Implication and risk due to imposed downstream boundary condition in flood forecasting modelling in sub-critical flow regime in flat terrain of Ganga, Bihar

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Abstract

In hydraulic modelling for flood forecasting, boundary conditions are mandatory input requirement for running model and generating water levels and flows. Mainly inflow at upstream boundaries and water level or stage-discharge rating curve at downstream boundaries are used. Obtaining inflows for future dates are relatively easy. However, obtaining downstream boundary condition is most challenging; simply because water levels for future dates do not exist, and stage-discharge rating curve in most cases are not available. Inflows at upstream boundaries are obtained from forecasted rainfall. Indian Meteorological Department (IMD) provides three to ten days of forecasted rainfalls which are then transformed into run-off through hydrological modelling. In case, stage-discharge rating curve is not available at downstream boundary, then using water level, which does not exist, remains an option. Sometimes, where water level gauge is available, daily average water levels, from historic observations say 20 to 30 years of data, are prepared and set as future water levels at the downstream boundary. Even, in some instances, water level of today is directly used, or used through extrapolation for next three days, which brings considerable uncertainty in rapidly varying flashy river. Sometimes, stage-discharge rating curve is also generated from hindcast modelling, but the curve remains uncalibrated in most cases. Thus, there remains substantial risk in all of the cases, for using as downstream boundary. Wrong estimates in boundary condition can influence model forecast for utpo 20 to 30 km river reach; influence zone could even be longer e.g., in tidal areas or shorter e.g., in fluvial steeper terrain. In the present paper, uncertainty and risk due to imposed boundary condition at downstream has been assessed in the major rivers of Bihar for Gandak, Kosi and Mahnanda basins, each in standalone sub-model. These sub-models are also integrated into a large network model of the Ganga in Bihar and all its tributaries. Three scenario simulations have been carried out over the baseline condition water level boundary to assess uncertainty. Baseline water level boundary at downstream of the Gandak, Kosi, Kamla and Mahananda sub-models has been extracted from the network model at their confluence with the Ganga. Then, three-scenario conditions on the baseline downstream boundary were set-up: i) baseline water level was raised by 0.5 m, ii) baseline water level was raised by 1.0 m, and iii) baseline water level was lowered by 0.5 m. The results from on longitudinal water level profiles and water level differences with baseline show that downstream boundary condition has considerable influence towards upstream water level. Relative to baseline, 0.5 m and 1.0 m rise and 0.5 m fall in downstream water level boundary will influence water level profile about 10 to 30 km towards upstream. Therefore, if the tributaries, if operated as a standalone model for forecasting purpose, then either the water levels at downstream boundary have to be very precise (future water level not possible) or stage-discharge rating curve has to be well calibrated. If there is any doubt or uncertainty in the boundary condition of the forecast model, then there should not be any forecasting point within 30 km reach from the downstream boundary; else an error in the range of 0.05 m to 1.0 m is possible on daily water level forecast. The best approach would be to keep the downstream boundary sufficiently away from any forecasting point. The forecasting models used in this paper have been developed using DHI software NAM for hydrological modelling and MIKE11 for hydrodynamic modelling.

Keywords: 1-D modelling, MIKE11, forecast, downstream boundary

1. Introduction

In hydraulic modelling for flood forecasting, boundary conditions are mandatory input requirement for running model and generating water levels and flows for flood risk assessment and preparation of flood maps. Mainly inflow at upstream boundaries and water level or stage-discharge rating curve at downstream boundaries are used. Obtaining inflows for future dates are relatively easy. However, obtaining downstream boundary condition is most challenging; simply because water levels for future dates do not exist, and stage-discharge rating curve in most cases are not available as we require long records of measured discharges for establishing stage-discharge curve. Inflows at upstream boundaries are obtained from forecasted rainfall, available from a number of sources. Indian Meteorological Department (IMD) provides three to ten days of forecasted rainfalls which are then transformed into run-off through hydrological modelling, e.g., NAM by Danish Hydraulic Institute (DHI, release 2016) or HEC-HMS by Hydrologic Engineering Centre (Version 4.2.1, 2017). For downstream boundary condition, in case, stage-discharge rating curve is not available, then using water level, which does not exist, remains an option. Sometimes, where water level gauge is available, daily average water levels, from historic observations say 20 to 30 years of data, are prepared and set as future water levels at the downstream boundary. Even, in some instances, water level of today is directly used, or used through extrapolation for next three days. Sometimes, stage-discharge rating curve is also generated from hindcast modelling, but the curve remains uncalibrated in most cases. Thus, there remains substantial risk in all of the cases, for using as downstream boundary. Wrong estimates in boundary condition can influence model forecast for utpo 20 to 30 km river reach; influence zone could even be longer e.g., in tidal areas or shorter e.g., in fluvial steeper terrain.

Thus, the use of uncertain downstream boundary could bring considerable risk in rapidly varying flashy rivers and in flat terrain of Bihar. Ganga and all its north bank tributaries have very mild hydraulic gradient, and this makes the use of downstream boundary a very sensitive parameter in flood forecasting and flood risk assessment.

2. Description of model area

Flood risk is always higher in flat terrain due to slow movement of flood waves. River flooding is one of the most common natural disasters in India. Most affected river basins are Ganga in the northern part and Brahmaputra in the north-eastern part of the country. Bihar is among the most flood affected states in India. Nearly all north Bihar rivers originate from Nepal or Tibbet from the higher and middle mountains, and have around 75 per cent of their catchment outside the State, mostly in the Himalayan ranges which have very high rains aggregating 2500 mm annually in upper portions, of which over 80 per cent occurs during the four rainy months from June to September. Higher rainfalls in upper catchments having very steep gradients result in formation of very high flows in these parts. As the gradients change sharply from very steep in mountainous and sub-mountainous areas to very mild in north Bihar plains over rather a short distance, the carrying capacity of the rivers in the plains (Fig.1) are far exceeded by the high monsoon flows, resulting in vast inundations over the plains.

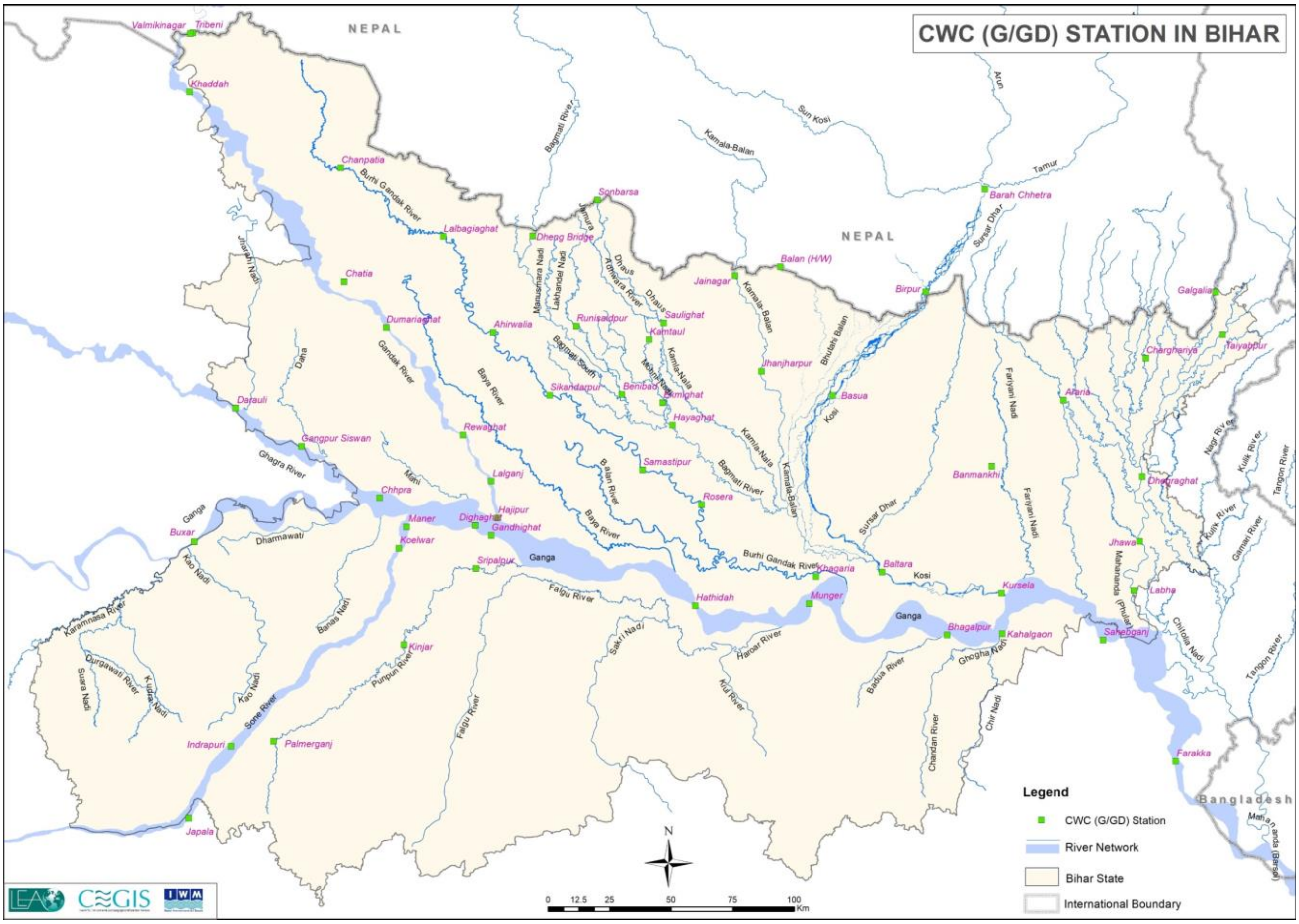

Fig.1 River systems in north and south Bihar including Ganga and locations of CWC gauge stations

All of the north bank tributaries of the Ganga in Bihar, such as Gandak, Budhi Gandak, Bagmati, Kamla, Kosi and Mahananda, originating from mountains in Nepal traverse through the Terai region (means low flat land) in Nepal. By the time, these rivers cross Indo-Nepal border and traverse to join the Ganga, river bed and hydraulic gradient become very mild. Such mild gradients slow down the travel time of the flood waves. This issue is further compounded by the backwater effect from the Ganga whose gradient is even milder than all the above tributaries (Table 1). Ganga has smallest hydraulic gradient than all the tributaries as was expected. Gradient in Ganga, in about 600km reach from Buxar Sahebganj, is mainly 0.05m to 0.07 m for every kilometer (km). The tributaries, Gandak, Bagmati, Kosi and Mahananda, while they have relatively higher gradient in the upper reaches near Indo-Nepal border in the range of 0.3 to 0.15m, they have very low gradient only about 01m in each km by the time, the tributaries approach to the Ganga. Therefore, flooding mechanism near the confluences of all of these tributaries with the Ganga becomes complicated due to the backwater effect from the Ganga, and creates higher flood risk in the basins of these tributaries due to blocking of flow. Therefore, hydraulic modelling of these complex confluences requires judicious approach and correct use of model parameters. Minor mistake in model parameters can create considerable uncertainty in in flood risk maps of larger areas and longer reaches.

River (Data period)	**Gauging station name**	**River Chainage (km), see note**	**Water level slope between consecutive gauge stations (m/km)**
Bagmati (2013-2017)	Sonakhan	4.19	-
	Dubbadhar	33.18	0.30
	Kansar	49.12	0.26
	Runisaidpur	66.30	0.20
	Benibad	104.60	0.19
	Hayaghat	154.80	0.11
Kosi (2011-2018)	Basua	2.09	-
	Baltara	93.8	0.15
	Kursela	154.06	0.08
Gandak (2015)	Chatia	159.5	-
	Rewaghat	224.2	0.18
	Hajipur	275.0	0.12
Ganga (2016)	Buxar	0	-
	Dighaghat	140	0.05
	Gandhighat	149.8	0.10
	Hatidah	254.9	0.07
	Munger	311.1	0.07
	Bhagalpur	391.5	0.06
	Kahalgaon	423.4	0.04
	Sahebganj	492.5	0.05
Mahananda	Dhengraghat	89.0	-
	Jhawa	55.1	0.14
Note: river chainages shown here are taken from a hydrodynamic model of river system in Bihar by FMISC			

3. Objectives

Main objectives of this study were to build one-dimensional hydraulic models of the major tributaries of north Bihar, and carry out sensitivity analysis of imposed downstream boundary condition of the models. We have developed 1-D models of the Gandak, Kosi, Mahananda and Kamla and have assessed the influence of downstream boundary condition.

4. Modelling technology

The 1-D models have been developed in MIKE11 modelling software. MIKE11 simulates Saint Venant equations of conservation of mass, Eq. (1) and momentum, Eq. (2). MIKE11 is a professional engineering software for simulation of flows, sediment transport and water quality in rivers, estuaries, channels, lakes, reservoirs and other water bodies. MIKE11 is a fully dynamic, one-dimensional modelling software The tool is used for detailed analysis, design, management and operation of simple and complex river/channel systems.

$$\frac{\partial Q}{\partial x} + b_s \frac{\partial h}{\partial t} = 0 \qquad (1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\beta \frac{Q^2}{A}\right) + gA\frac{\partial}{\partial x}(h + H) + gA\frac{|Q|Q}{K^2} = 0 \qquad (2)$$

where Q is discharge, h is water depth, b_s is flow width, A is Cross-sectional area, K is Conveyance (where $K= CAR^{1/2}$), C is Chezy resistance coefficient, R is hydraulic radius, β is Boussinesq Coefficient, H is bottom elevation, g= Acceleration due to gravity.

5. Models of Ganga north bank tributaries

1-D models in MIKE11 have been developed for the north bank major tributaries of the Ganga; they are Kosi, Bagmati, Gandak, Mahananda and Kamla. All the tributary models are part of a large network model of all the river systems of north and south Bihar, maintained by Flood Management Information Support Centre (FMISC), Water Resources Department 9WRD), Bihar. The network model is calibrated and validated for 2015, 2016, 2017 and 2018 hydrological year. Calibrated results at some selected gauging stations in Kosi and Bagmati are presented in Table 2 and Fig. 2.

River name	Gauge station name	River chainage (m)	Observed water level (m)	MIKE11-1d (m)
Bagmati	Sonakhan	4,190	70.70	71.10
	Dubbadhar	33,179	63.62	63.95
	Hayaghat	154,750	45.05	45.05
Kosi	Basua	58,800	49.20	48.65
	Dumri	87,000	35.03	35.1
	Baltara	93,800	36.00	35.11

Table 2: Observed and modelled peak water levels of monsoon 2016

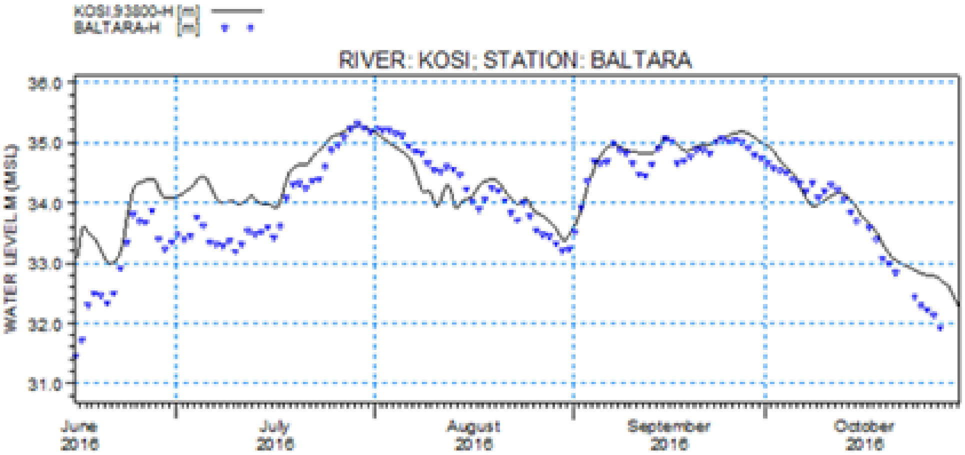

Fig.2 Time series of water level in Kosi from observed CWC gauge and 1-D model

6. Modelling scenarios

Three scenarios have been carried out over the baseline downstream water level boundary condition to assess uncertainty and its consequences in upstream reach of the river. Baseline water level boundary at downstream of each of the tributary sub-models has been extracted from the Network model at the confluence point of tributary and the Ganga. In case of Kamla, the boundary has been extracted from the confluence of Kamla and Kosi. Then, the three-scenario conditions on the downstream boundary were set-up: i) baseline water level boundary was raised by 0.5m, ii) baseline water level was raised by 1.0m, and iii) Baseline water level boundary was lowered by 0.5m. Model runs were carried out for unsteady flow condition of 2016 monsoon (15 July to 15 October). Model uses the same calibration parameters (Manning's roughness coefficient) as in the network model. The present model's cross-sections were based on JAXA satellite imagery, used applying a constant datum correction of -4m. If these cross-sections are replaced by surveyed cross-sections in future, the above uncertainty of downstream boundary would remain an issue in anyway. Water levels for peak flow condition have been analysed in each sub-model to quantify the effect of uncertainty in downstream model boundary.

Mahananda model results

Results from the sensitivity runs from Mahananda are shown in Fig. 3 and 4. Longitudinal profiles of peak water levels (Fig. 3) and water level differences (Fig. 4) relative to baseline clearly demonstrate that downstream boundary condition has considerable influence towards upstream water levels in the Mahananda. Relative to baseline, 0.5m and 1.0 rise and 0.5m fall in the use of downstream water level boundary, will influence water level profile about 50 to 55km towards upstream. Therefore, if Mahananda model is operated as a standalone model for forecasting purpose or even for flood risk mapping, then either the water level data at downstream boundary for forecast run should be very precise from observed gauge data or if there is any doubt or uncertainty in the water level boundary data of the forecast model, then there should not be any forecasting point within 50 to 55km reach towards upstream from the downstream boundary location; else an error in the range of 0.05m to 1.0m is possible. This in fact recommends that Mahananda should not be applied as a standalone model in such flat terrain of Ganga basin. Once Mahananda is within the Network model, then there will not be any issue of downstream boundary in the Mahananda; however, this issue has to be considered at the downstream boundary of the Network model at Farakka.

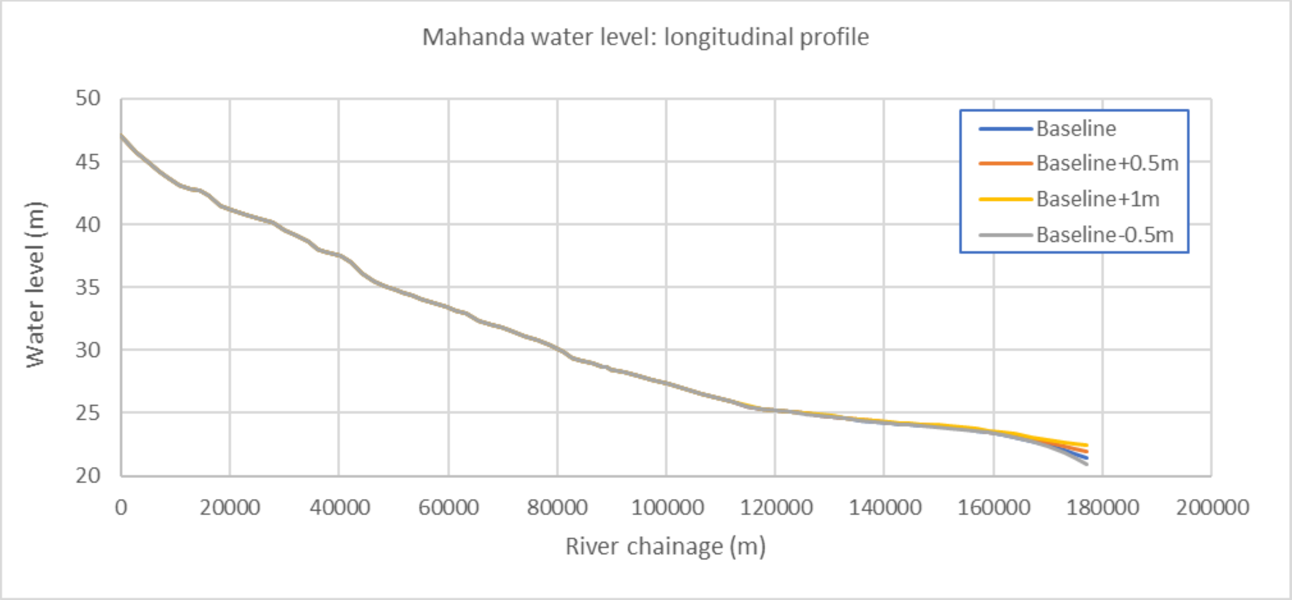

Fig. 3: Longitudinal water level profile in Mahananda River

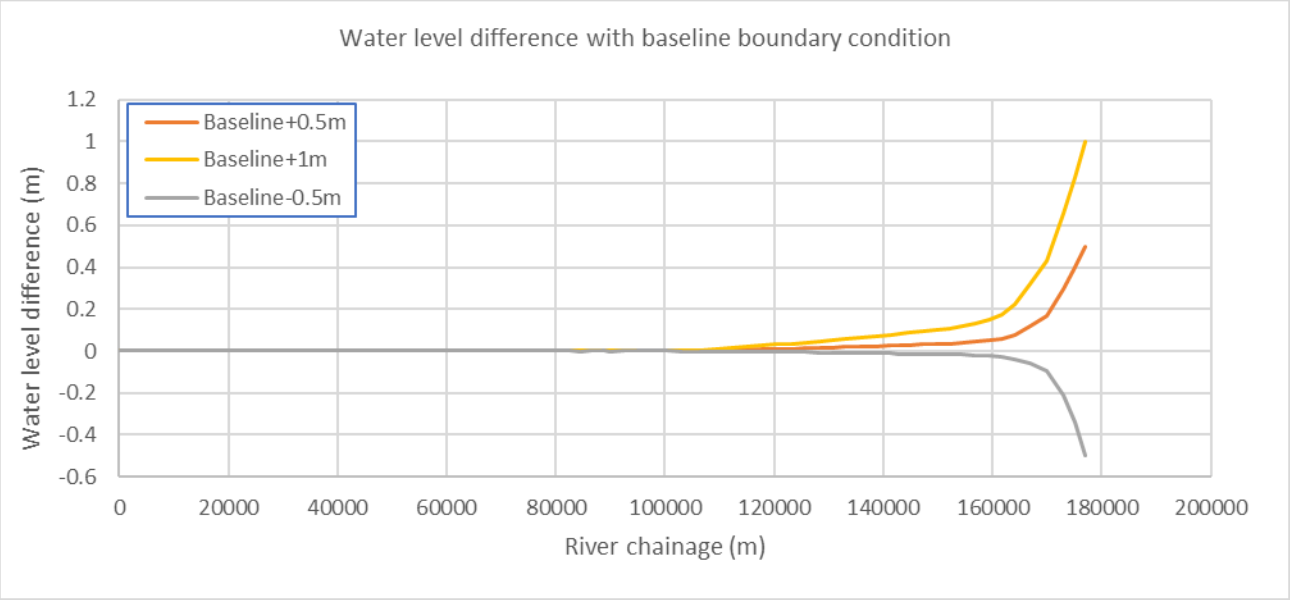

Fig. 4: Water level difference relative to baseline due to 0.5m, 1.0m rise and 0.5m fall in downstream boundary water level

Kosi Model results

Results from the sensitivity runs from Kosi sub-model are shown in Fig. 5 and 6. Longitudinal profiles of peak water levels (Fig. 5) and water level differences (Fig. 6) relative to baseline clearly demonstrate that downstream boundary condition has considerable influence towards upstream water levels in the Kosi. Relative to baseline, 0.5m and 1.0 rise and 0.5m fall in the use of downstream water level boundary, will influence water level profile about 45 to 50km towards upstream. Therefore, if Kosi model is operated as a standalone model for forecasting purpose or even for flood risk mapping, then either the water level data at downstream boundary for forecast run should be very precise from observed gauge data or if there is any doubt or uncertainty in the water level boundary data of the forecast model, then there should not be any forecasting point within 45km reach towards upstream from the downstream boundary location; else an error in the range of 0.05m to 1.0m is possible. This in fact recommends that Kosi should not be applied as a standalone model in such flat terrain of Ganga basin. Once Kosi is within the Network model, then there will not be any issue of downstream boundary in the Kosi; however, this issue has to be considered at the downstream boundary of the Network model at Farakka.

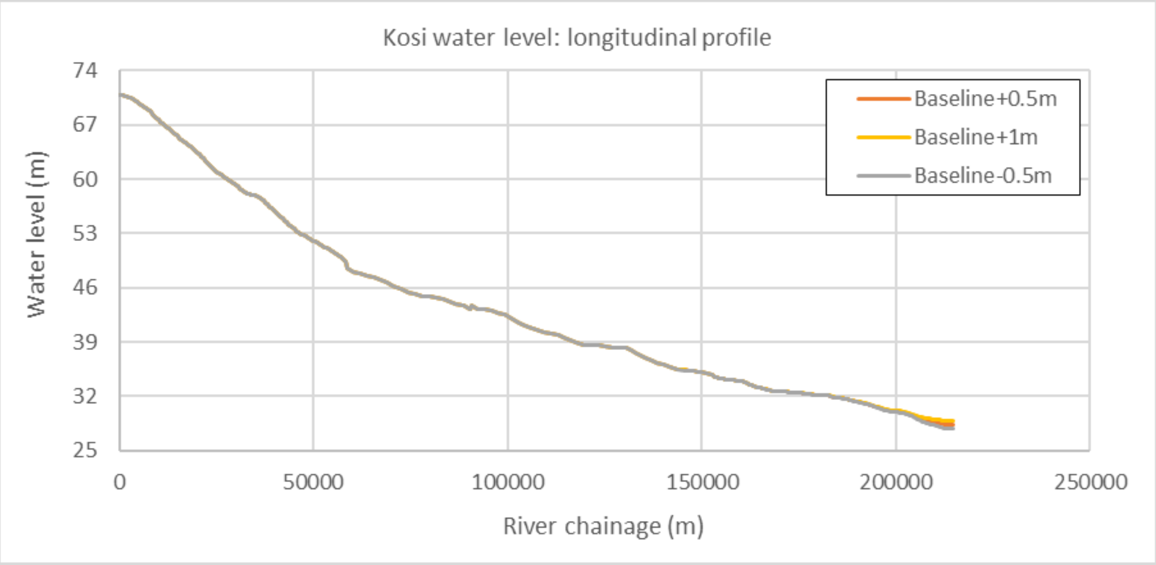

Fig. 5: Longitudinal water level profile in Kosi River

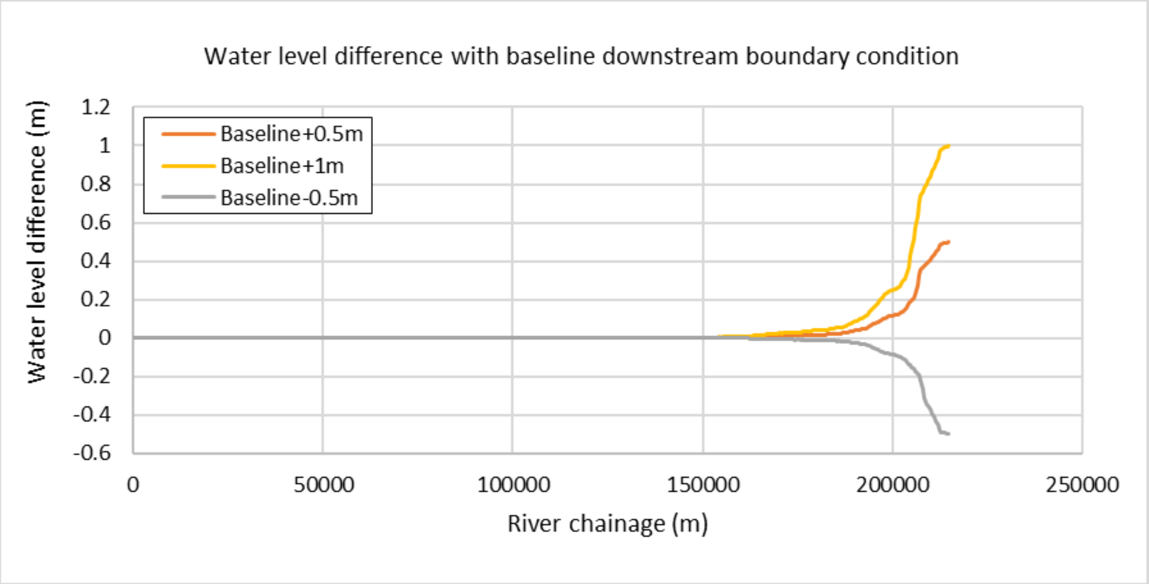

Fig. 6: Water level difference relative to baseline due to 0.5m, 1.0m rise and 0.5m fall in downstream boundary water level in Kosi

Gandak model

Results from the sensitivity runs from Gandak sub-model are shown in Fig. 7 and 8. Longitudinal profiles of peak water levels (Fig. 7) and water level differences (Fig. 8) relative to baseline clearly demonstrate that downstream boundary condition has considerable influence towards upstream water levels in the Gandak. Relative to baseline, 0.5m and 1.0 rise and 0.5m fall in the use of downstream water level boundary, will influence water level profile about 25 to 28km towards upstream. Therefore, if Gandak model is operated as a standalone model for forecasting purpose or even for flood risk mapping, then either the water level data at downstream boundary for forecast run should be very precise from observed gauge data or if there is any doubt or uncertainty in the water level boundary data of the forecast model, then there should not be any forecasting point within 25km reach towards upstream from the downstream boundary location; else an error in the range of 0.05m to 1.0m is possible. This in fact recommends that Gandak should not be applied as a standalone model in such flat terrain of Ganga basin. Once Kosi is within the Network model, then there will not be any issue of downstream boundary in the Gandak; however, this issue has to be considered at the downstream boundary of the Network model at Farakka.

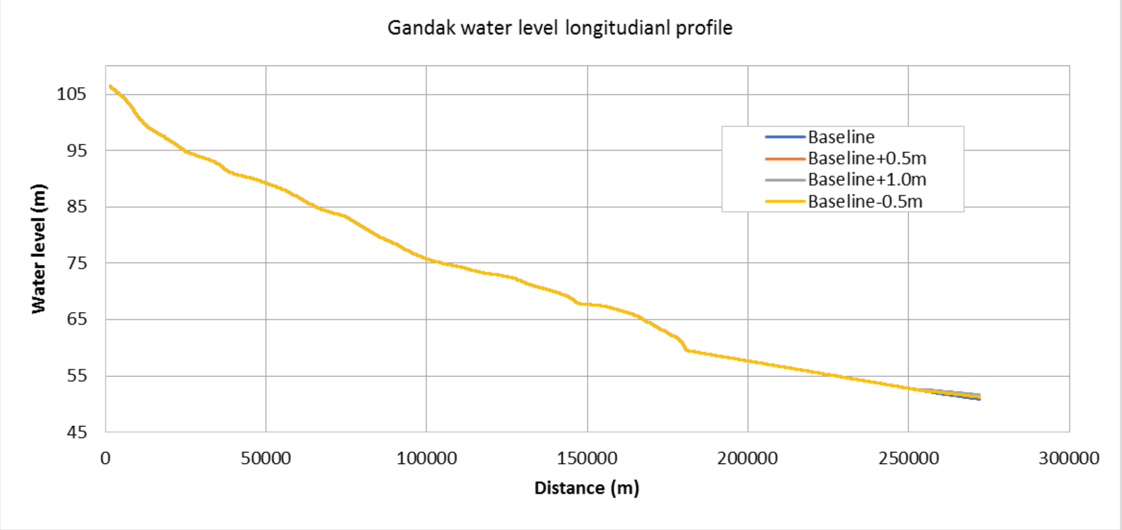

Fig. 7 Longitudinal water level profile in Kosi River

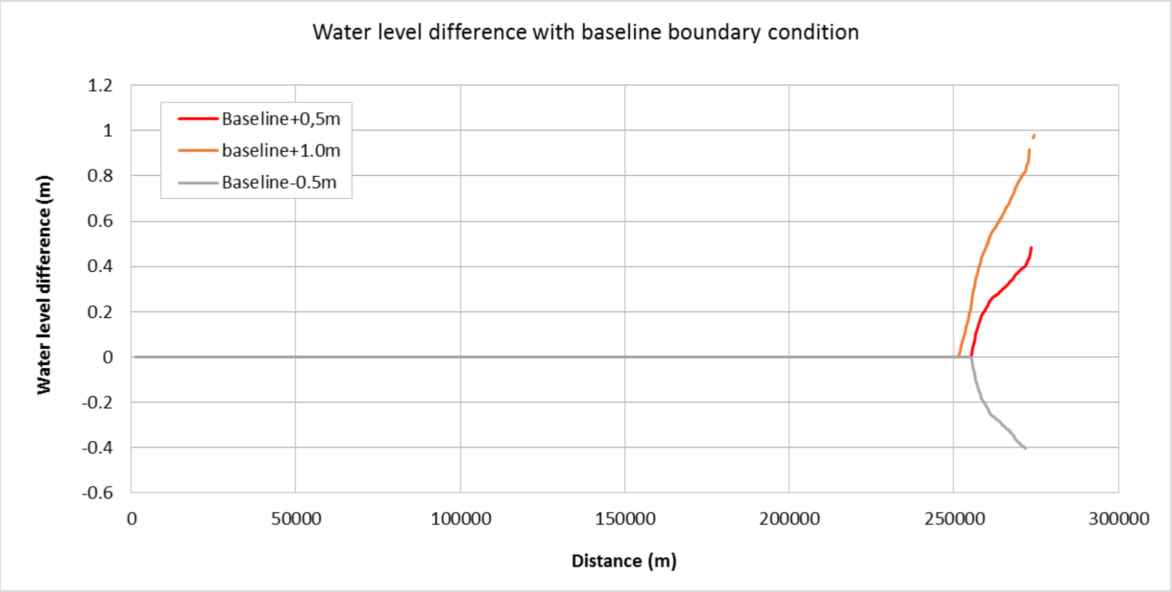

Fig. 8: Water level difference relative to baseline due to 0.5m, 1.0m rise and 0.5m fall in downstream boundary water level in Gandak

Kamla model

Results from the sensitivity runs from Kamla sub-model have also been analysed given the recent failure of Kamla embankments in July 2019. Longitudinal profiles of peak water levels and water level differences relative to baseline clearly demonstrate that downstream boundary condition has considerable influence towards upstream water levels in the Kamla. Relative to baseline, 0.5m and 1.0 rise and 0.5m fall in the use of downstream water level boundary, will influence water level profile about 5 to 8km towards upstream. Therefore, if Kamla model is operated as a standalone model for forecasting purpose or even for flood risk mapping, then either the water level data at downstream boundary for forecast run should be very precise from observed gauge data or if there is any doubt or uncertainty in the water level boundary data of the forecast model, then there should not be any forecasting point within 8km reach towards upstream from the downstream boundary location; else an error in the range of 0.05m to 1.0m is possible. This in fact recommends that Kamla should not be applied as a standalone model in such flat terrain of Ganga basin. Once Kamla is within the Network model, then there will not be any issue of downstream boundary.

7. Conclusions and recommendations

Erroneous and uncertain downstream boundary in hydraulic modelling can lead to considerable error in flood forecast and flood inundation maps in the flat terrain of Bihar. 1-D hydraulic models of the north bank tributaries of Ganga, namely Gandak, Kosi, Mahananda and Kamla, have been developed. Model results indicate that wrong use of boundary can influence upto 60km upstream in water level profile. It is clear that Ganga water level is the major control of flooding in in all the tributaries in the reach of their confluence with Ganga. Mahananda and Kosi were found more sensitive to downstream boundary; nearly 40 to 50km reach can be influenced in these two rivers if erroneous or uncalibrated downstream boundary condition is used. Gandak was found relatively less sensitive. And clearly Kamla is least sensitive as it is a upper terrain river in the plains of Kosi. Therefore, very careful and judicious consideration has to be given in the choice of downstream boundary. In a river of 200km length, nearly 25% reach could be affected due to an inappropriate use of downstream boundary.

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