfactory	2.28	Unsatisfactory	9.71	Very Good	0.64
10	Manu	MouloviBazar	-0.25	Unsatisfactory	-0.46	Unsatisfactory	2.35	Unsatisfactory	14.12	Good	1.00
11	Dhalai	Kamalganj	-0.24	Unsatisfactory	-0.29	Unsatisfactory	2.92	Unsatisfactory	6.22	Very Good	1.16
12	Kushiyara	Fenchuganj	0.85	Good	0.60	Good	1.04	Unsatisfactory	9.90	Very Good	0.39

Sl	River	Station	R2	Remarks	NSE	Remarks	RSR	Remarks	PBIAS	Remarks	RMSE
13	Kushiyara	Sheola	0.79	Acceptable	0.53	Good	0.69	Acceptable	8.62	Very Good	0.41
14	Kushiyara	Amalshid	0.27	Unsatisfactory	-0.06	Unsatisfactory	1.65	Unsatisfactory	5.81	Very Good	0.58
15	Surma	Kanarghat	0.66	Min. Acceptable	0.21	Unsatisfactory	1.15	Unsatisfactory	7.61	Very Good	0.00
16	Surma	Sylhet	0.95	Very Good	0.40	Min. Acceptable	1.14	Unsatisfactory	22.19	Acceptable	0.50
17	Sarigowain	Sarighat	0.13	Unsatisfactory	-0.28	Unsatisfactory	1.65	Unsatisfactory	12.45	Good	0.59
18	Kushiyara	Sherpur	0.86	Good	0.59	Acceptable	1.09	Unsatisfactory	12.81	Good	0.37
19	Kalni	Markuli	0.88	Good	0.55	Acceptable	1.05	Unsatisfactory	13.54	Good	0.36
20	Surma	Sunamganj	0.92	Very Good	0.36	Min. Acceptable	1.53	Unsatisfactory	22.95	Acceptable	0.47
21	Titas	B_Baria	0.78	Acceptable	0.50	Acceptable	1.51	Unsatisfactory	17.88	Acceptable	0.29
22	Jadukatha	Lourergorh	0.07	Unsatisfactory	-0.10	Unsatisfactory	2.76	Unsatisfactory	0.00	Very Good	0.00
23	Someswari	Durgapur	0.06	Unsatisfactory	-0.89	Unsatisfactory	1.34	Unsatisfactory	2.00	Very Good	0.26
24	Bhugai	Nakuagaon	0.12	Unsatisfactory	-0.75	Unsatisfactory	1.29	Unsatisfactory	0.77	Very Good	0.18
25	Kangsha	Jarijanjail	0.71	Acceptable	0.42	Acceptable	1.07	Unsatisfactory	7.66	Very Good	0.60
26	Kalni	Azmiriganj	0.87	Good	0.55	Acceptable	1.00	Min. Acceptable	16.27	Good	0.40

5. Causes of forecast errors

Water level forecasts of few stations are not found satisfactory due to a number of reasons-

1) Errors in rainfall forecasts

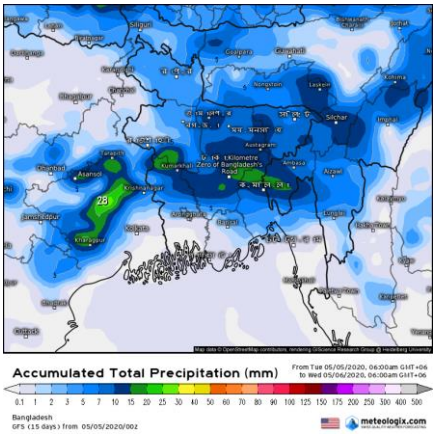
Rainfall forecasts are generated using weather models which is forced by using boundary condition data from NCEP GFS model. Comparing with the European Center for Medium-Range Weather Forecasts model or ECMWF, which is generally regarded as an all-around a better model, forecast errors are found between these two products (Figure 3). A comparison of 1-day, 3-day and 10-day maximum accumulated rainfall from ECMWF and GFS for the first 10 days of May 2020 is shown in Table 6.

Table 6: Comparison of rainfall forecast from ECMWF and NCEP-GFS models.

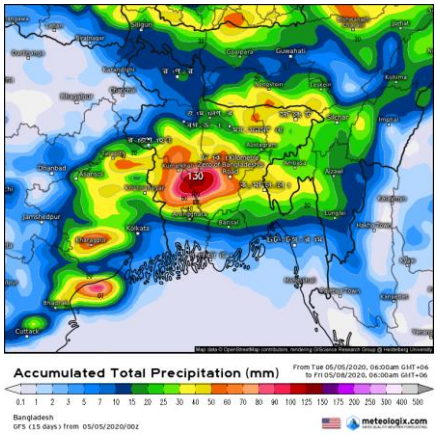
Date	Rainfall Forecast Products	Accumulated Maximum Rainfall (mm)			Ratio			Average Ratio
		1-day	3-day	10-day	1-day	2-day	10-day	
1 May 2020	ECMWF	15	50	100	0.60	0.71	0.37	0.56
	GFS	25	70	273				
2 May 2020	ECMWF	20	70	150	0.67	0.88	0.46	0.67
	GFS	30	80	329				
3 May 2020	ECMWF	60	100	175	1.50	0.77	0.58	0.95
	GFS	40	130	303				
4 May 2020	ECMWF	10	30	175	0.25	0.23	0.58	0.35
	GFS	40	130	303				
5 May 2020	ECMWF	50	80	150	2.5	1.3	0.6	1.48
	GFS	20	60	250				
6 May 2020	ECMWF	10	30	209	0.67	0.45	0.63	0.58
	GFS	15	66	332				
7 May 2020	ECMWF	20	30	298	4.0	0.5	1.7	2.07

	GFS	5	60	175				
8 May 2020	ECMWF	10	10	221	3.33	0.67	1.02	1.67
	GFS	3	15	217				
9 May 2020	ECMWF	3	15	361	3.00	0.38	1.76	1.71
	GFS	1	40	205				
10 May 2020	ECMWF	5	25	295	2.5	0.63	1.00	1.38
	GFS	2	40	294				

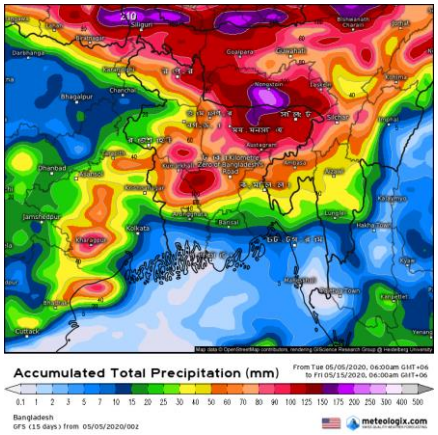
GFS Day-1 Forecast RF



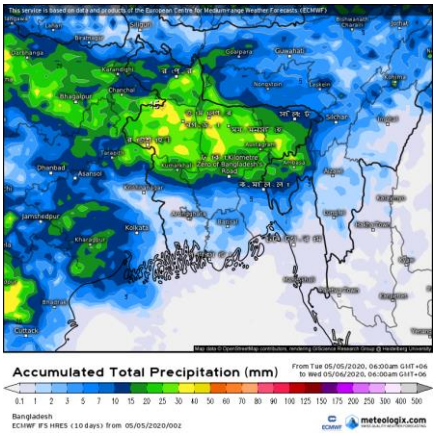
GFS Day-3 Forecast RF



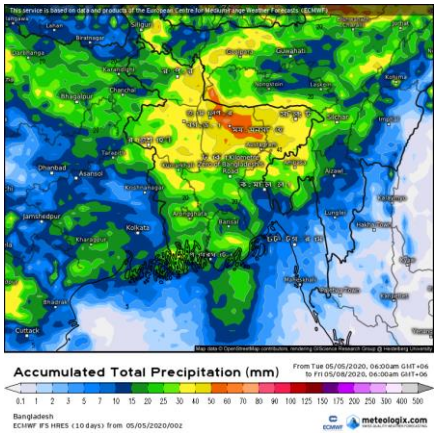
GFS Day-10 Forecast RF



ECMWF Day-1 Forecast RF



ECMWF Day-3 Forecast RF



ECMWF Day-10 Forecast RF

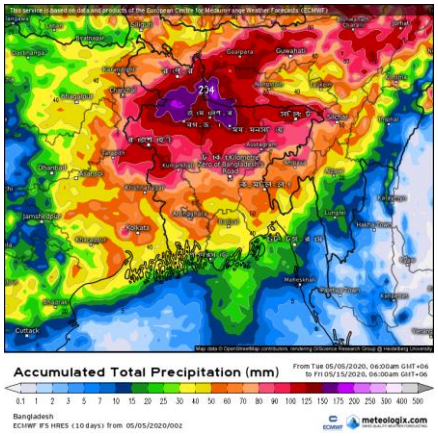


Figure 3: Comparison of 1, 3 and 10-days accumulated precipitation forecast from GFS and ECMWF models.

2) Lack of observations of discharge in the hydrodynamic model boundary

Real-time observations of both water level and discharge for all the model boundary nodes are essential to improve the model calibration and validation. Due to in sufficient observations of discharge, it was not possible to accurately calibrate and validate hydrologic and hydraulic models.

3) Lack of observations of rainfall in the upper catchment areas outside Bangladesh

Real-time observation of rainfall from gauges and radar data are not currently available. Transboundary collaborations on sharing observed data from the rainfall stations inside India is very limited.

4) Lack of high resolution bathymetry and topographic data

Although 200 number of x-sections of several rivers data are collected by IWM under this project. However, x-section data of many rivers are not updated and should be periodically collected.

APPENDIX-A: COMPARISON OF OBSERVED VERSUS FORECASTED STAGE FOR ALL LEAD TIMES

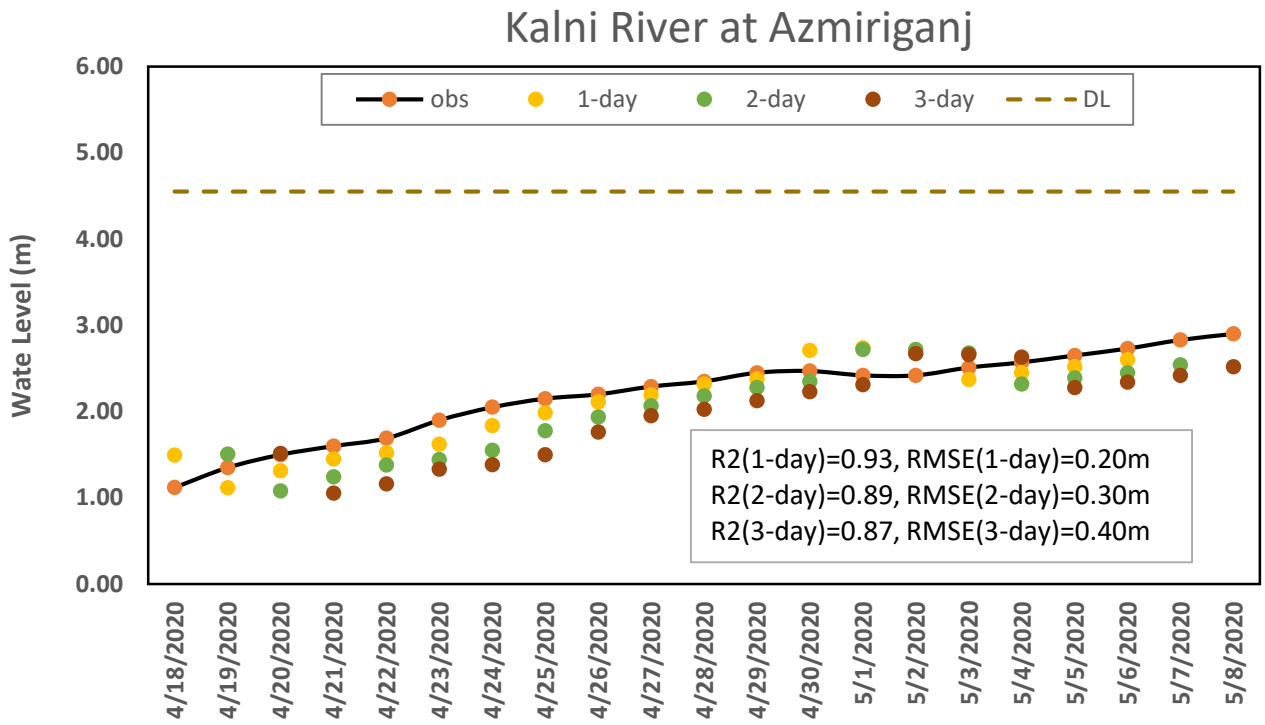


Figure A.1: Comparison of stage forecast for all lead times at Azmiriganj station of the Kalni river.

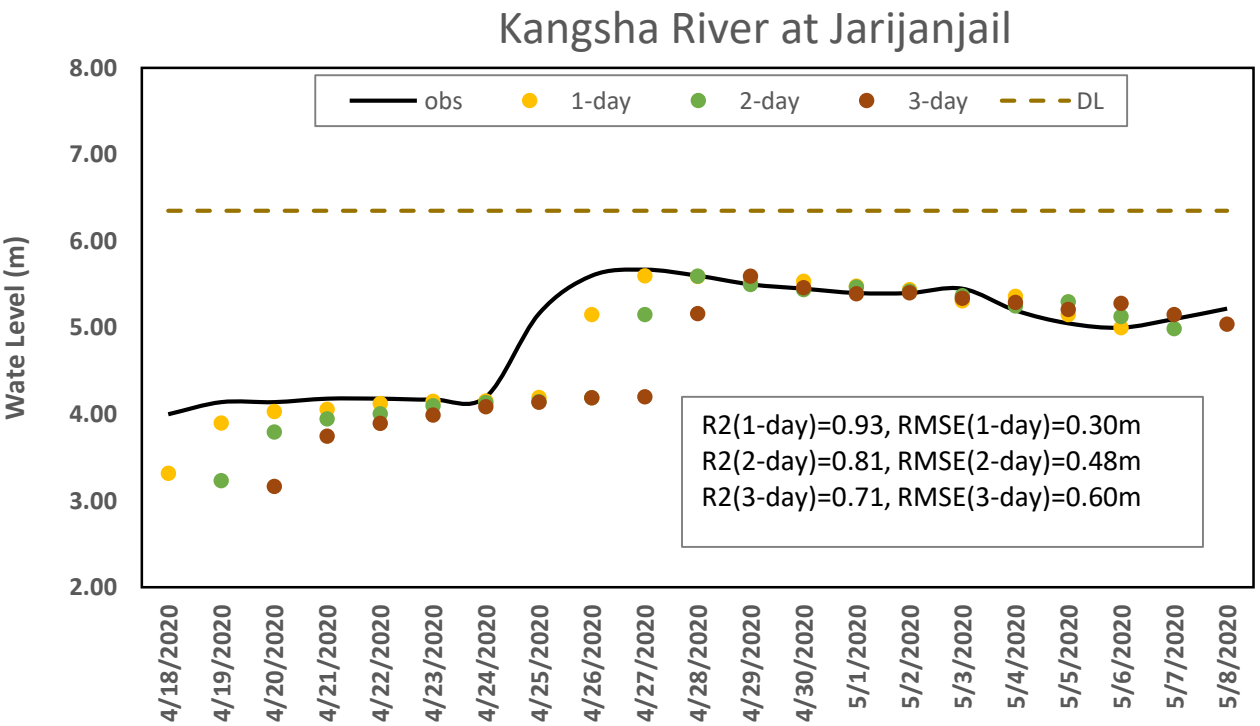


Figure A.2: Comparison of stage forecast for all lead times at Jarijanjail station of the Kangsha river.

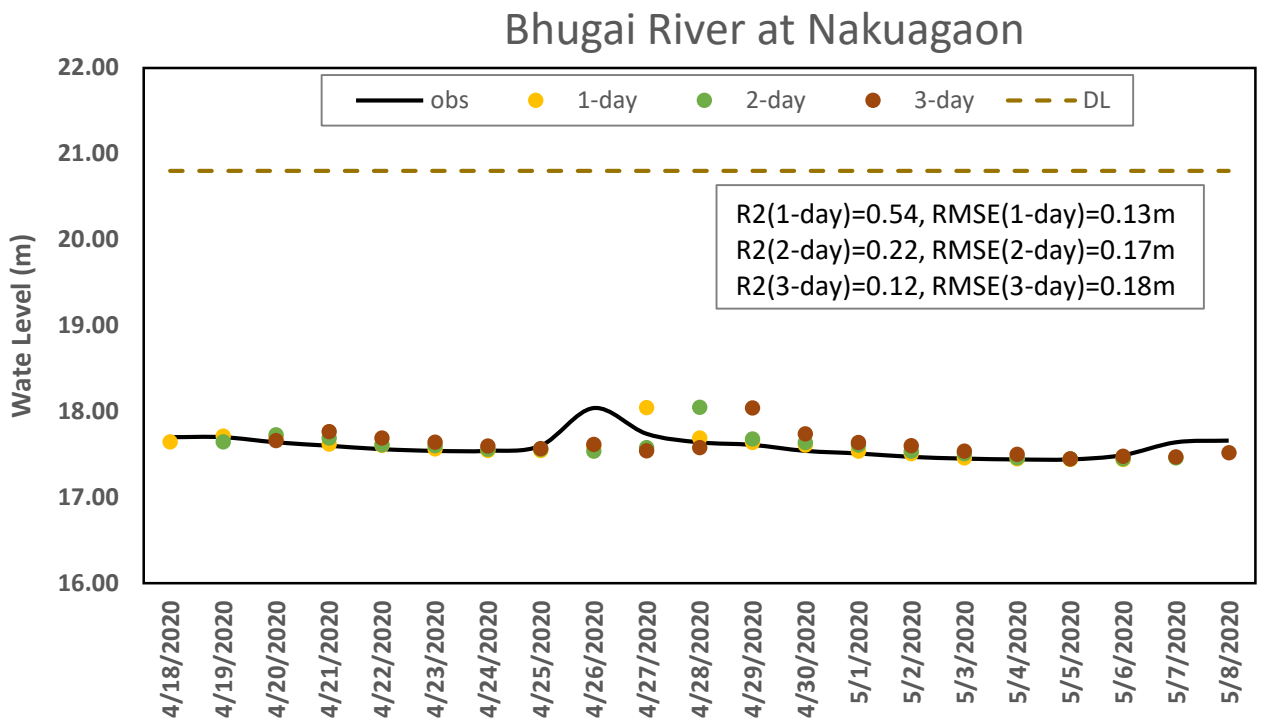


Figure A.3: Comparison of stage forecast for all lead times at Nakuagaon station of the Bhugai river.

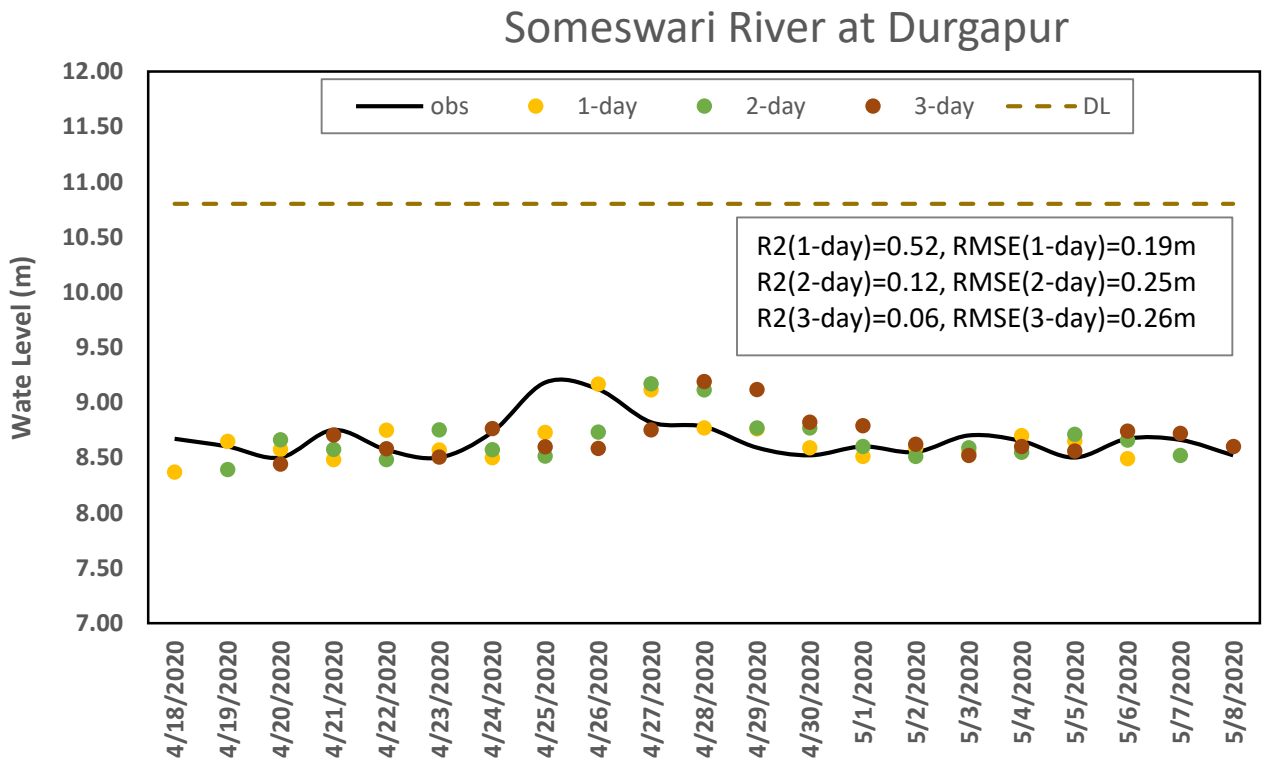


Figure A.4: Comparison of stage forecast for all lead times at Durgapur station of the Someswari river.

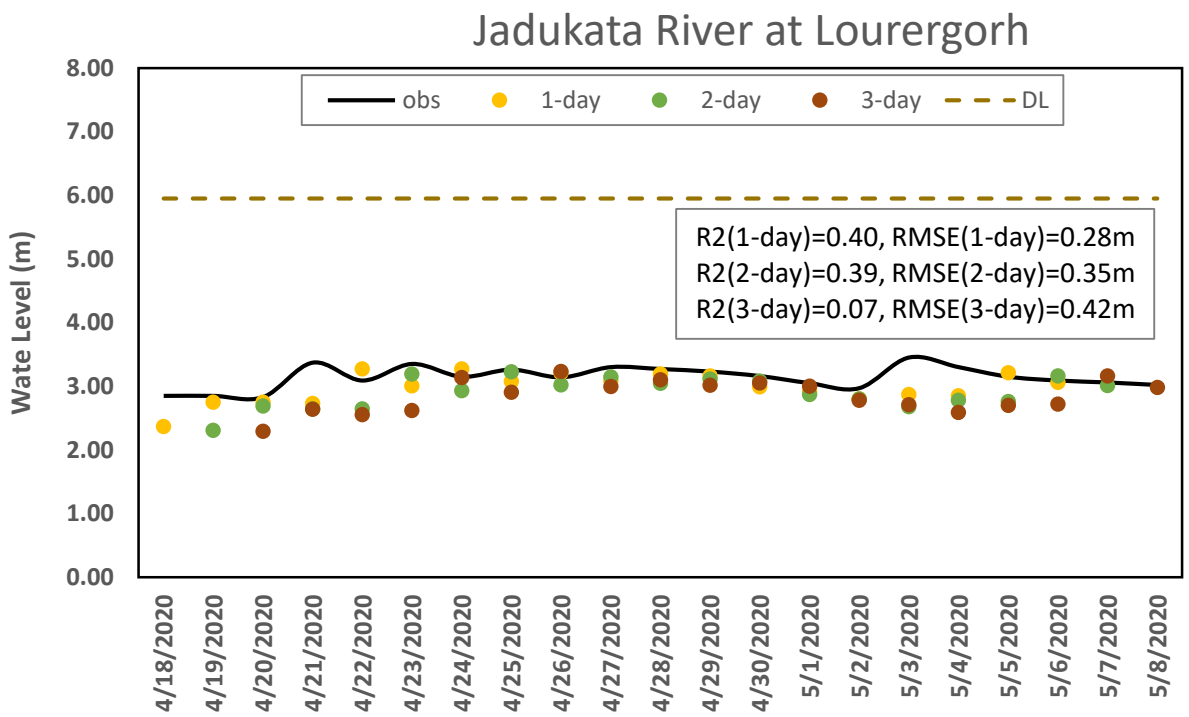


Figure A.5: Comparison of stage forecast for all lead times at Lourergorh station of the Jadukata river.

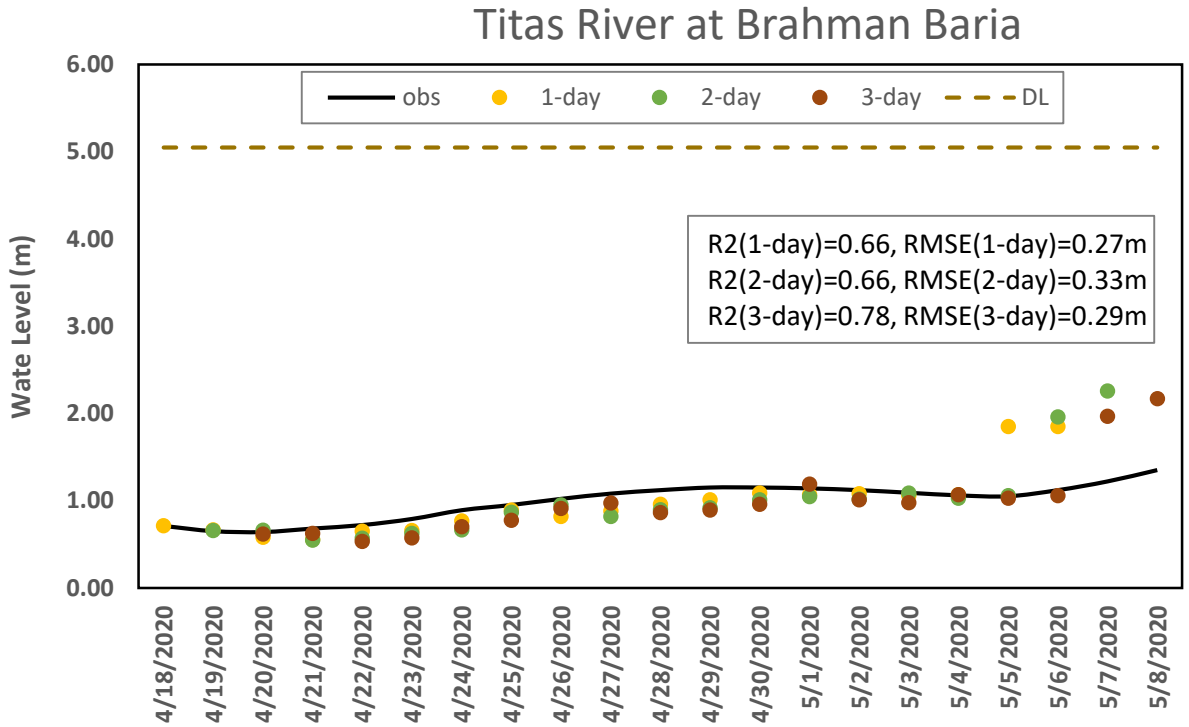


Figure A.6: Comparison of stage forecast for all lead times at Brahman Baria station of the Titas river.

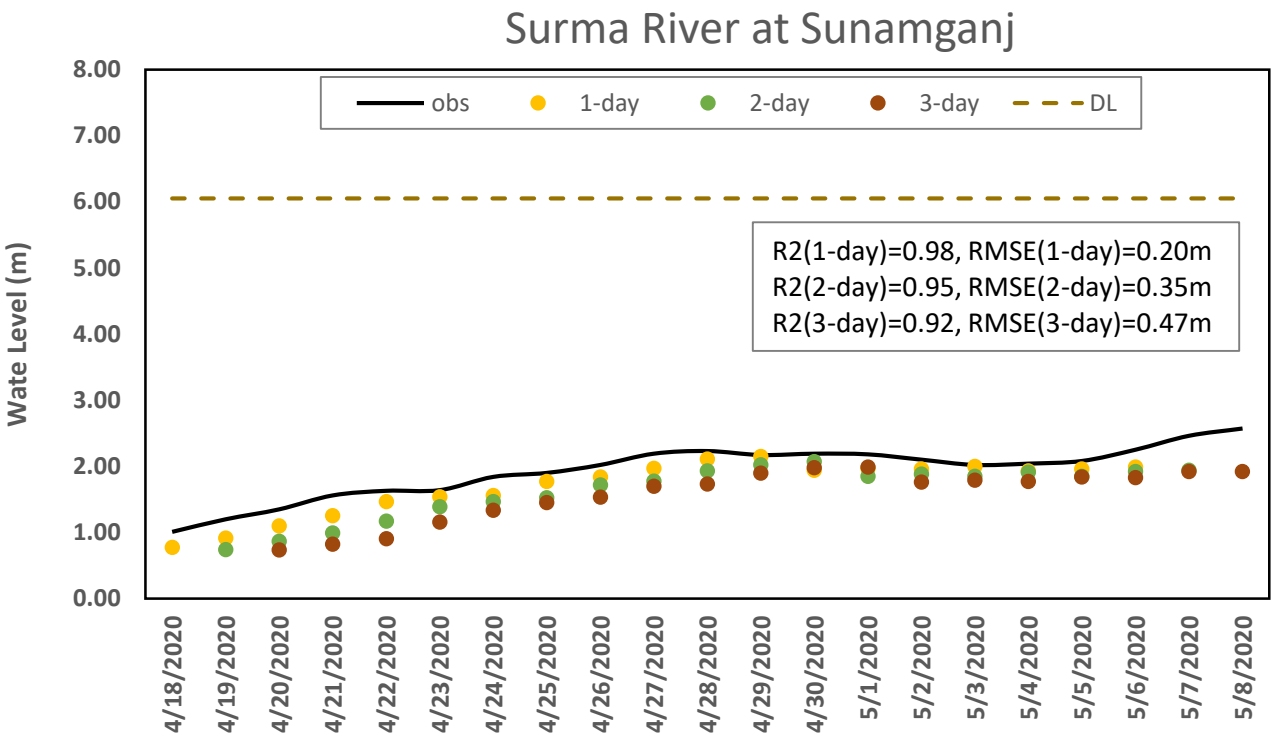


Figure A.7: Comparison of stage forecast for all lead times at Sunamganj station of the Surma river.

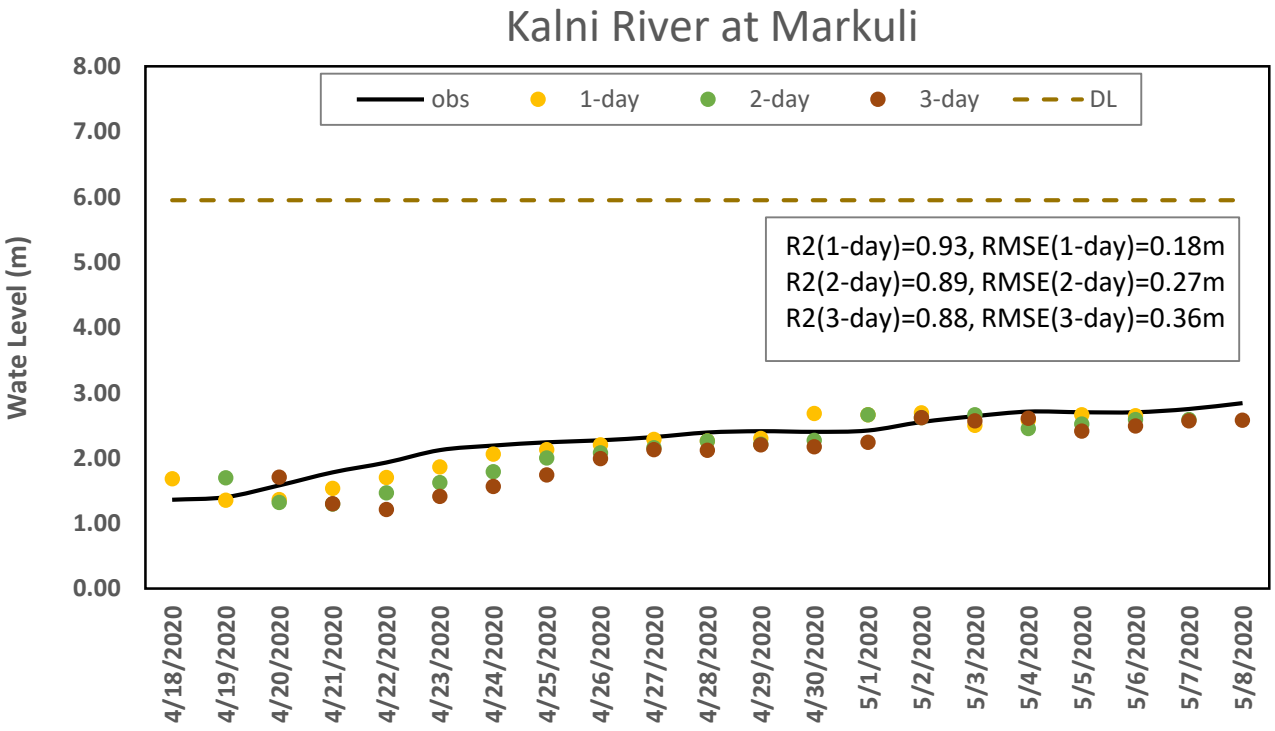


Figure A.8: Comparison of stage forecast for all lead times at Markuli station of the Kalni river.

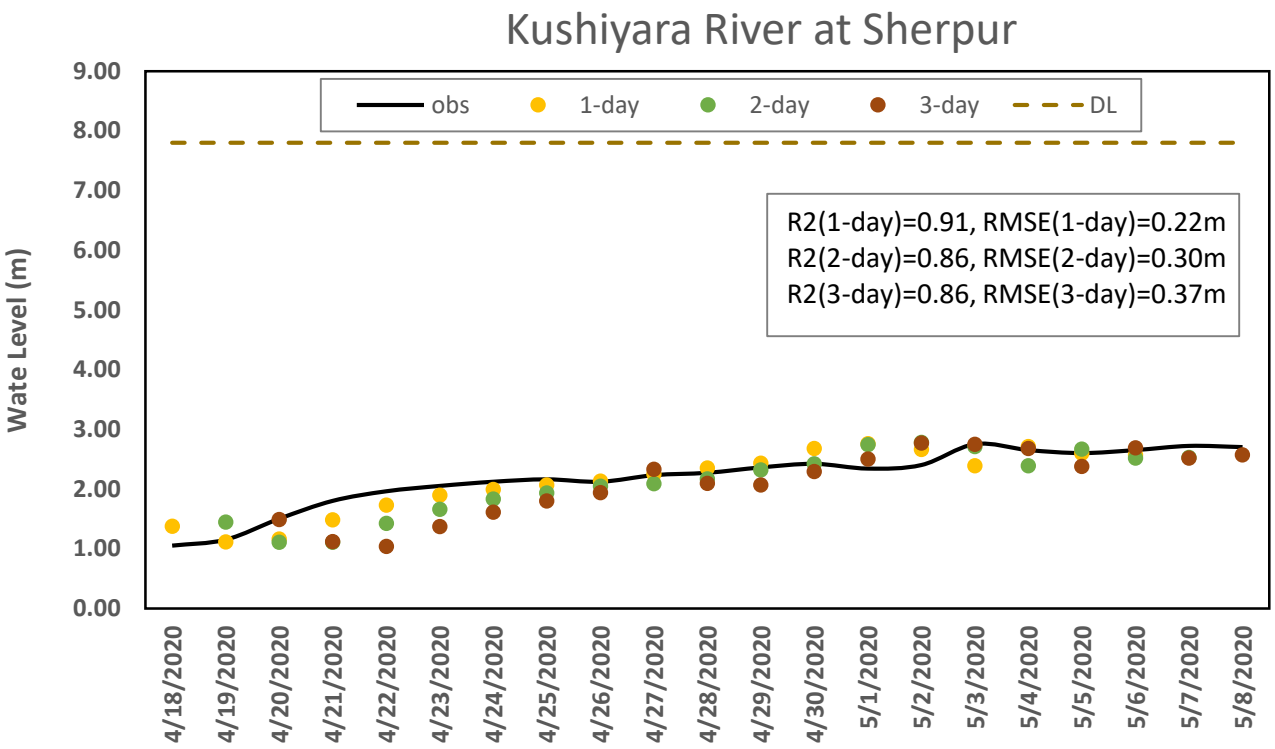


Figure A.9: Comparison of stage forecast for all lead times at Sherpur station of the Kushiyara river.

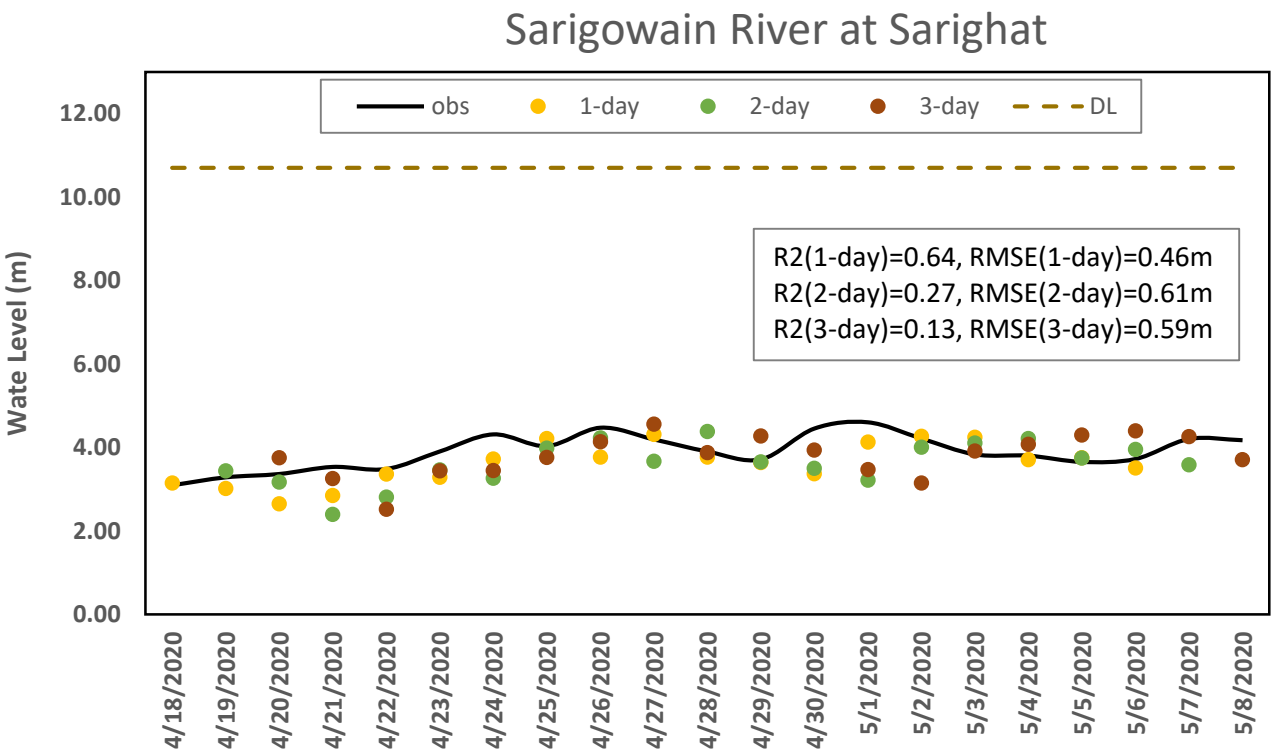


Figure A.10: Comparison of stage forecast for all lead times at Sarighat station of the Sarigowain river.

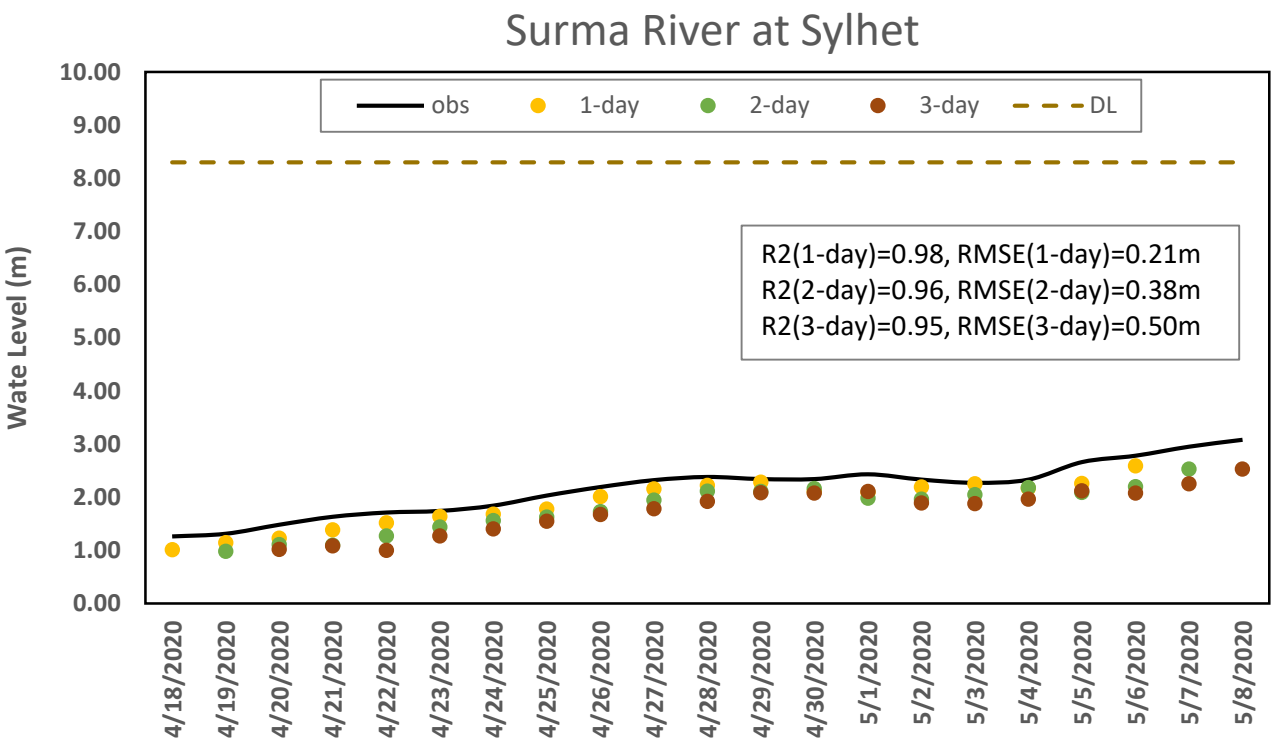


Figure A.11: Comparison of stage forecast for all lead times at Sylhet station of the Surma river.

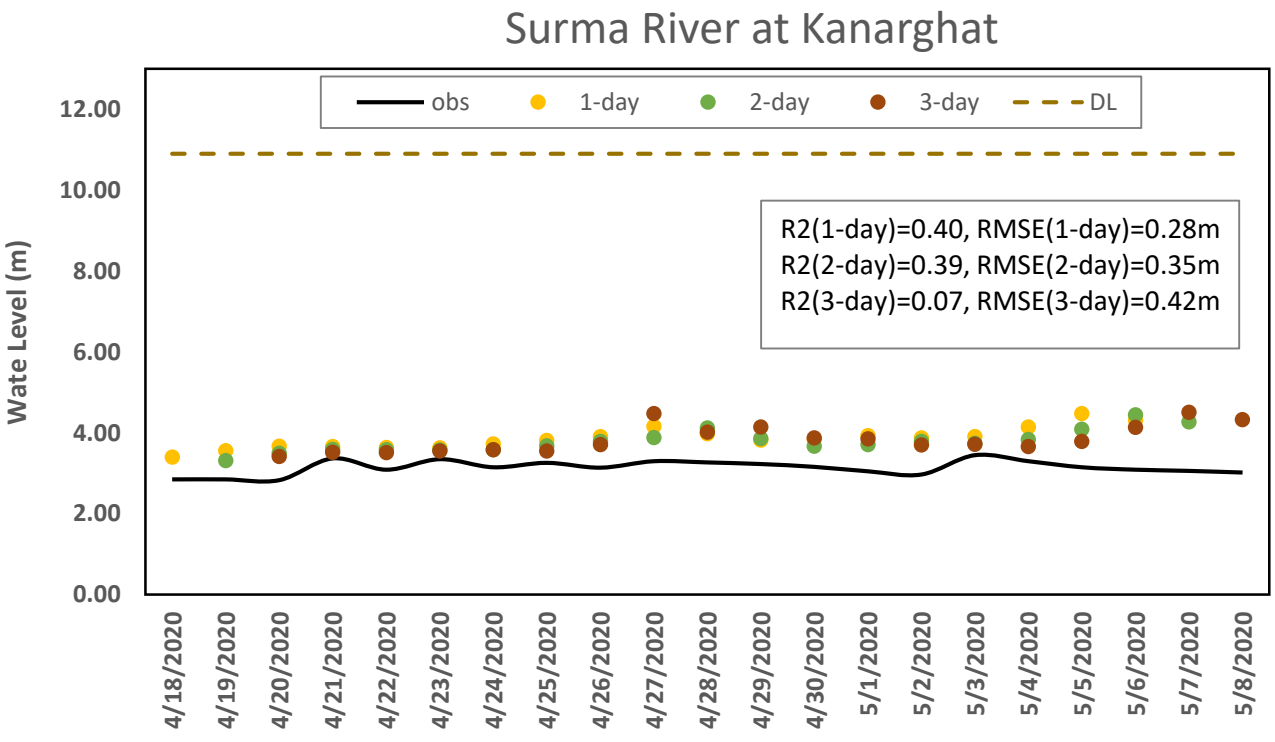


Figure A.12: Comparison of stage forecast for all lead times at Kanarghat station of the Surma river.

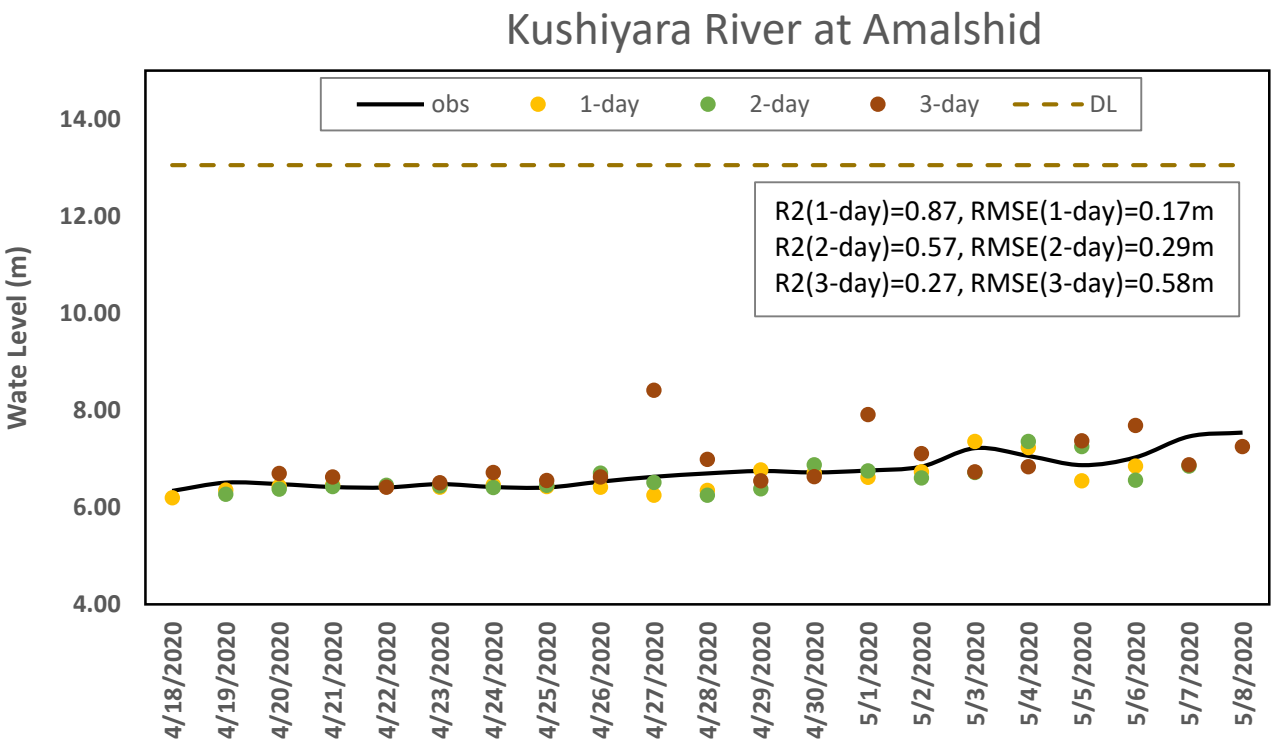


Figure A.13: Comparison of stage forecast for all lead times at Amalshid station of the Kushiyara river.

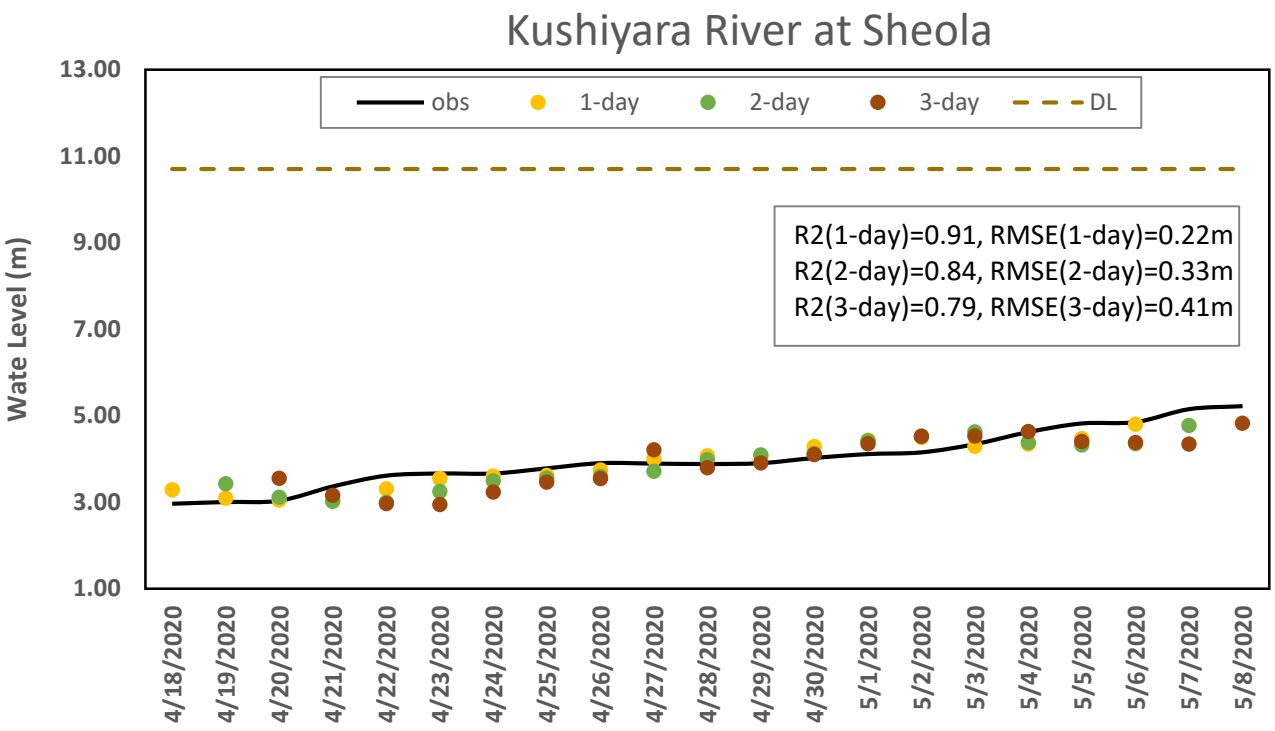


Figure A.14: Comparison of stage forecast for all lead times at Sheola station of the Kushiyara river.

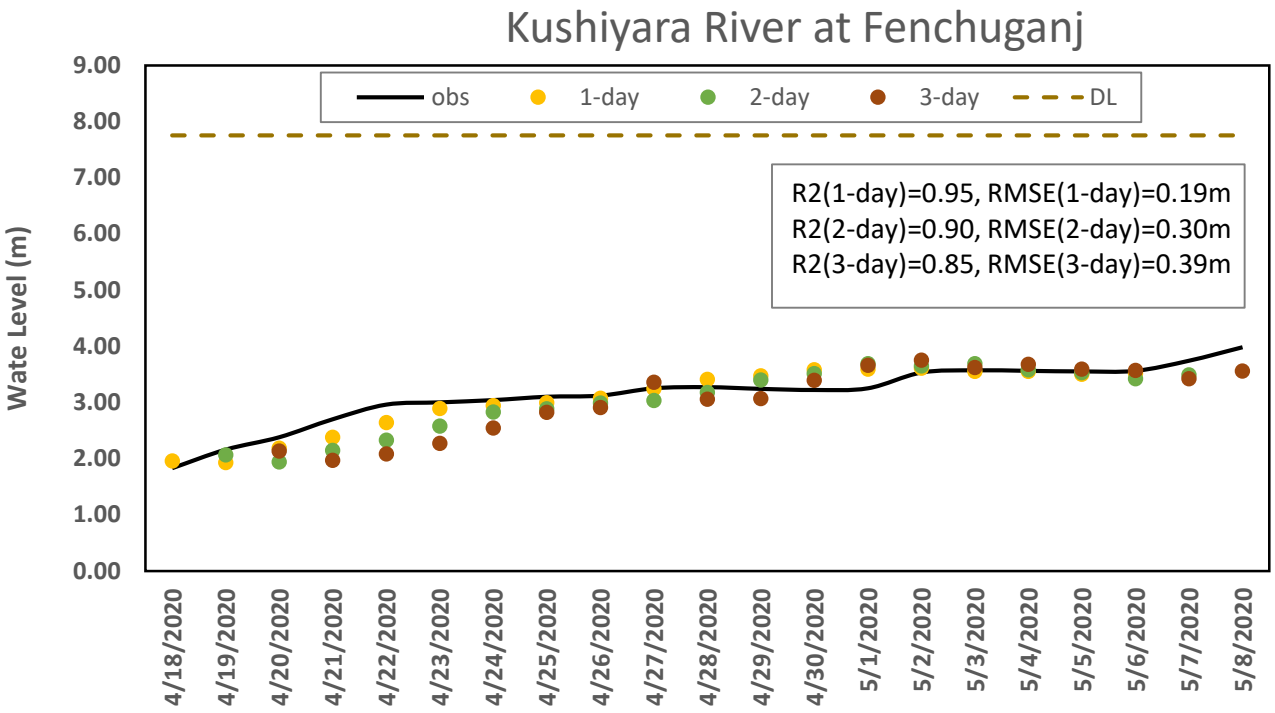


Figure A.15: Comparison of stage forecast for all lead times at Fenchuganj station of the Kushiyara river.

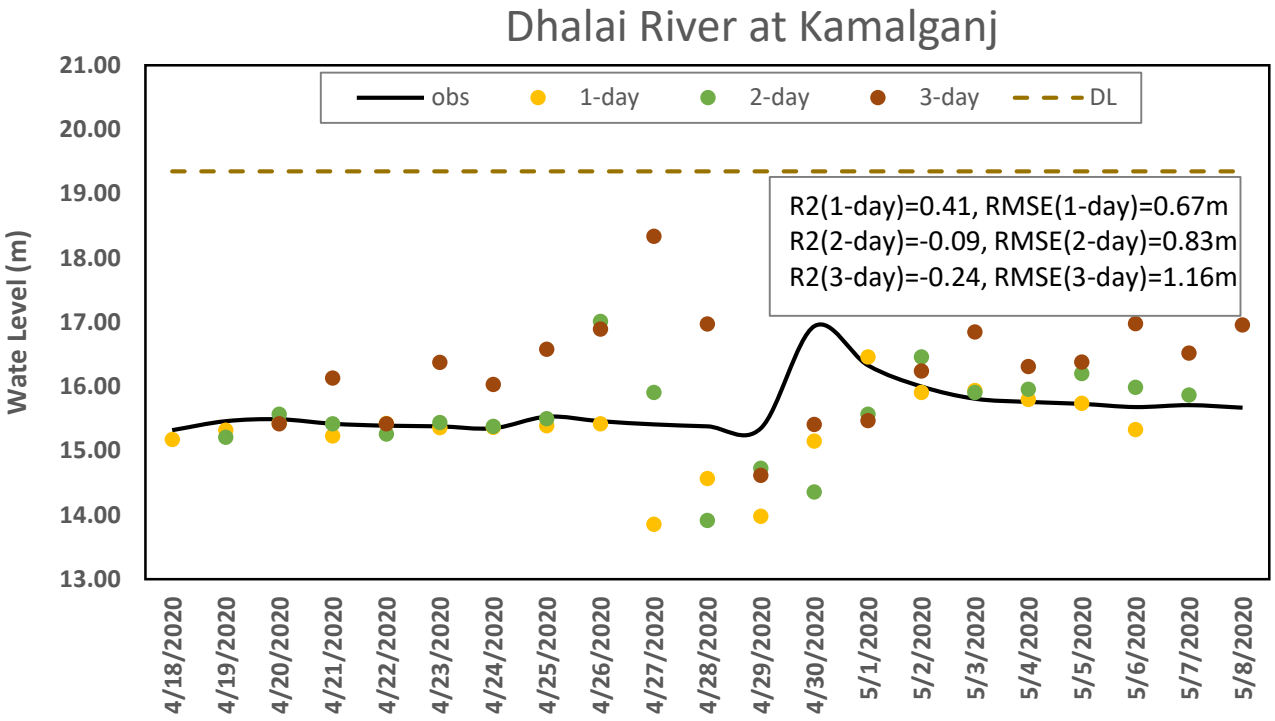


Figure A.16: Comparison of stage forecast for all lead times at Kamalganj station of the Dhalai river.

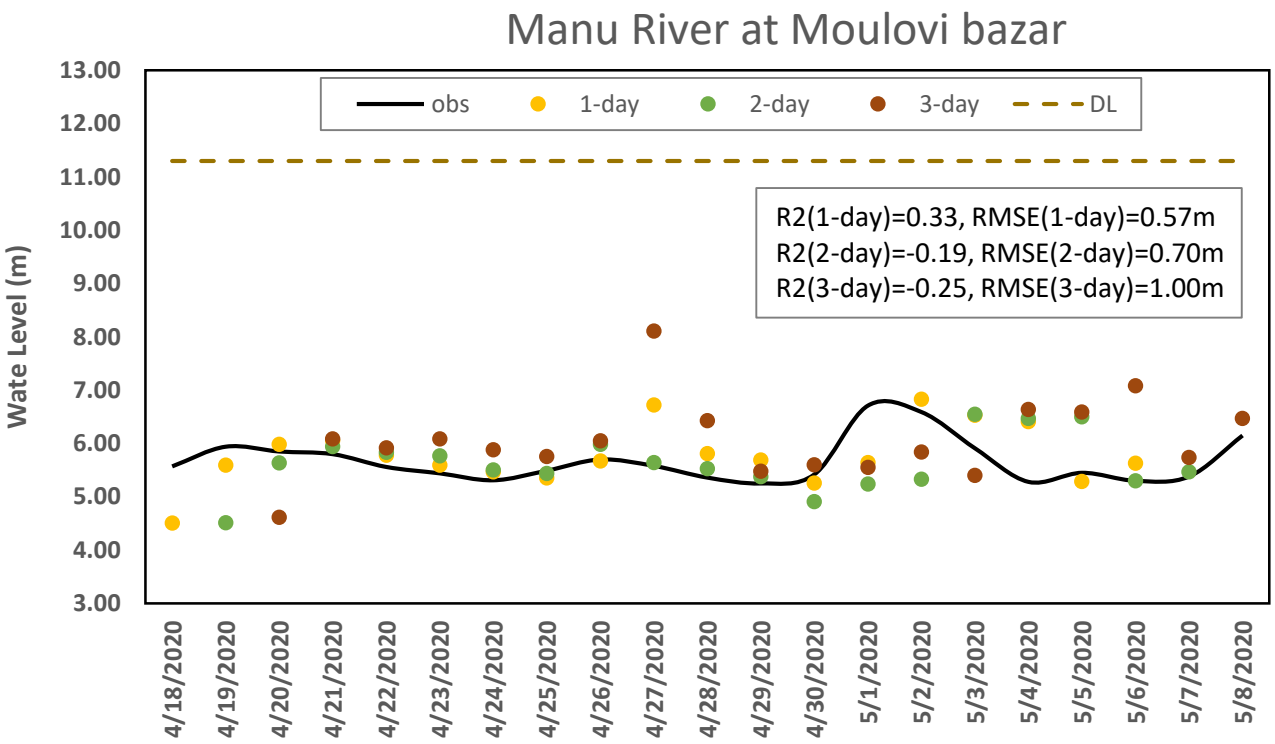


Figure A.17: Comparison of stage forecast for all lead times at Moulovi bazar station of the Manu river.

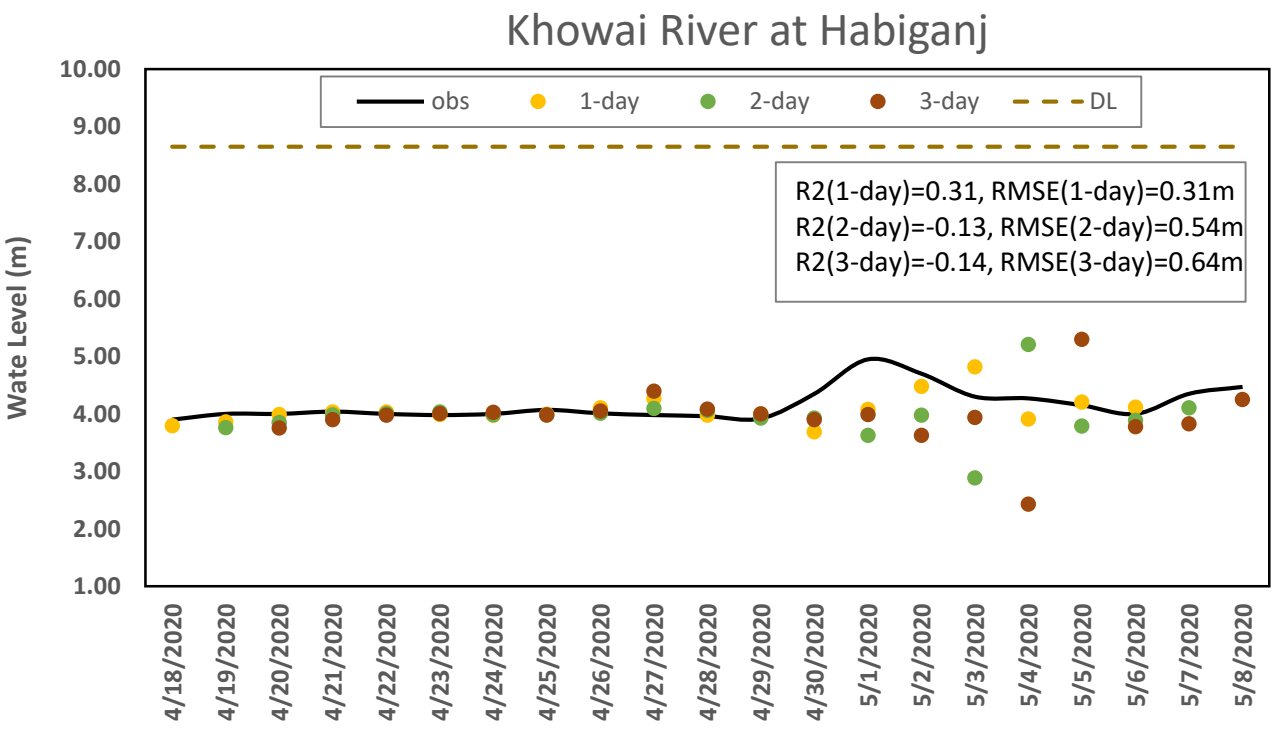


Figure A.18: Comparison of stage forecast for all lead times at Habiganj station of the Khowai river.

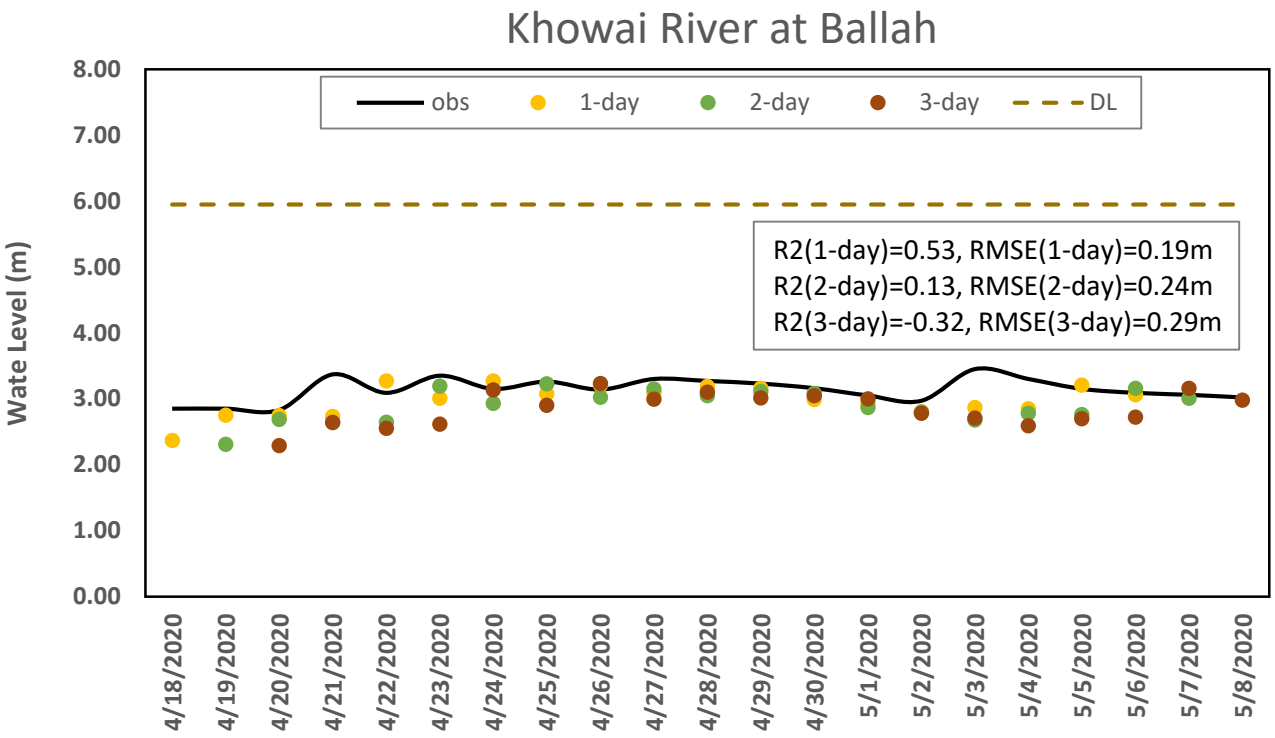


Figure A.19: Comparison of stage forecast for all lead times at Ballah station of the Khowai river.

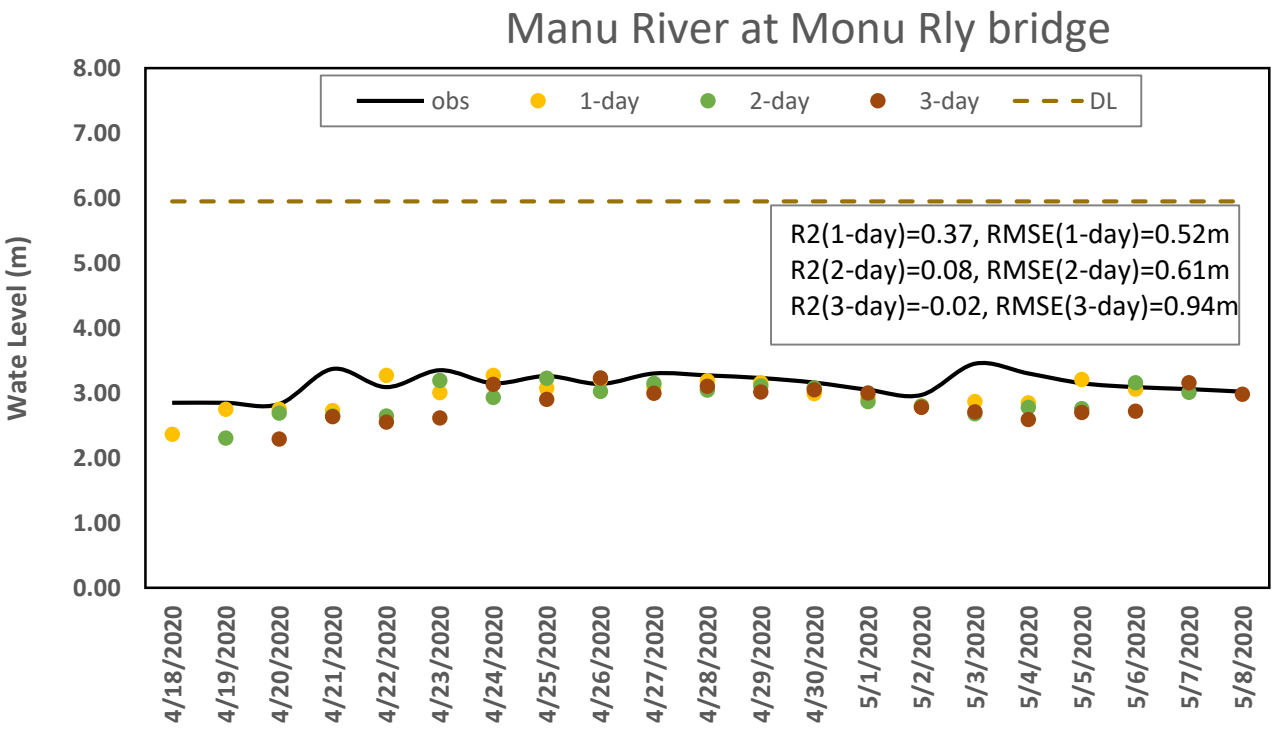


Figure A.20: Comparison of stage forecast for all lead times at Manu Railway Bridge station of the Manu river.

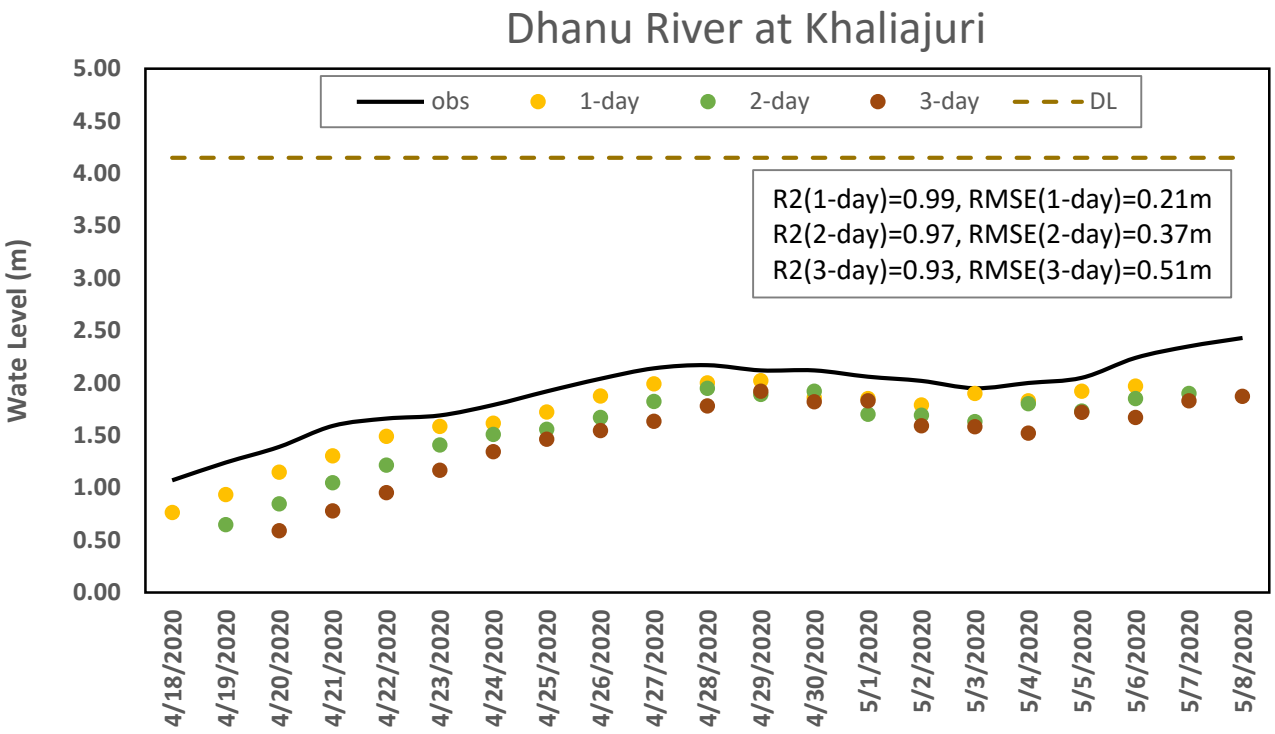


Figure A.21: Comparison of stage forecast for all lead times at Khaliajuri station of the Dhanu river.

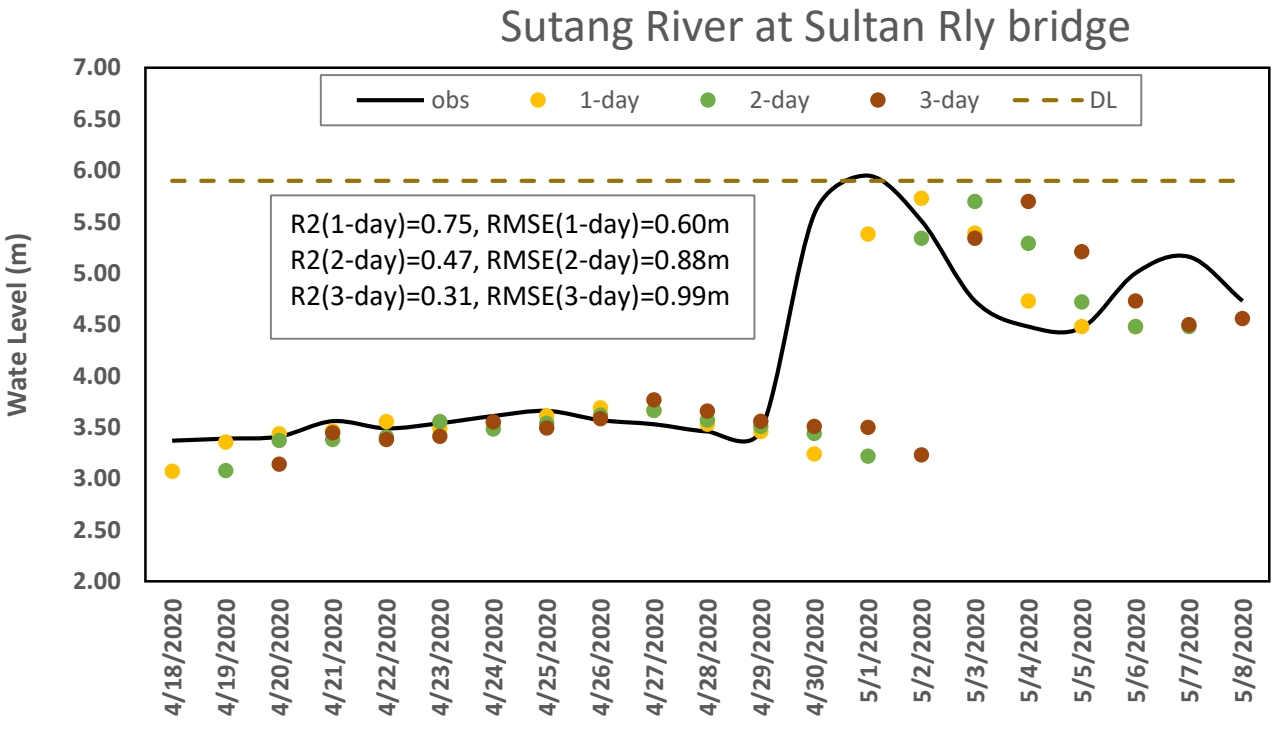


Figure A.22: Comparison of stage forecast for all lead times at Sutang Railway Bridge station of the Sutang river.

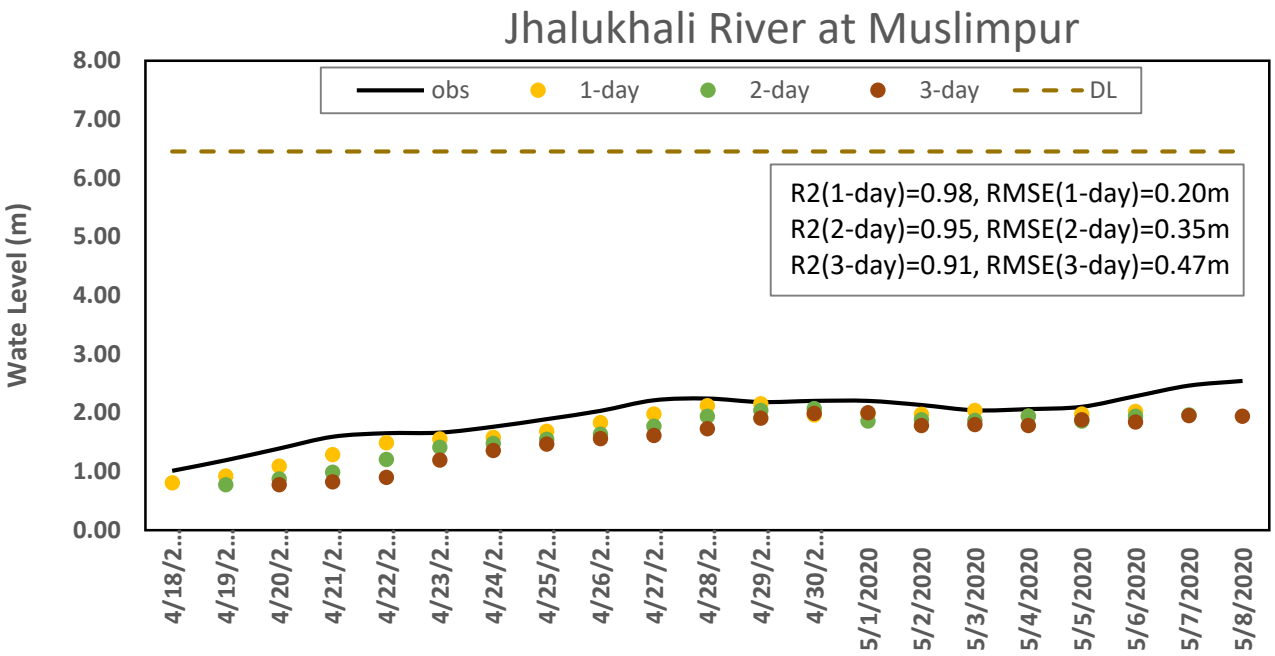


Figure A.23: Comparison of stage forecast for all lead times at Muslimpur station of the Jhalukhali river.

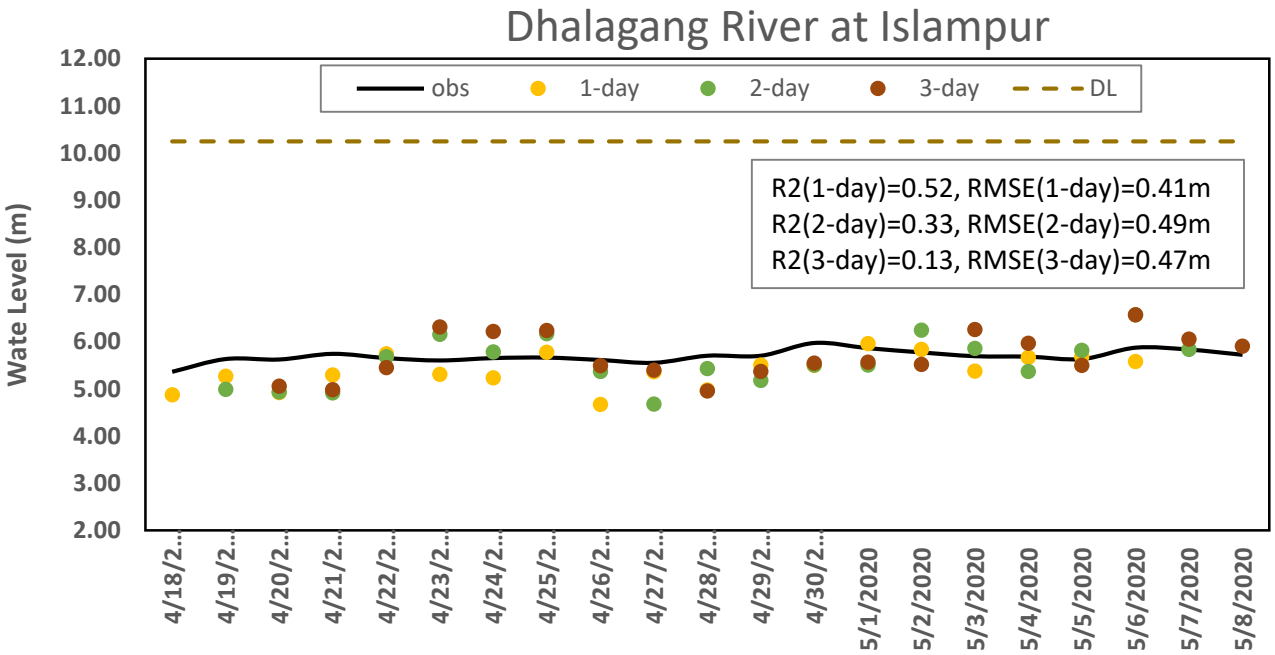


Figure A.24: Comparison of stage forecast for all lead times at Islampur station of the Dhalagang river.

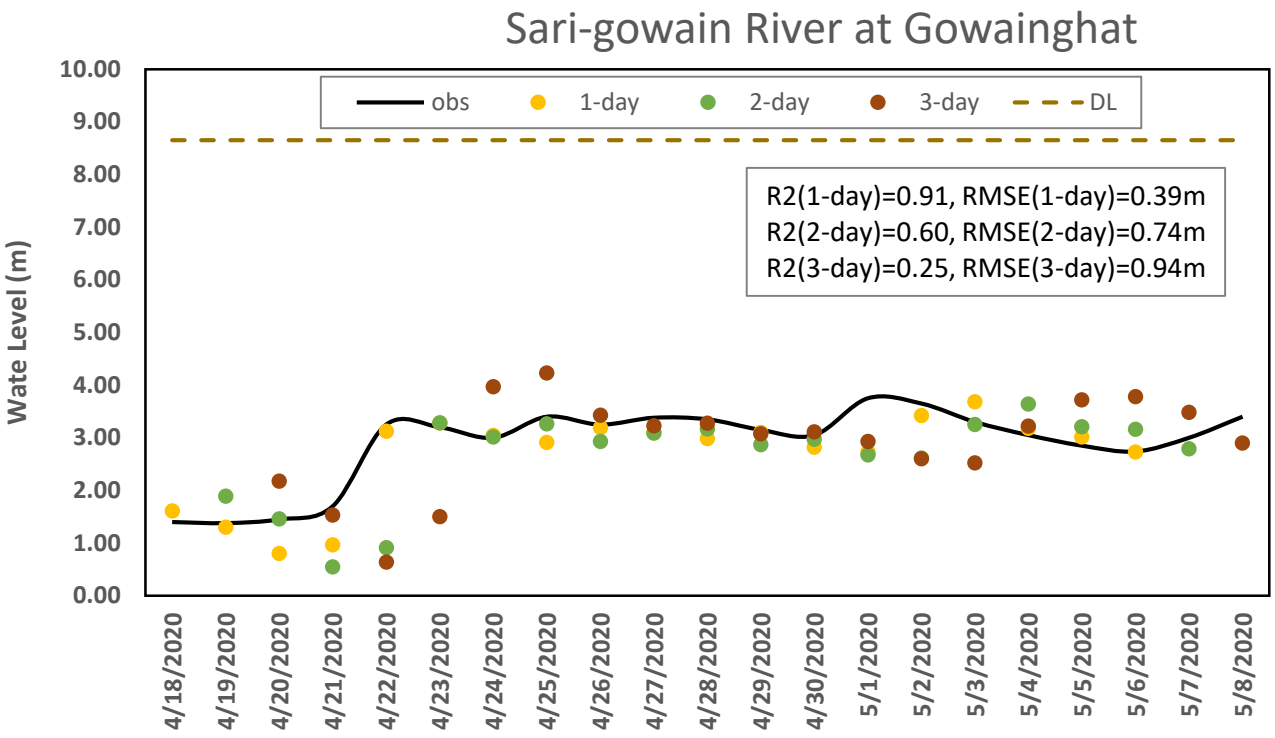


Figure A.25: Comparison of stage forecast for all lead times at Gowainghat station of the Sari-gowain river.

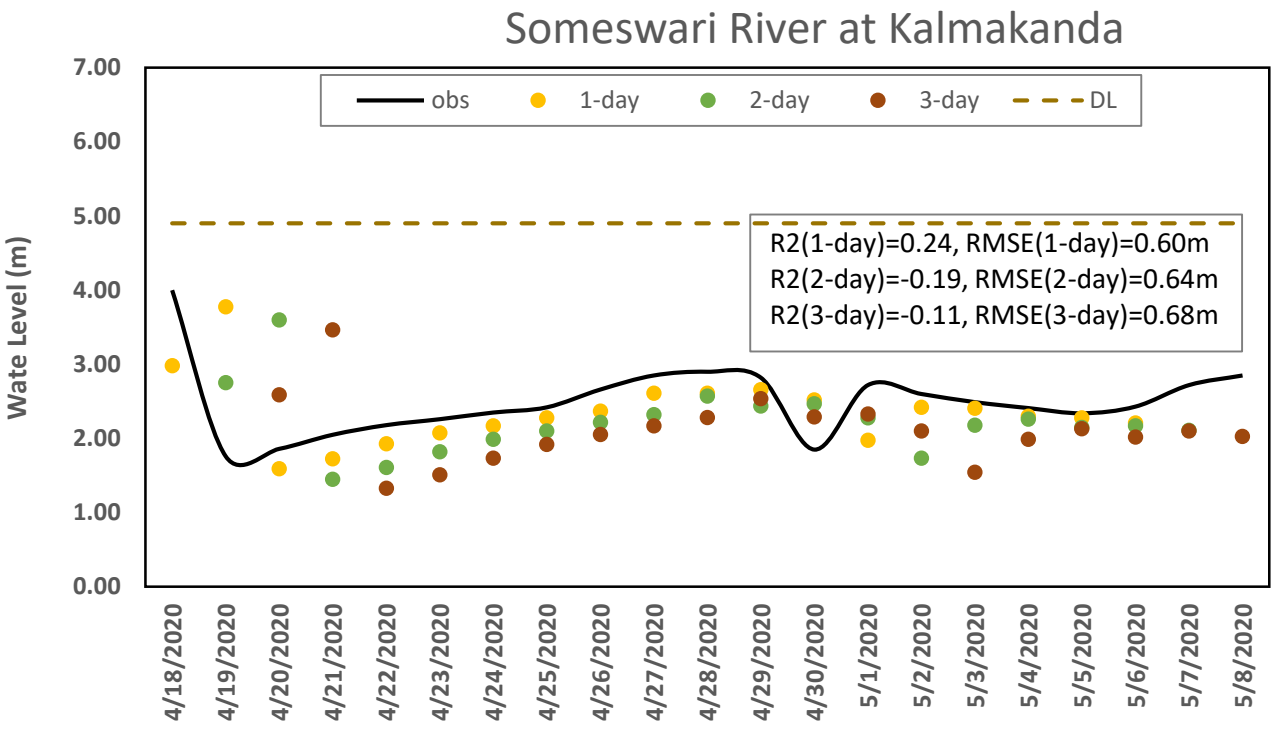


Figure A.26: Comparison of stage forecast for all lead times at Kalmakanda station of the Someswari river.

APPENDIX-B: EXTENDED WATER LEVEL FORECAST USING IFEWS ON APRIL 27, 2020

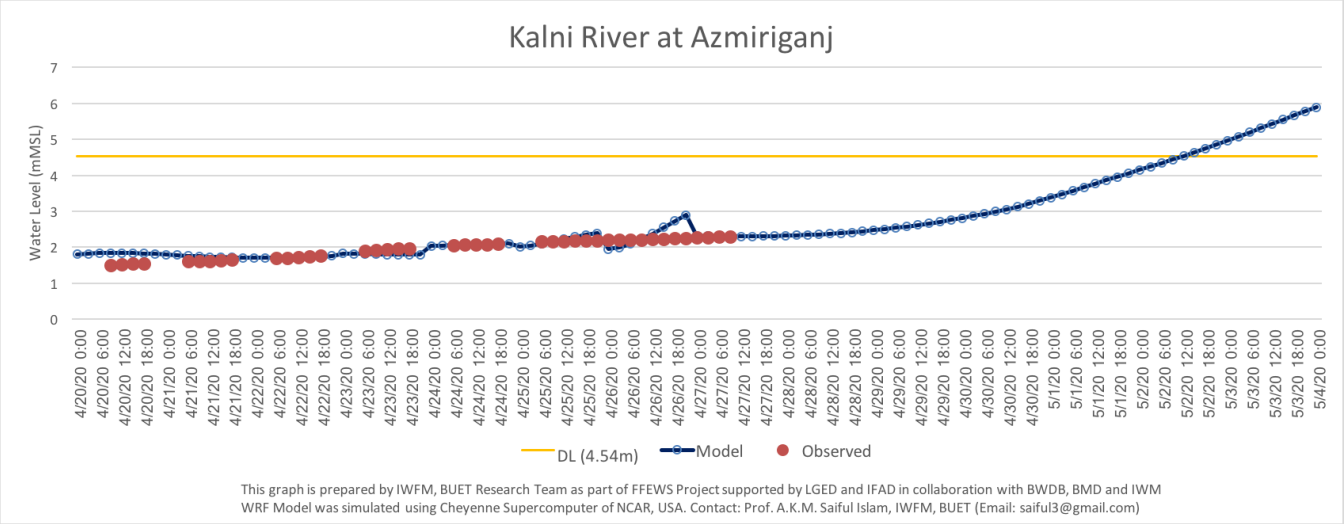


Figure B.1: Water level forecasts with a lead time of 10-day at Azmiriganj station of the Kalni river.

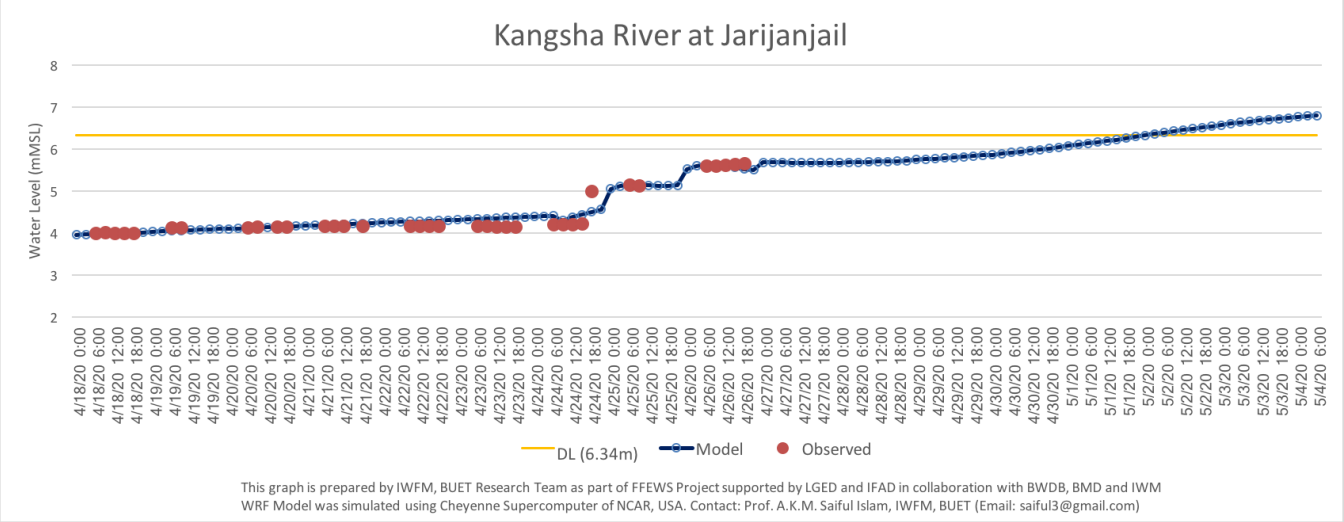


Figure B.2: Water level forecasts with a lead time of 10-day at Jarijanjail station of the Kangsha river.

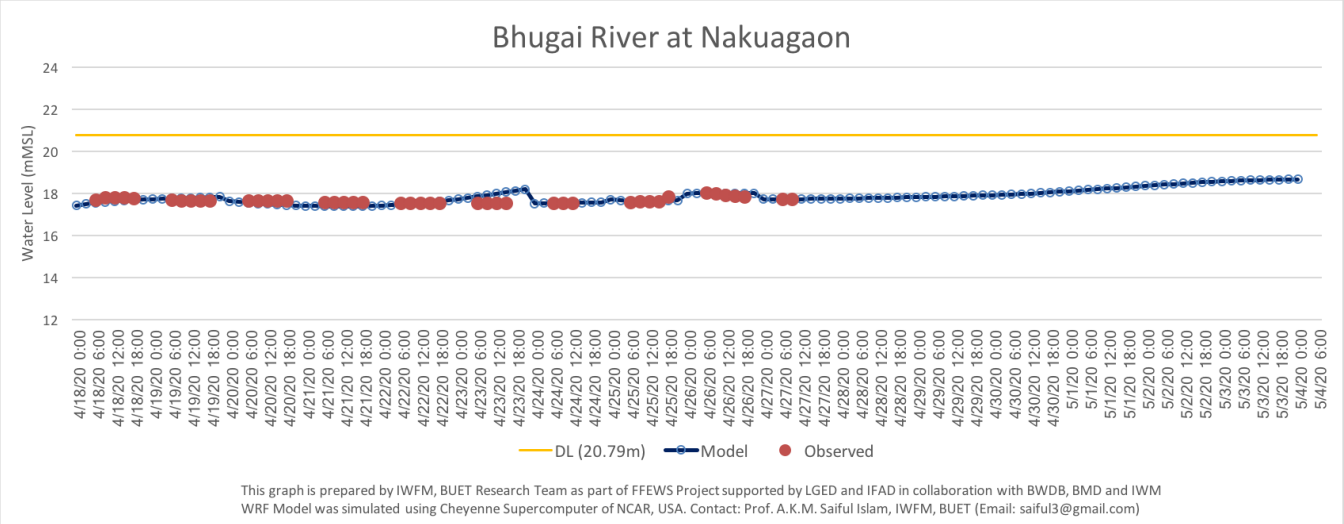


Figure B.3: Water level forecasts with a lead time of 10-day at Nakuagaon station of the Bhugai river.

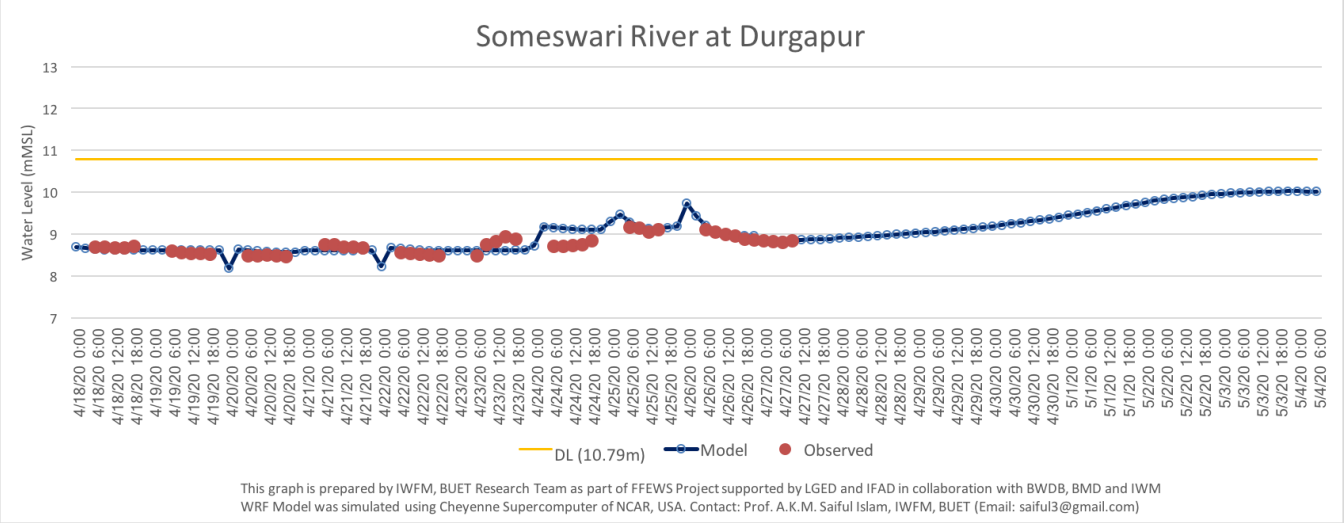


Figure B.4: Water level forecasts with a lead time of 10-day at Durgapur station of the Someswari river.

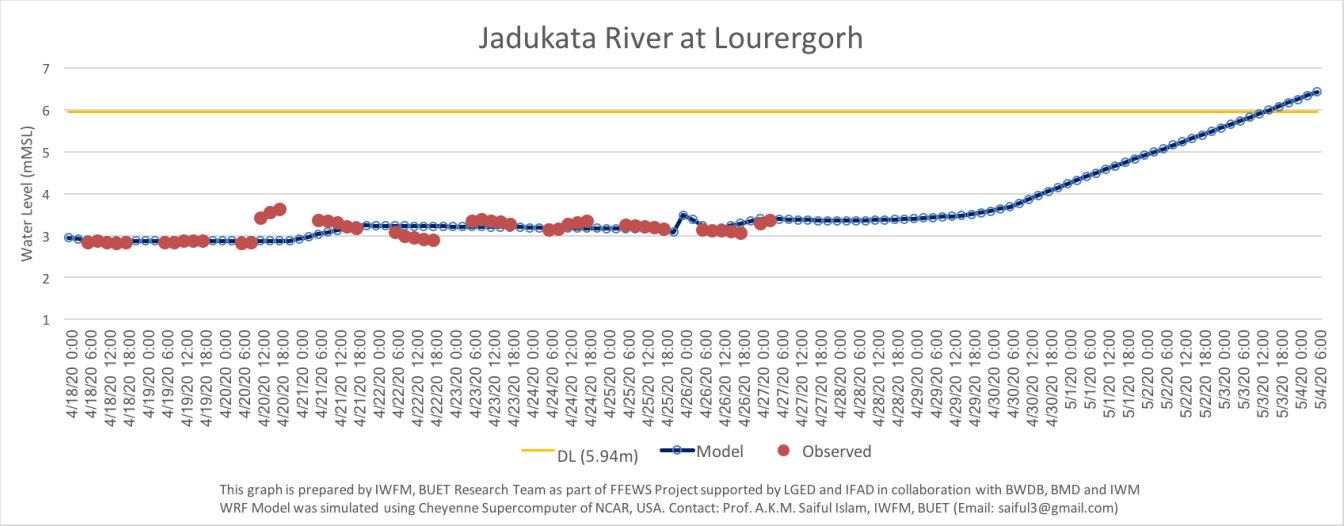


Figure B.5: Water level forecasts with a lead time of 10-day at Lourergorh station of the Jadukata river.

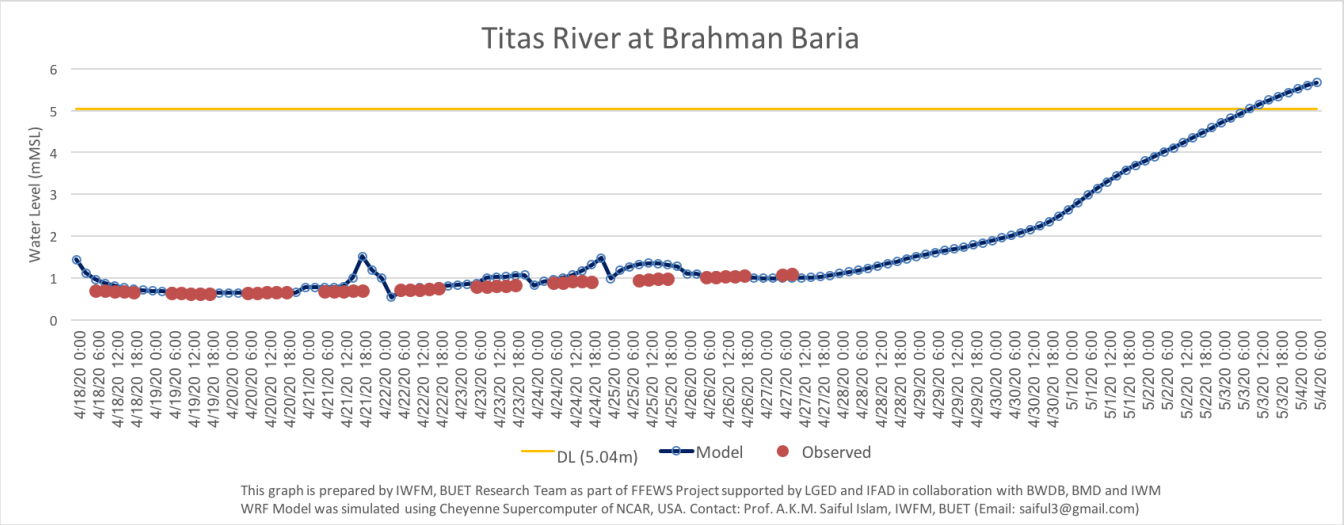


Figure B.6: Water level forecasts with a lead time of 10-day at Brahman Baria station of the Titas river.

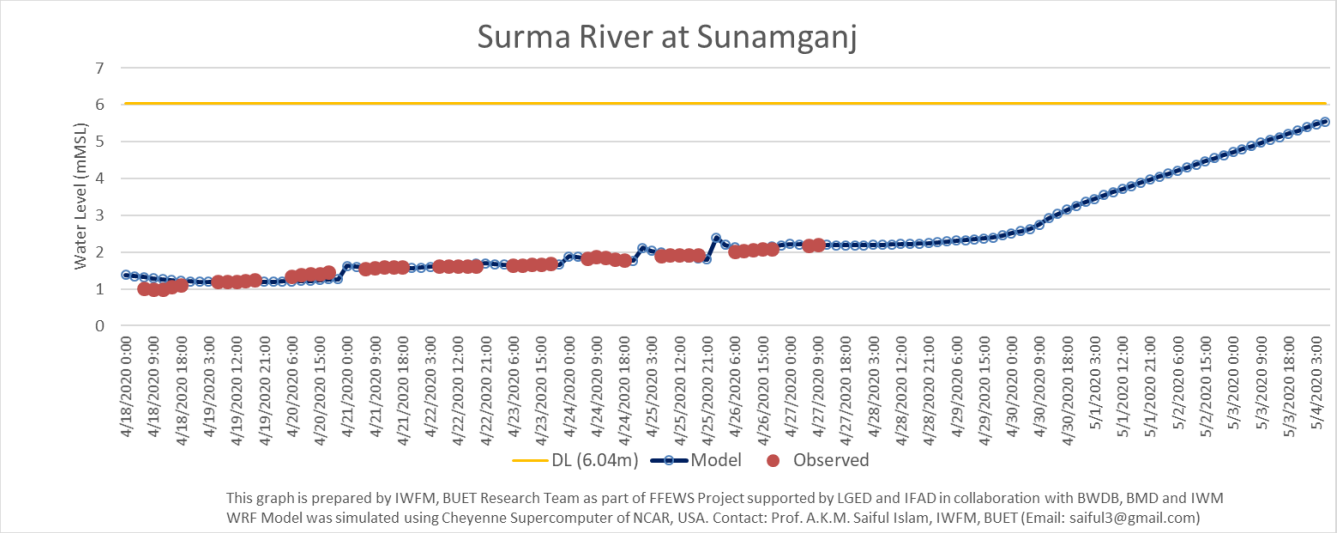


Figure B.7: Water level forecasts with a lead time of 10-day at Sunamganj station of the Surma river.

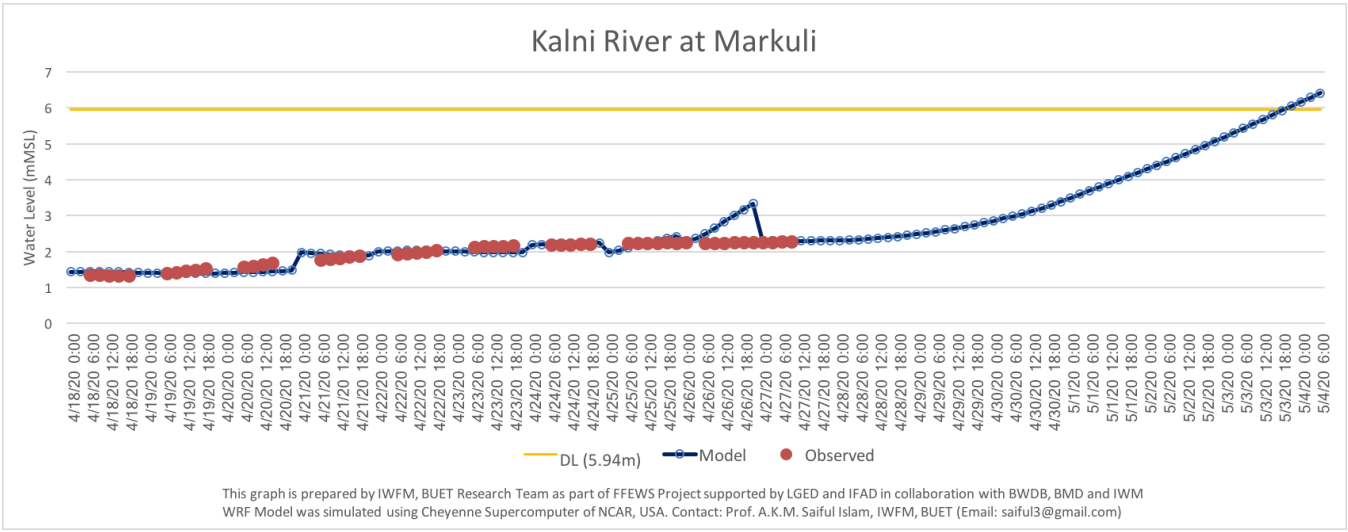


Figure B.8: Water level forecasts with a lead time of 10-day at Markuli station of the Kalni river.

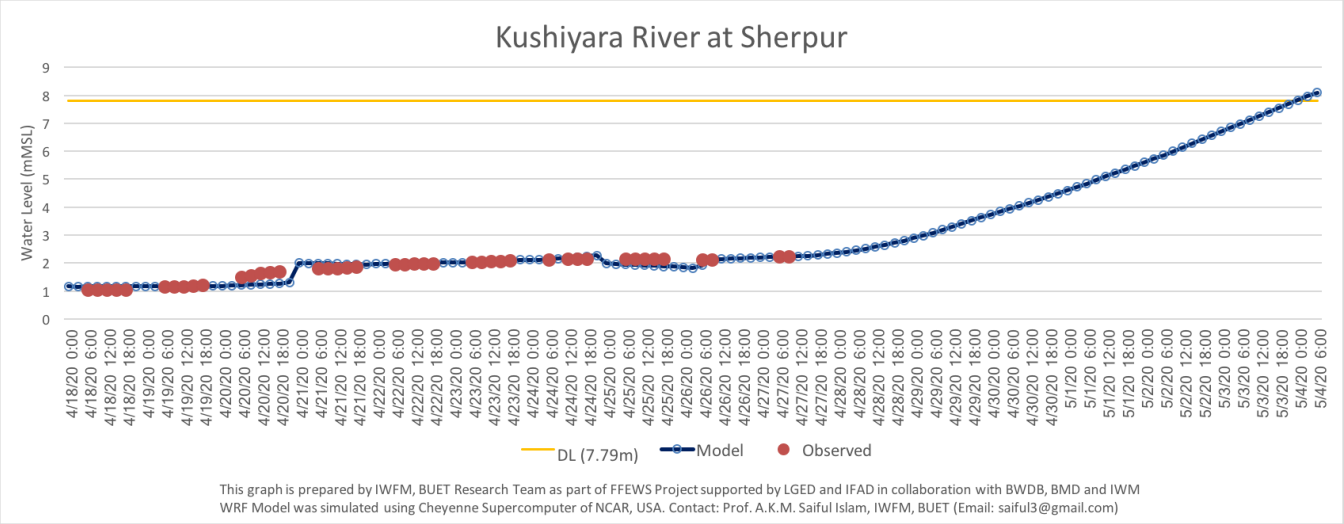


Figure B.9: Water level forecasts with a lead time of 10-day at Sherpur station of the Kushiyara river.

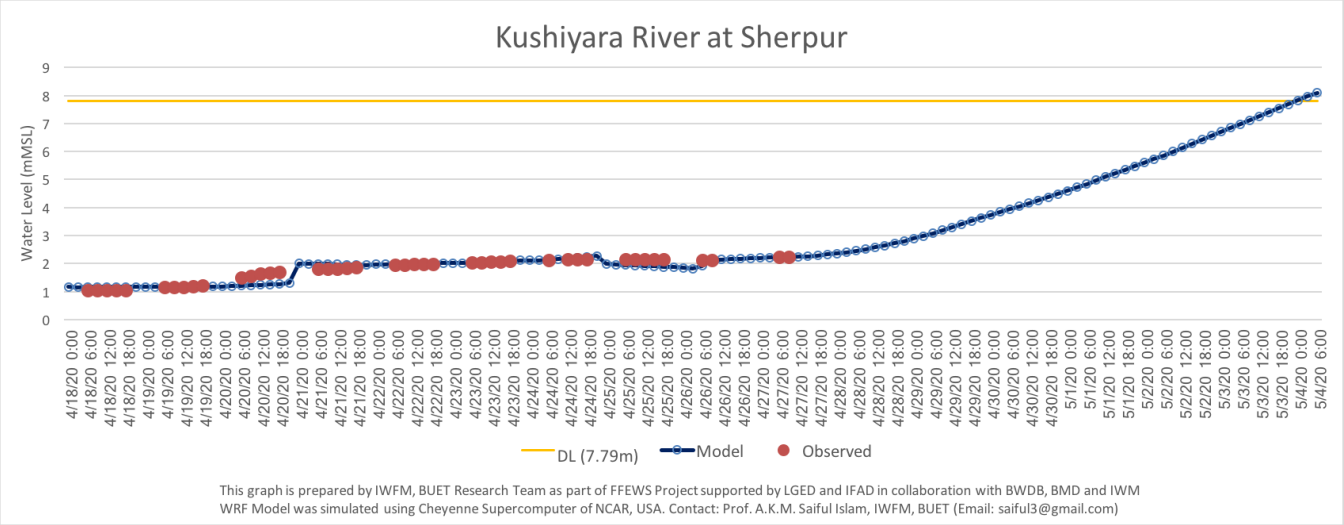


Figure B.10: Water level forecasts with a lead time of 10-day at Sarighat station of the Sarigowain river.

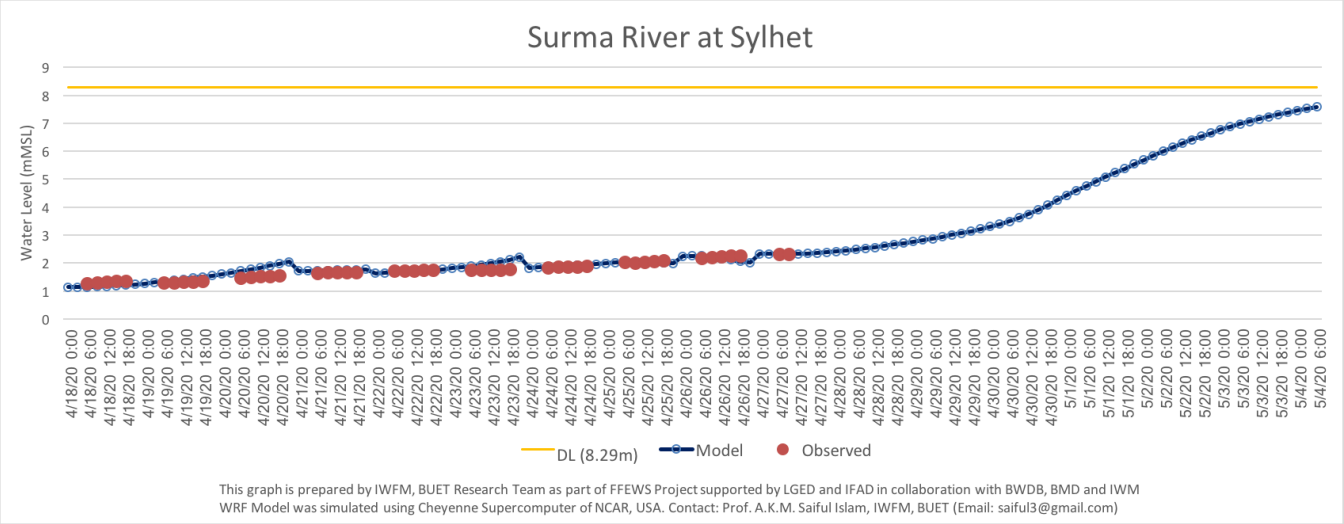


Figure B.11: Water level forecasts with a lead time of 10-day at Sylhet station of the Surma river.

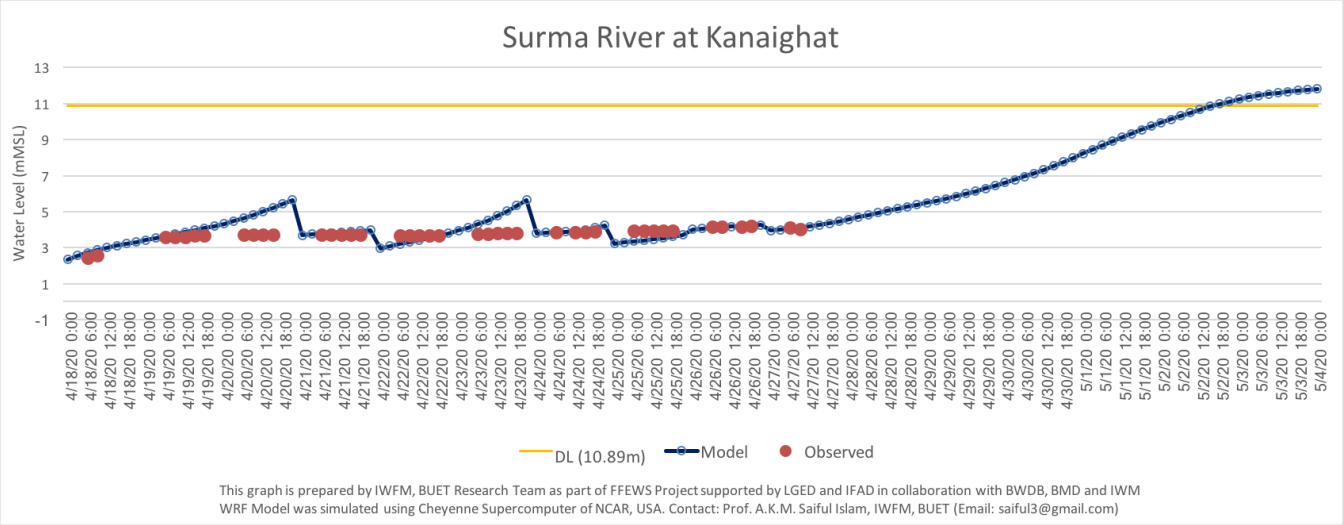


Figure B.12: Water level forecasts with a lead time of 10-day at Kanarghat station of the Surma river.

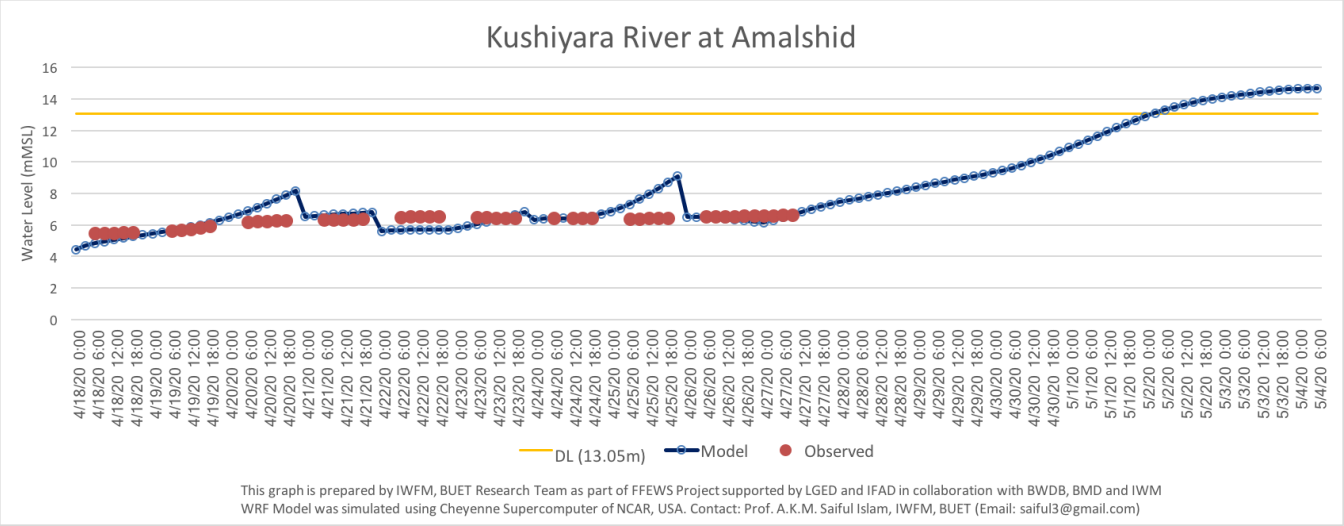


Figure B.13: Water level forecasts with a lead time of 10-day at Amalshid station of the Kushiyara river.

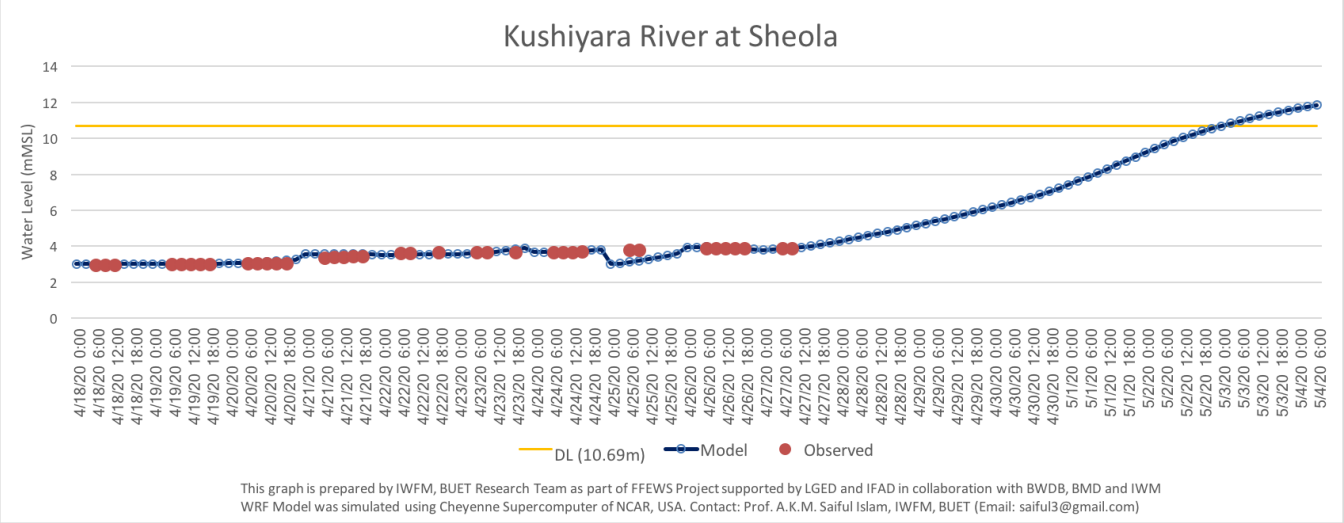


Figure B.14: Water level forecasts with a lead time of 10-day at Sheola station of the Kushiyara river.

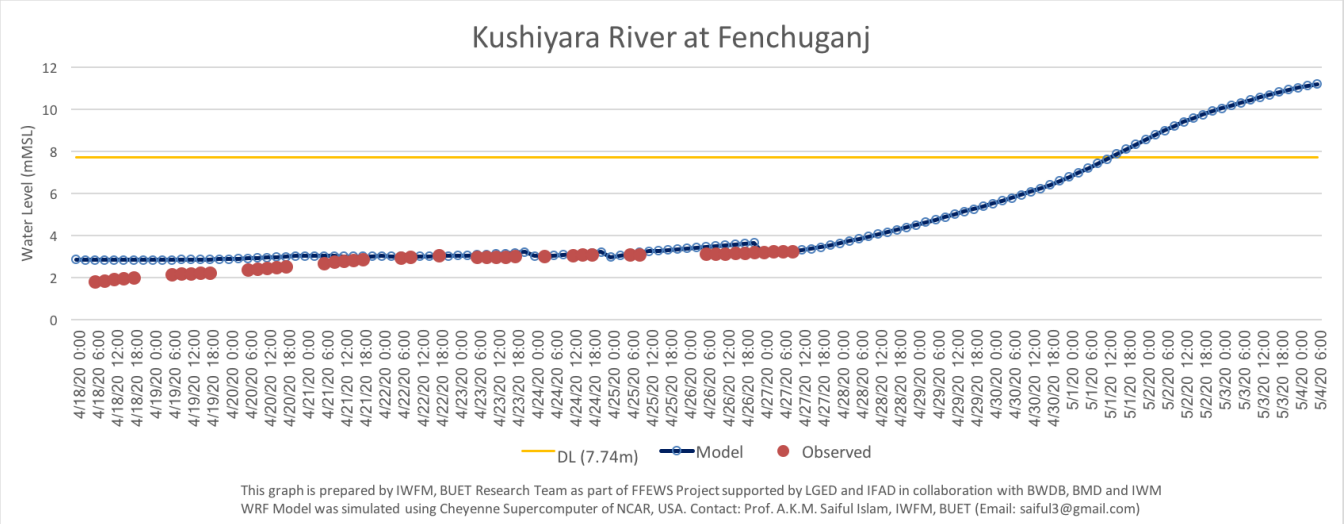


Figure B.15: Water level forecasts with a lead time of 10-day at Fenchuganj station of the Kushiyara river.

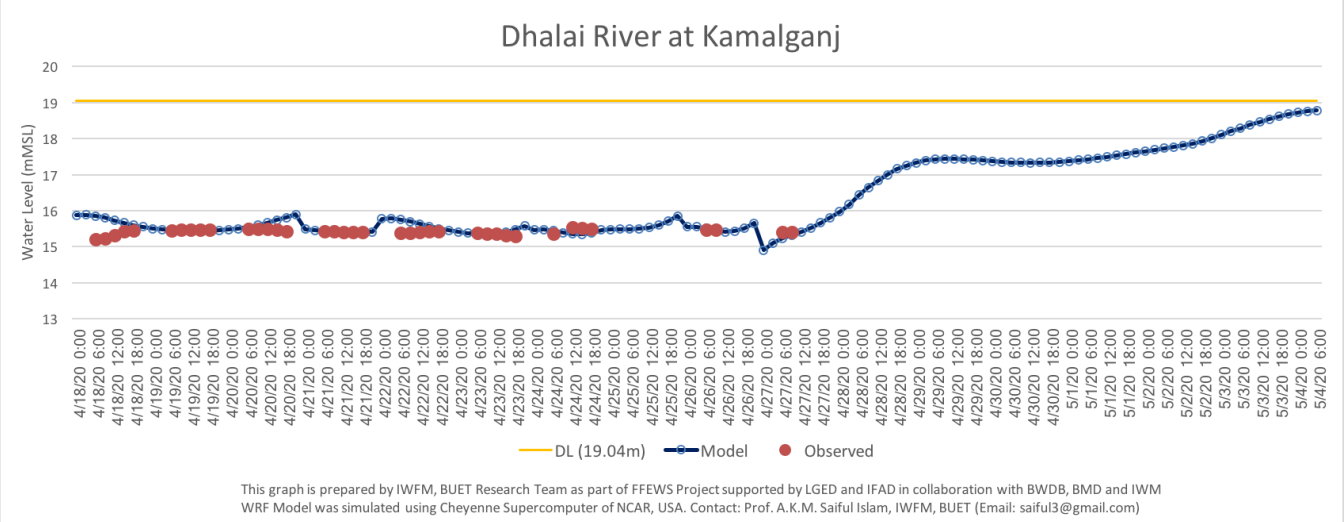


Figure B.16: Water level forecasts with a lead time of 10-day at Kamalganj station of the Dhalai river.

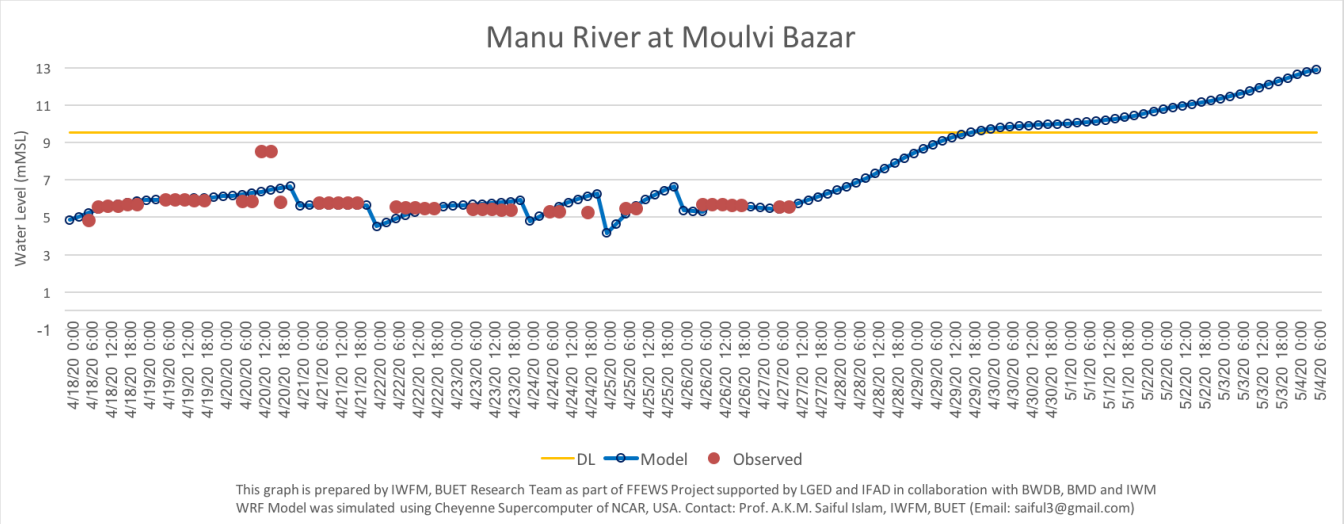


Figure B.17: Water level forecasts with a lead time of 10-day at Moulovi bazar station of the Manu river.

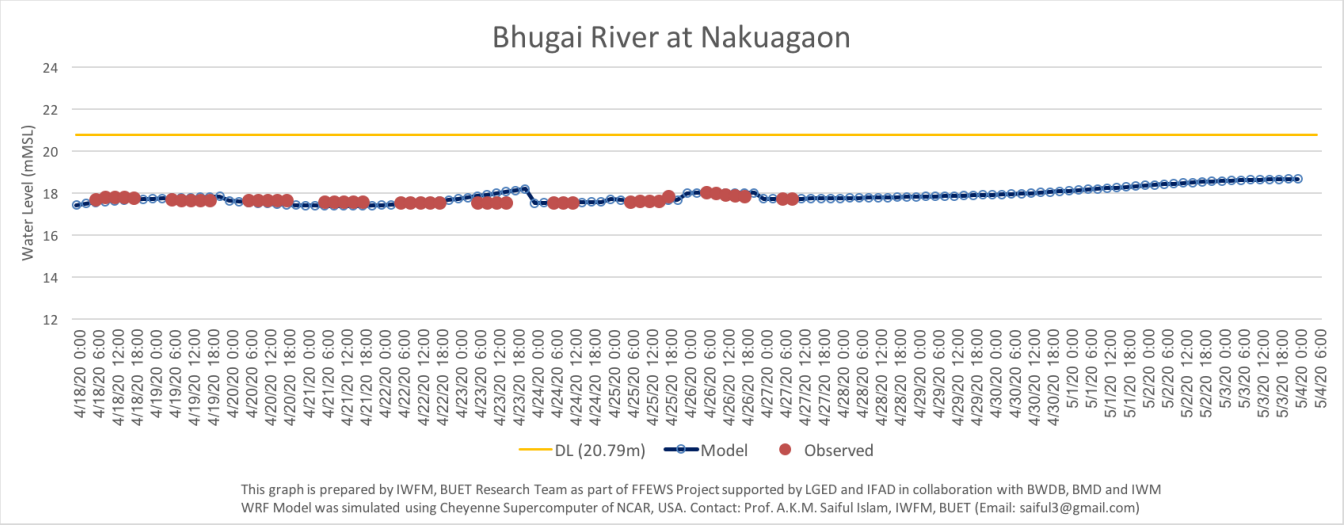


Figure B.18: Water level forecasts with a lead time of 10-day at Habiganj station of the Khowai river.

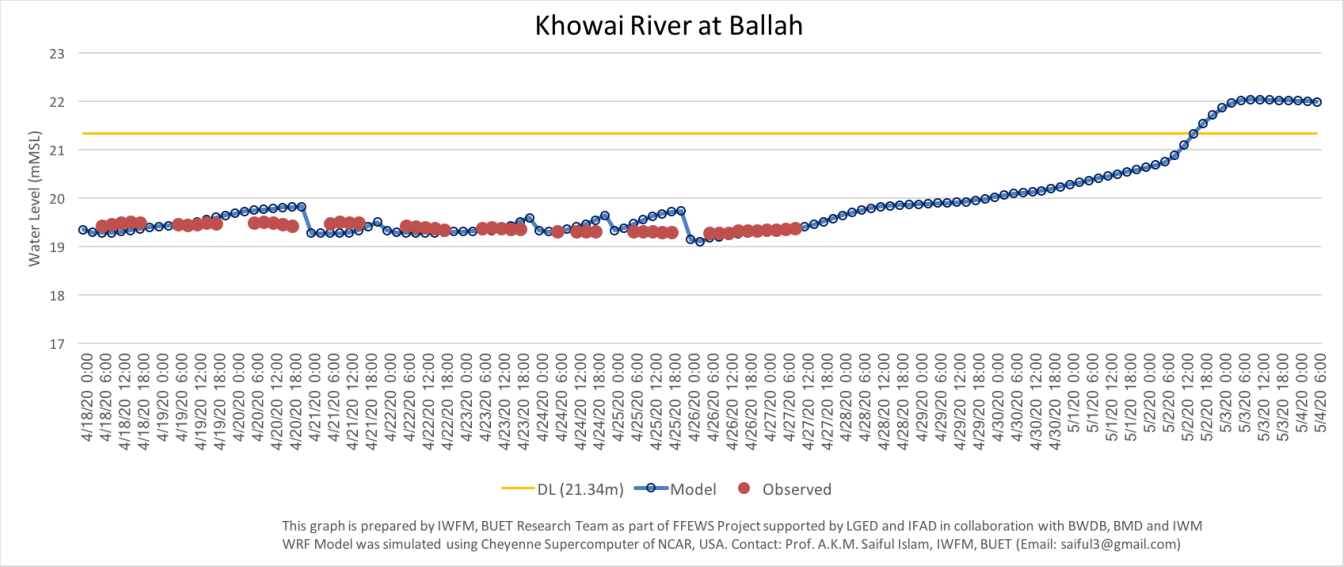


Figure B.19: Water level forecasts with a lead time of 10-day at Ballah station of the Khowai river.

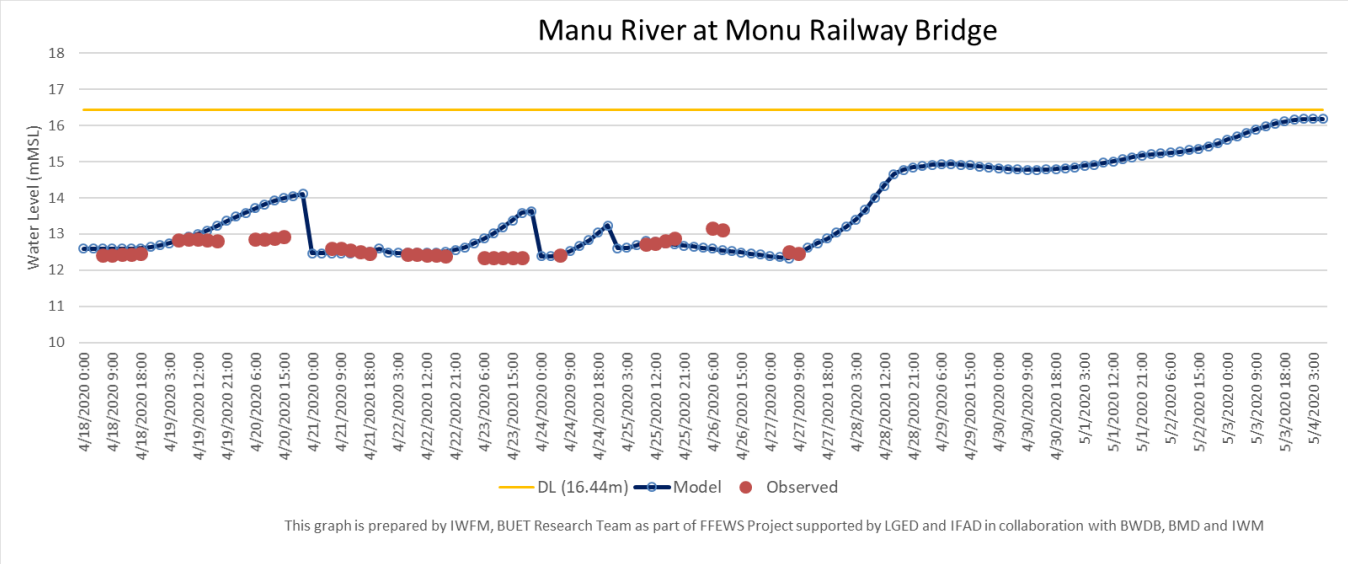


Figure B.20: Water level forecasts with a lead time of 10-day at Manu Railway Bridge station of the Manu river.

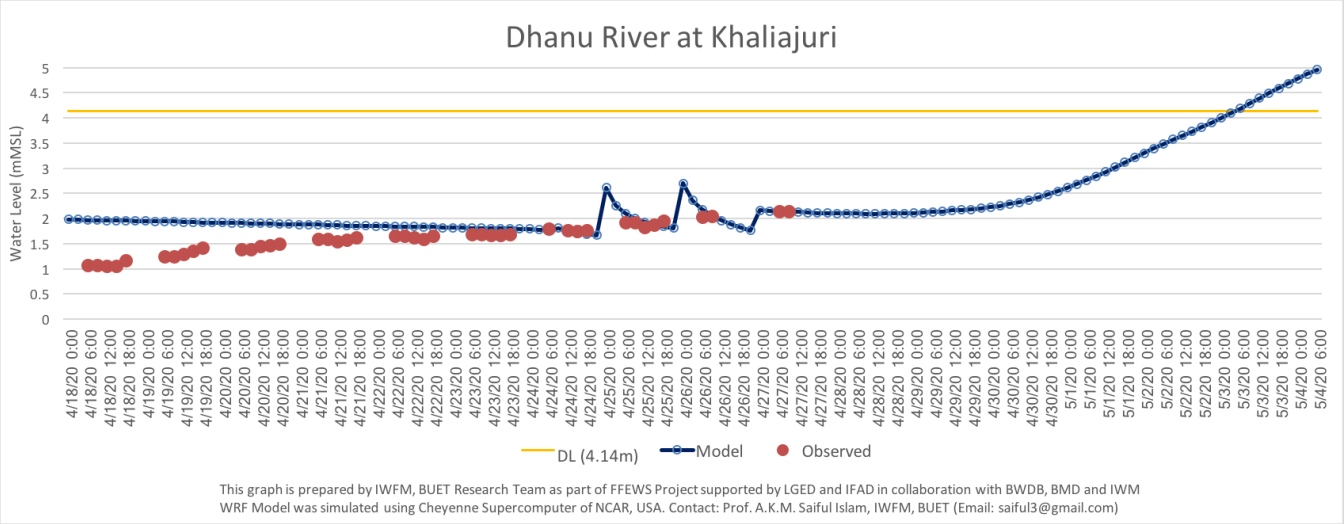


Figure B.21: Water level forecasts with a lead time of 10-day at Khaliajuri station of the Dhanu river.

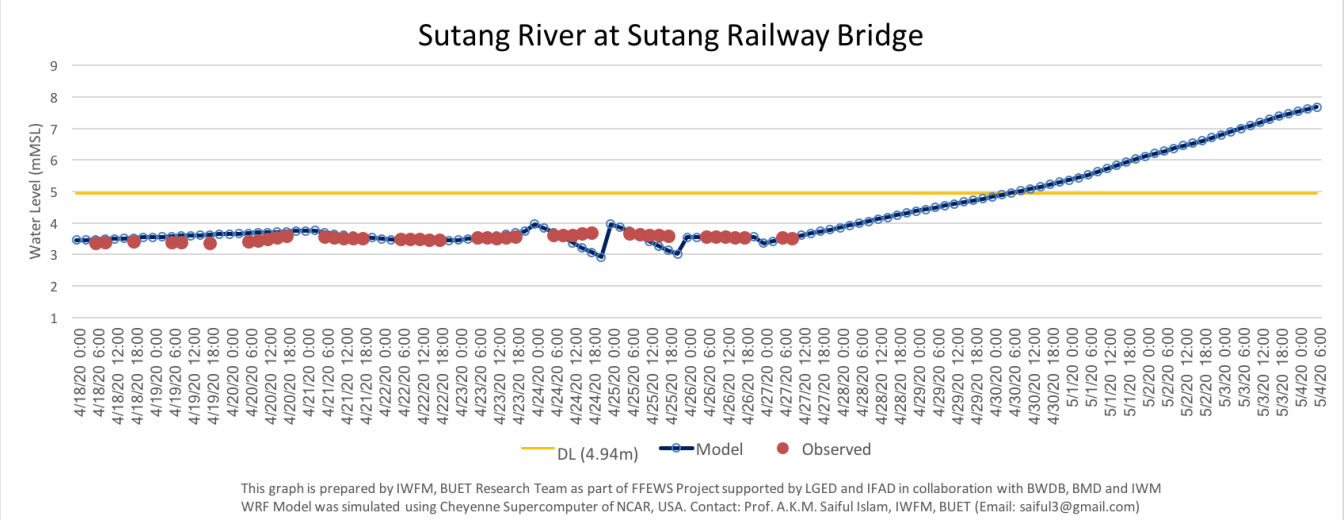


Figure B.22: Water level forecasts with a lead time of 10-day at Sutang Railway Bridge station of the Sutang river.

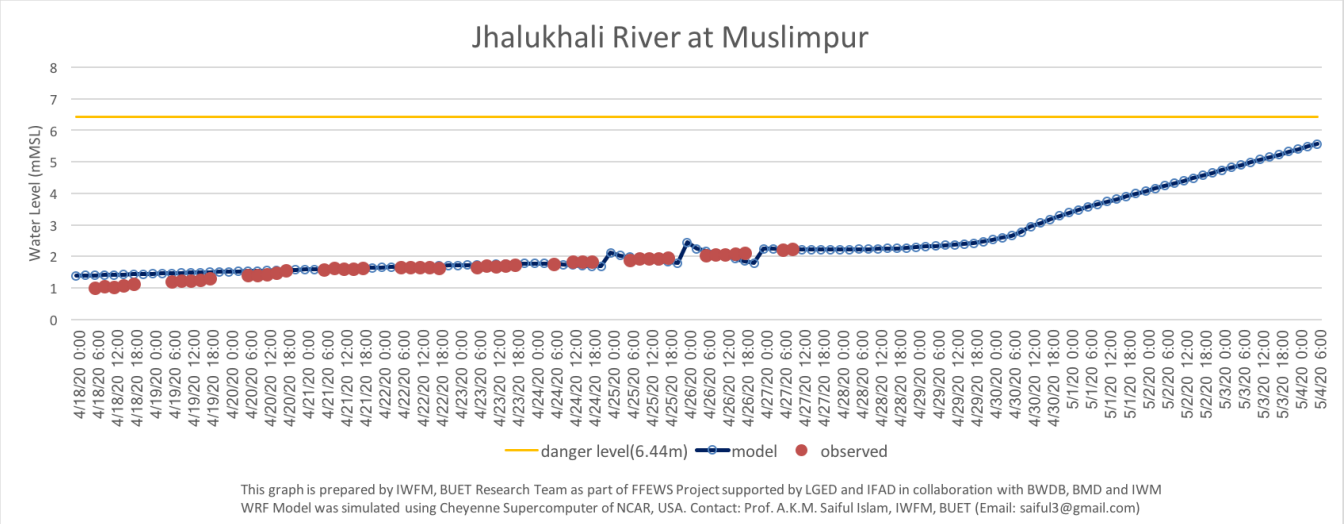


Figure B.23: Water level forecasts with a lead time of 10-day at Muslimpur station of the Jhalukhali river.

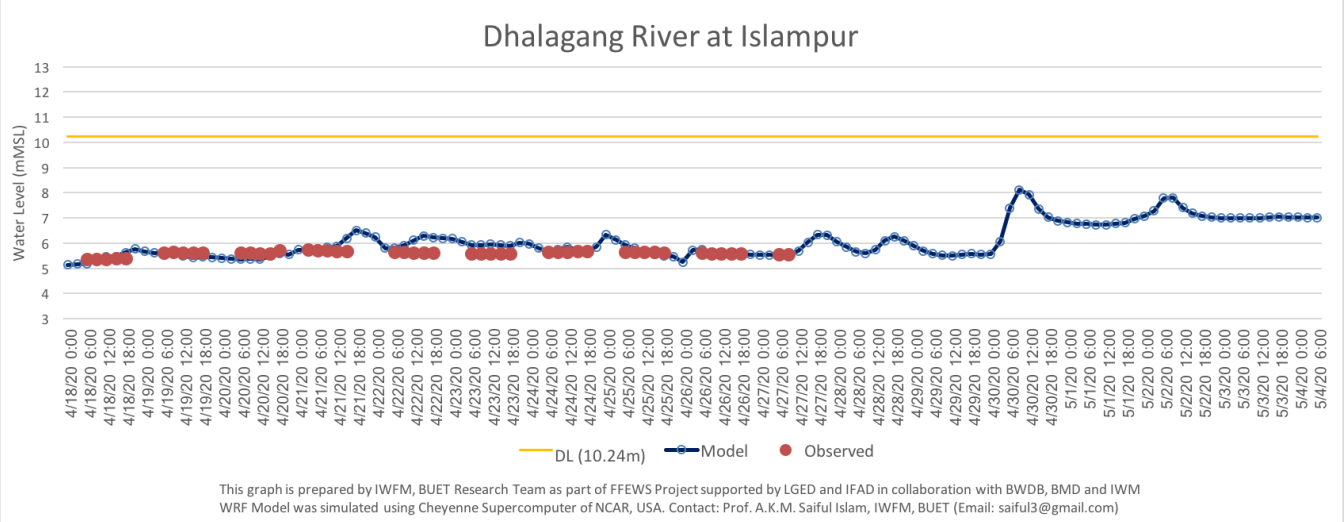


Figure B.24: Water level forecasts with a lead time of 10-day at Islampur station of the Dhalagang river.

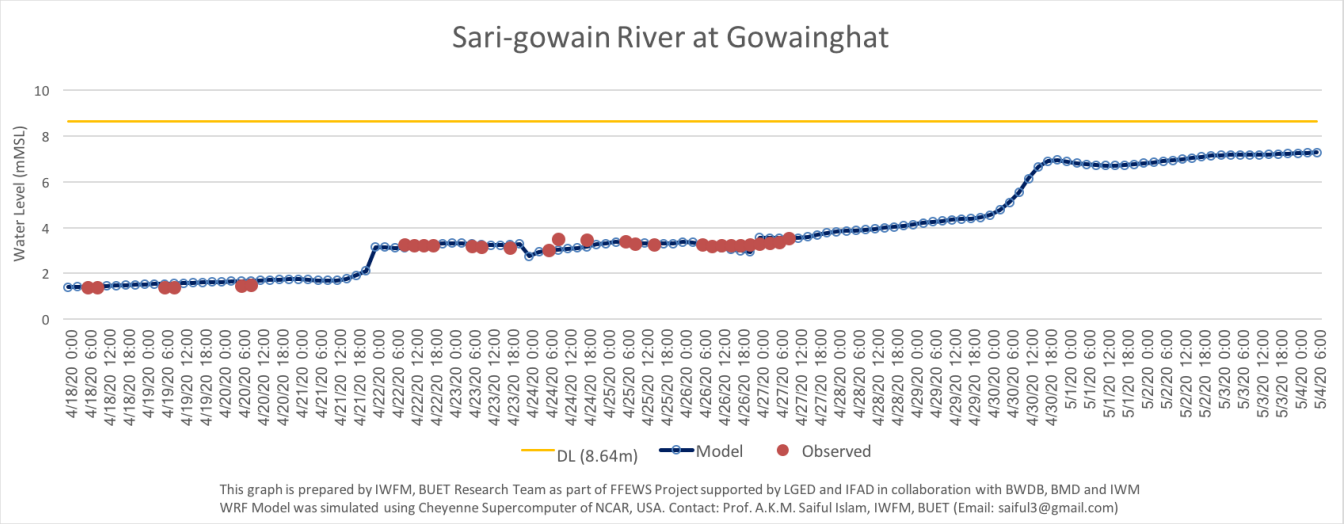


Figure B.25: Water level forecasts with a lead time of 10-day at Gowainghat station of the Sari-gowain river.

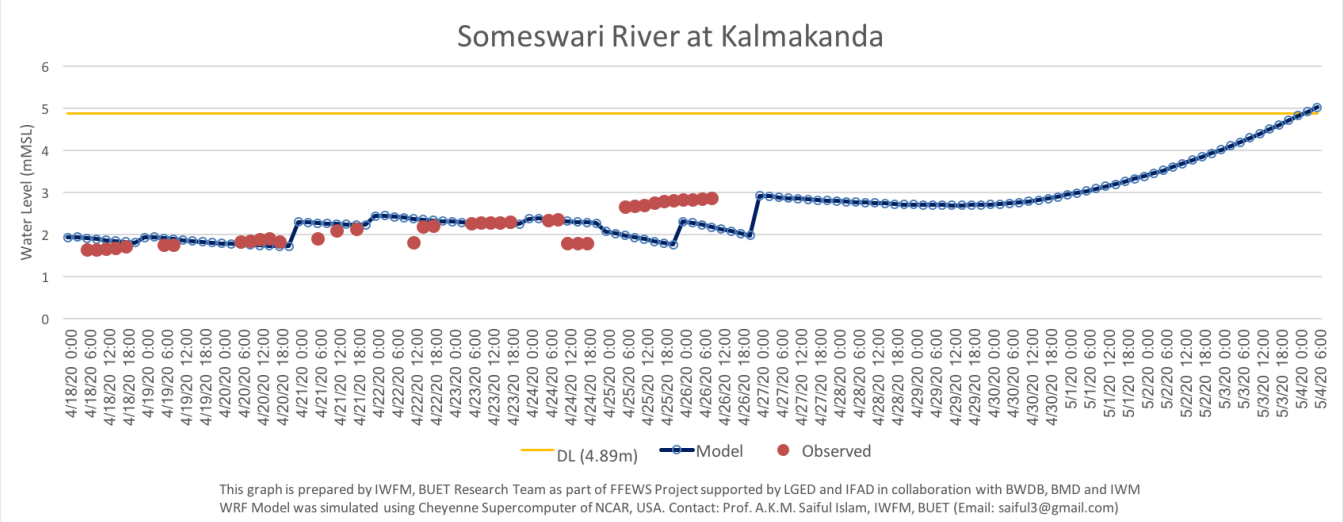


Figure B.26: Water level forecasts with a lead time of 10-day at Kalmakanda station of the Someswari