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River flow simulation using MIKE11 and SRTM DEM data: Case of Mahanadi Delta region in India

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ABSTRACT

Simulation of water levels at different sections of a river using physically based flood routing models is quite cumbersome, because it requires many types of data such as hydrologic time series, river geometry, hydraulics of existing control structures and channel roughness coefficients. River cross-sections are the prime input to any river hydraulic model for simulation of water level and discharge. Field measurements of river cross-sections are labour intensive and expensive activities. Availability of measured river cross sections is scanty in most of the developing countries, thereby making it difficult to simulate the water level and discharge using hydraulic models. In this study, Digital elevation model (DEM) from shuttle radar topography mission (SRTM) was used to extract the cross section elevation. The extracted river cross-sections were used to simulate the magnitude of flood in the deltaic reaches of Mahanadi river basin located in the eastern India. Simulation of MIKE11 was carried out for the monsoon period of the years 2001, 2002 and 2003. The model setup was calibrated for the monsoon period of 2001 and validated for the years 2002 and 2003. The calibration and validation results of MIKE11 showed that the freely available SRTM DEM-extracted river cross-sections could be used in hydraulic models to simulate stage and discharge hydrographs for the Mahanadi river system.

Keyword: Hydrodynamic model, SRTM DEM, MIKE 11, River flow simulation, Mahanadi

INTRODUCTION

The delta region of Mahanadi river basin in eastern India is a highly populated and major paddy growing region in the state of Orissa. Floods are a frequent phenomena occurring in this part of the state during monsoon period (June- October), which causes severe damage to crops as well as lives. The main causes of flood in this region are the low carrying capacity of the rivers due to sedimentation, poor drainage system especially in the low land deltaic part of the basins and poor flood management practices (Beura, 2015). Floods are one of the major causes of the loss of life and property and have an adverse effect on the economy across the globe. The prediction of river stages plays a vital role in the structural and non-structural measures of flood management. The predictions are also useful to prepare the flood maps in river floodplains (Rahman *et al.* 2011). With rapid advancement in computational technology and research in numerical techniques, various one-dimensional (1D) hydrodynamic models, based on hydraulic routing, have been developed, calibrated, validated and successfully applied for flood forecasting and inundation mapping(Gharbi *et al.* 2016). Hydrodynamic models that reproduce the hydraulic behaviour of river channels have been proven to be effective tools in floodplain management (Kadam and Sen 2012; Samantaray et al 2015). In the past few years, various researchers have used the hydrodynamic modeling approach to simulate river flow and flood inundation in the floodplains (Shumuk *et al.* 2000; Vijay *et al.* 2007). The flood water levels along the 79 km long Kalu River in Sri Lanka were simulated using the 1D HEC-RAS hydrodynamic model to prepare the people to survive during floods with minimum damages by Nandalal (2009). The urban flash flood in 2001 in Gdańsk, Poland was simulated using a 1D model for the operation of storm gates under different conditions and technical solutions were proposed to mitigate the consequences of similar floods by Majewski *et al.* (2008). MIKE 11HD model is a one-dimensional hydraulic modeling package, developed at Danish Hydraulic Institute in 1987. The model has been widely used to simulate water levels and flow in the river systems (Hammersmark *et al.* 2005; Kamel 2008; Panda *et al.* 2010).The integration of geographic information system (GIS) with the hydraulic models is the recent advance in computational river hydraulics (Merwade *et al.* 2008, Nunes *et al.* 1998, Rodrigo *et al.* 2011). A hydraulic model coupled with GIS use the digital elevation model (DEM) to extract the river cross-

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sections, which define the geometry of the river. The extracted river cross-sections are then used in the hydraulic model for the computation of water level and flow. Accurate simulation of river stage is of paramount importance in flood control operations. Hydrodynamic models provide a sound physical basis for this purpose and have the capabilities to simulate a wide range of flow situations. However, these models require accurate river geometry data, which may not be available at the desired locations in the rivers. Therefore, in the reported study, Digital elevation model (DEM) from shuttle radar topography mission (SRTM) was used to extract the cross section elevation. The SRTM was launched in February 2000. A survey of the land masses were made between 60^0 north and 58^0 south latitudes. The objective of the SRTM was to obtain elevation radar data on a near global scale to generate the most complete high resolution digital topographic database of Earth (Ernesto *et al.* 2006; Jacob 2001; Sanders 2007). The SRTM generated consistent, comprehensive topographic data and radar images to model the terrain and map the land of most of the inhabited surface of the Earth.

MATERIAL AND METHOD

Study area

Delta region of Mahanadi River basin in India forms study area. It is located in the north-eastern part of coastal Orissa in India and lies between the longitudes $85^0 30^'$ E and $86^0 52^'$ E and the latitudes $19^0 40^'$ N and $20^0 45^'$ N. The areal extent of the delta is about 6800 km^2 in which more than 80% of the total cropped area is affected by floods during the monsoon period. The average surface elevation of the delta region ranges from 5m to 30m. The flooding in the delta region is due to the river Mahanadi and its distributaries. The distributaries of the river Mahanadi include Kuakhai, Devi, Kathajodi, Kandal, Serua, Luna, Paika, Kushabhadra, Bhargavi, Chitrotpala, Daya and Biluakhai (Fig. 1).

Data used

The data used in this study were the time series of daily discharge and water level of different gauging stations for the years 2001, 2002 and 2003, hourly and daily rainfall of different raingauge stations, river cross sections at different locations, topographical map and published data related to floods in the study area from different sources.

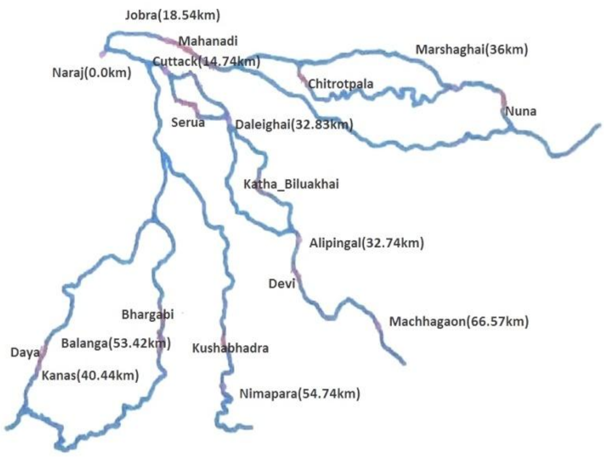

Fig. 1: Map of Mahanadi delta showing its distributaries

Methodology

The MIKE11 model setup was prepared to represent the entire river system in the delta region. The main input includes river cross sections, time series of discharge or water level or both, and topographical map. The layout of MIKE 11 river network was prepared by digitizing the geo- referenced topographical map (Fig. 2) of the study area in the MIKE 11 network editor tool.

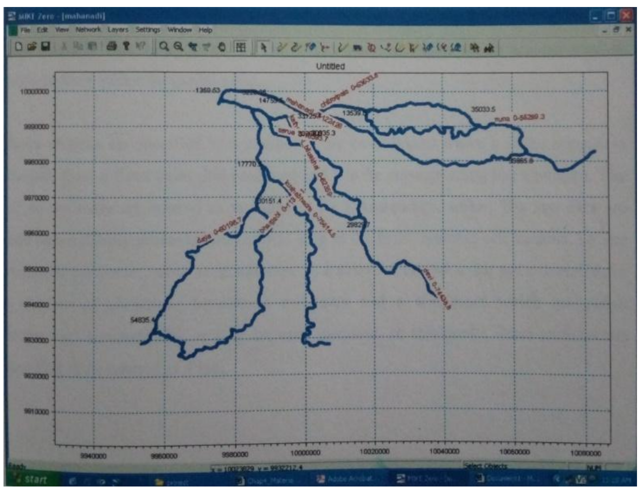

Fig. 2.Digitized river system of the study area

Cross section elevation was extracted from SRTM DEM. SRTM DEM was converted into DFS2 grid file (Fig. 3). The grid spacing of the prepared DFS2 grid file was 90mx 90m.
To obtain the cross section elevation, digitized river network and toposheet had been overlaid on the DFS2 grid file. A line was drawn perpendicular to the river flow (Fig. 4). The value of each grid along this line appears with particular color in the tabular view. This value gives the cross- section elevations which were exported to cross- section editor for model setup. In this study, cross-sections were specified at an interval of 4km.

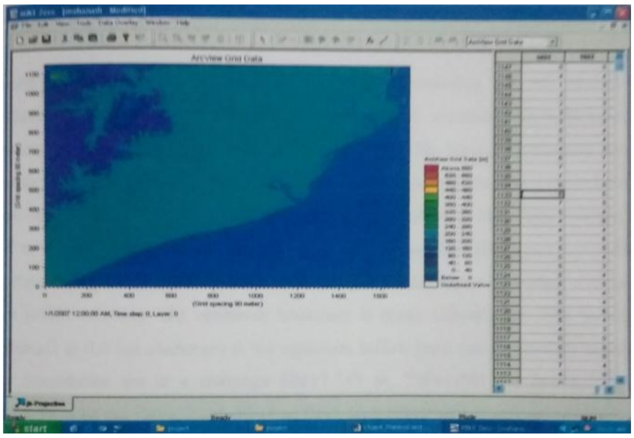

Fig 3: DFS2 grid file of the study area

The study area has five open hydrodynamic boundaries (Fig. 1). All the four downstream boundaries were provided with constant water level whereas the upstream boundary was made inflow type. The point, Naraj (Mahanadi at 0.0km chainage) was the upstream inflow type open boundary whereas the other boundaries were at a chainage 60117.745m, 75614.481m, 74438.771m and 122415.54m of the Daya, Kushabhadra, Devi, and Mahanadi rivers respectively. The time series database file to serve as boundary condition were prepared from the available data. Daily discharge data starting from 1st July to 30th October (monsoon period) was given as input at Naraj gauging site. The HD parameters, in the present study, include the initial conditions of water level and discharge, friction coefficient (n), and output parameter options.

The set up was calibrated by comparing the results (computed water level and discharge) with the observed values of the year 2001. To get the overall acceptability of the result, two goodness of fit criteria were used; such as Nash Sutcliffe index (E_{ns}) and index of agreement (d).

$$E_{ns} = 1 - \frac{\sum (Q_O - Q_S)^2}{\sum (Q_O - Q_{av})^2}$$

(1)

$$d = 1 - \frac{\sum (Q_O - Q_s)^2}{\sum (|Q_O - Q_{av}| + |Q_s - Q_{av}|)^2}$$

(2)

Where, E_{ns}= modeling efficiency, Q_O= observed discharge (m^3/s), Q_S= Simulated discharge (m^3/s),
Q_{av} = mean of observed discharge (m^3/s), d= index of agreement
After the calibration of MIKE 11, the simulation was validated for the same time period by taking the data of the years 2002, 2003 for different gauge stations.

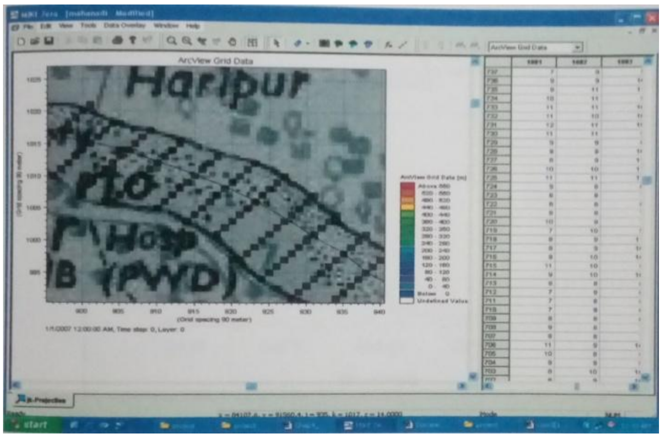

Fig 4: Extraction of cross section from DFS2 grid file

RESULTS AND DISCUSSION

Calibration of MIKE11 Hydrodynamic Model

For the calibration of MIKE11 HD model, the manning's roughness coefficient, n of the riverbed was used as the calibration parameter. Initially, the setup was simulated using the default values of HD parameters. The default global value for n is 0.033 for the riverbed. The calibration was carried out for the monsoon period of 2001. The simulated water level at five gauge stations viz. Alipingal, Cuttack, Daleighai, Marshaghai and Machhagaon were compared with the corresponding observed values. The process was continued until the observed and the simulated values were in close agreement. Fig 5 to fig. 9 presented the comparison of the observed and simulated water levels at Alipingal, Cuttack, Daleighai, Marshaghai and Machhagaon respectively. The performance of the model was evaluated using two goodness of fit criteria i.e., Nash- Sutcliffe coefficient, Ens and the index of agreement, d.

Initially, during simulation, the computed discharge and the water level at all gauging stations were observed to be high but followed the same trend. By changing the global roughness coefficient, n from 0.033 to 0.012 and fixing the local roughness coefficients of all rivers as constant, the setup was simulated and the results were compared with the observed values. Further, the local roughness coefficient varied from 0.010 to 0.120 and fixing the global value of n, the setup was executed during calibration. The final value of the calibrated parameters, i.e., the global value of n was found to be 0.012, whereas the local values ranged from 0.013 to 0.114 (Table 1).

Table 1: Local value of calibrated manning's values for MIKE11 set up

River	Chainage (m)	Mannings roughness coefficient, n
Daya	0	0.056
Serua	0	0.013
	15000	0.013
Devi	0	0.084
	10000	0.084
Nuna	0	0.099
	0	0.114
	10000	0.114
Chitrotpala	15000	0.084
	35000	0.013
	60000	0.013

Reasonably good values of goodness of fit measures (E_{ns} and d) were obtained for all the five gauging stations after the calibration period 2001 (Table 2).

Table 2: Values of goodness of fit measures at selected locations for calibration period 2001

Statistical parameter	Locations				
	Alipingal	Cuttack	Daleighai	Marshaghai	Machhagaon
E_{ns}	0.85	0.85	0.70	0.81	0.71
d	0.94	0.95	0.90	0.88	0.90

The simulated peak water levels at all the locations were in close agreement with corresponding observed values, as evident from the Figs. 5 to 9.

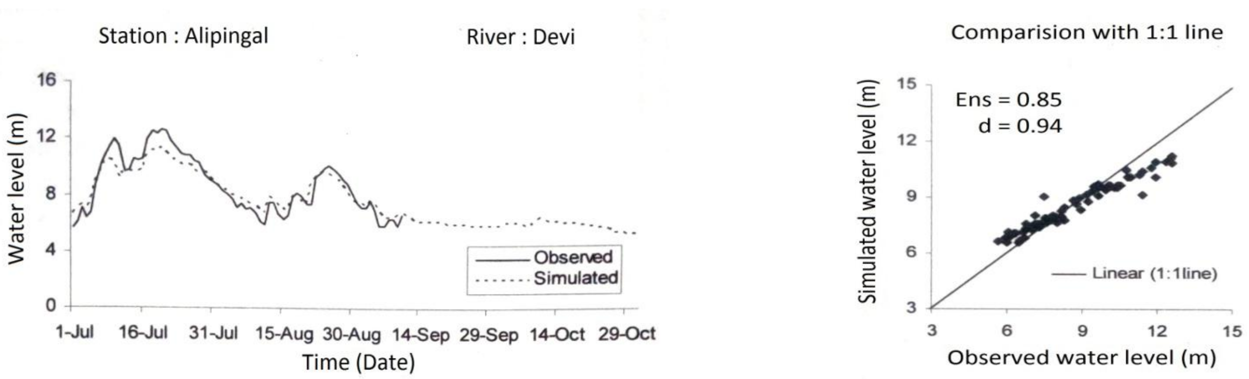

Fig. 5: Comparision of observed and simulated water level at Alipingal gauging site during calibration for the Year 2001

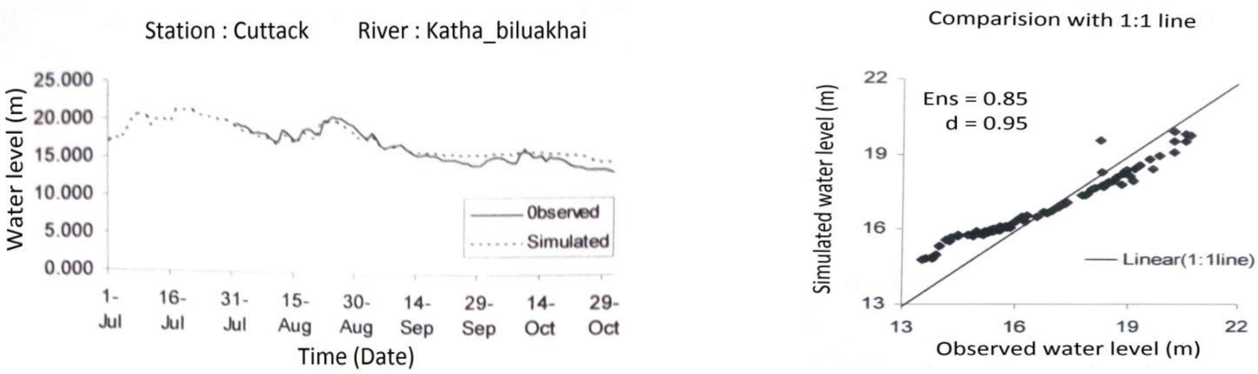

Fig. 6: Comparision of observed and simulated water level at Cuttack gauging site during calibration for the year 2001

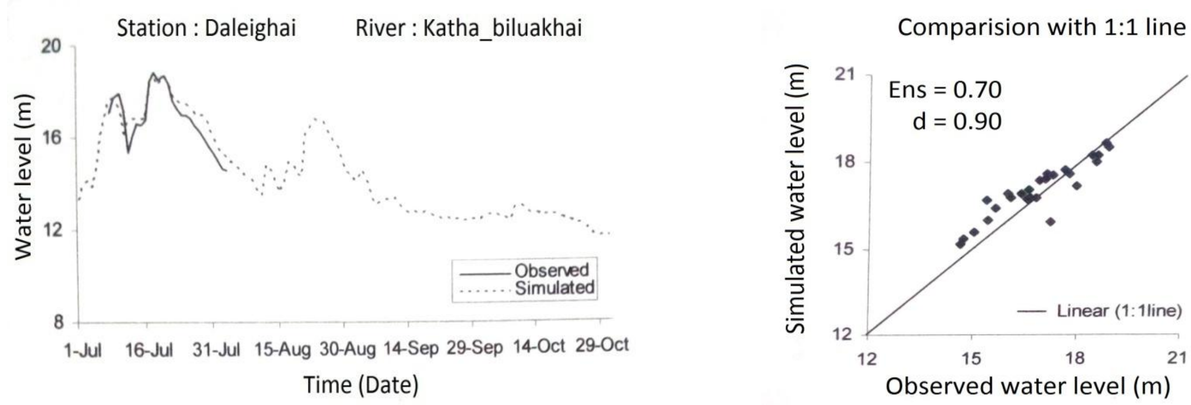

Fig.7: Comparision of observed and simulated water level at Daleighai gauging site during calibration for the year 2001

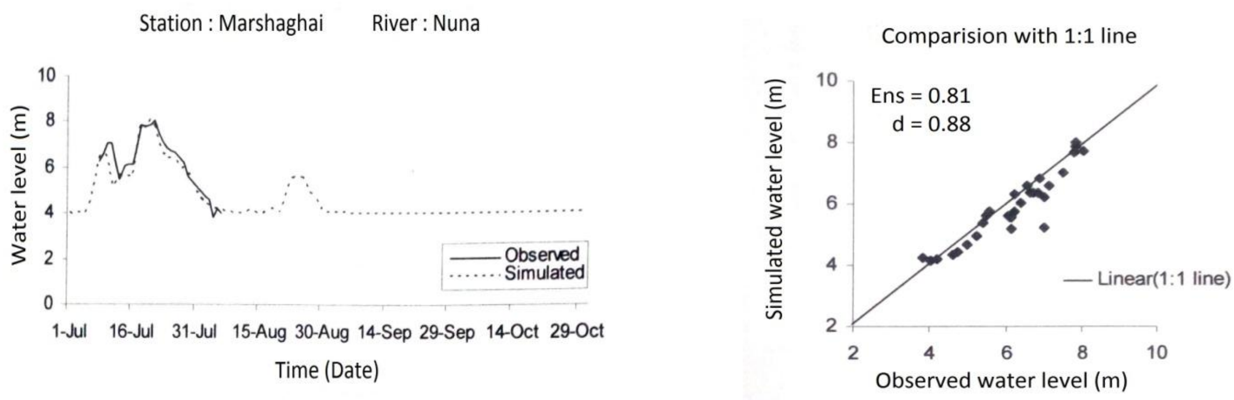

Fig.8. Comparision of observed and simulated water level at Marshaghai gauging site during calibration for the year 2001

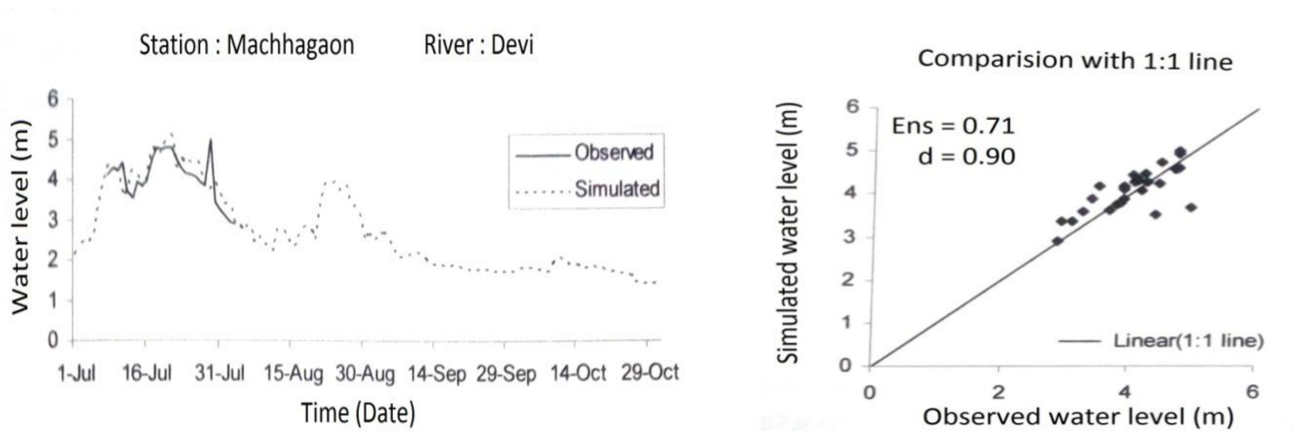

Fig.9. Comparision of observed and simulated water level at Machhagaon gauging site during calibration for the year 2001

Validation of MIKE 11 Model

To validate the calibrated model, the data for the monsoon period from 11th August to 30th September for the years 2002 and from 1st July to 30th September for the year 2003 were used.Figures 10 to 12 presented the comparison between the observed and simulated water levels at Cuttack, Machhagaon and Alipingal respectively during validation for the year 2002. The simulated water levels were found to be in reasonably close agreement with the corresponding observed values for the year, 2002. The peak water level was found to occur on 15th September in 2002 and its values were found to be near about same for both observed and simulated cases (Panda *et al.*2010). The values of the goodness of fit measures were similar to those obtained in calibration period (Table 3).

Table 3: Values of goodness of fit measures at selected locations for validation period 2002

Statistical parameter	Locations		
	Cuttack	Machhagaon	Alipingal
E_{ns}	0.81	0.81	0.71
D	0.92	0.95	0.89

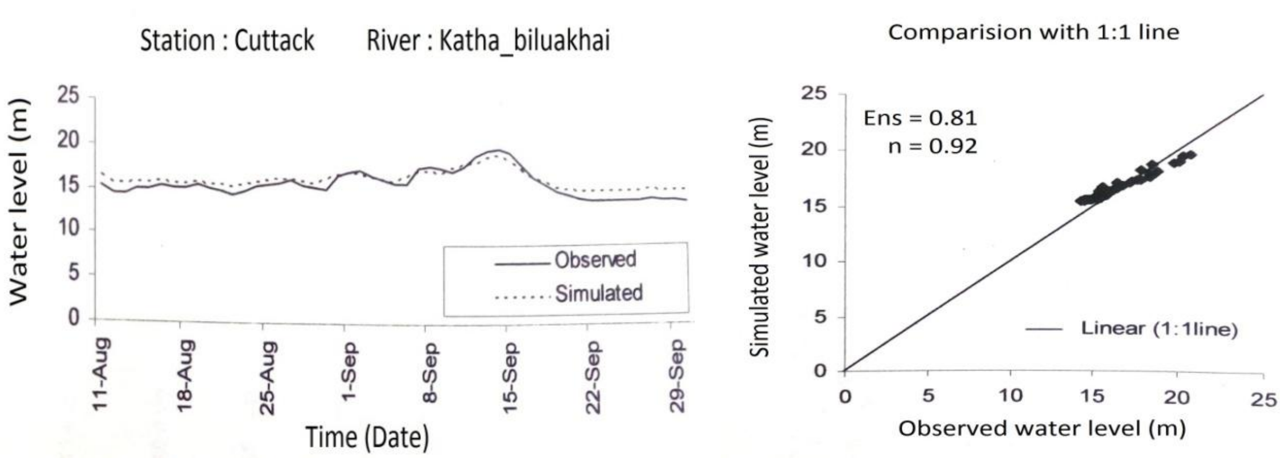

Fig.10: Comparision of observed and simulated water level at Cuttack gauging site during validation period 2002

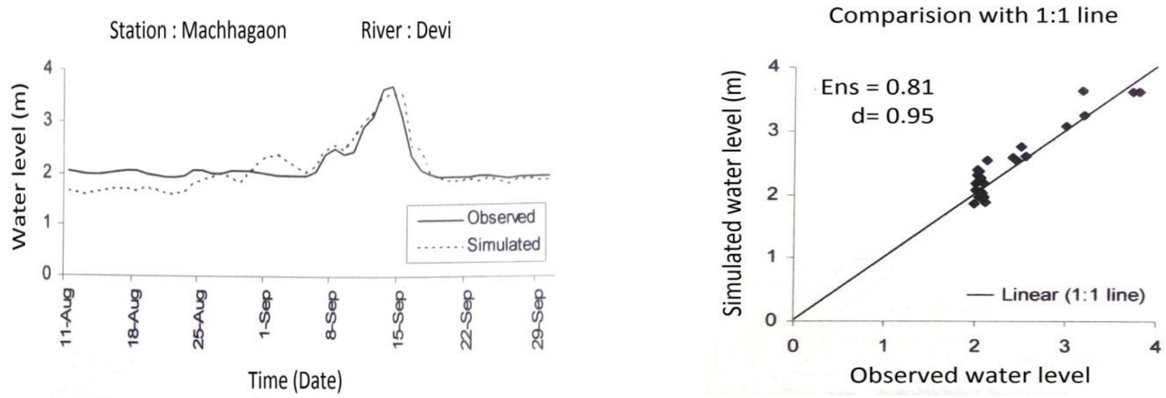

Fig.11: Comparision of observed and simulated water level at Machhagaon gauging site during validation period 2002

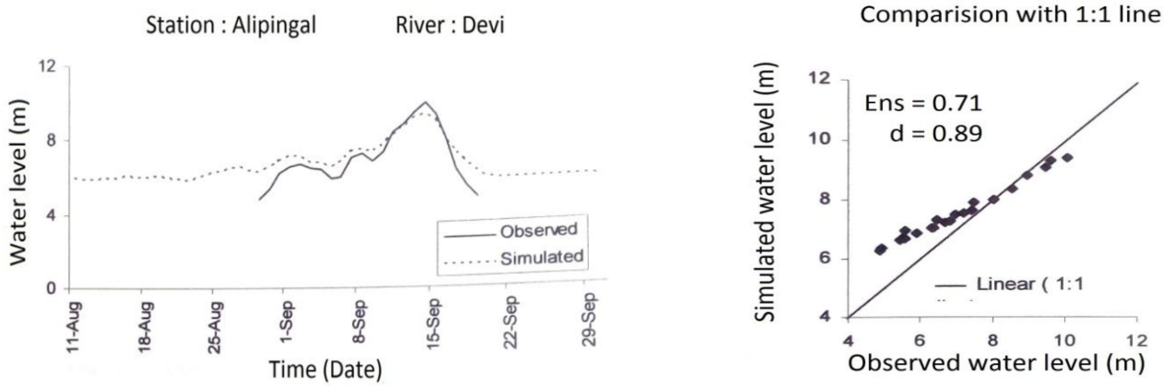

Fig.12: Comparision of observed and simulated water level at Alipingal gauging site during validation period 2002

Figs 13 to 16 presented the comparison between observed and simulated water levels at Cuttack, Macchagaon, Daleighai and Alipingal, respectively during validation for the year 2003. The simulated water levels were found to be in reasonably close agreement with the corresponding observed values. The peak water level was found to be near about same for both observed and simulated cases. The good values of the goodness of fit measures (E_{ns} and d) were obtained at selected locations during validation for the year 2003 (Table 4).

Table 4: Values of goodness of fit measures at selected locations for validation period 2003

Statistical parameter	Locations			
	Cuttack	Machhagaon	Daleighai	Alipingal
E_{ns}	0.74	0.70	0.62	0.76
d	0.90	0.93	0.85	0.91

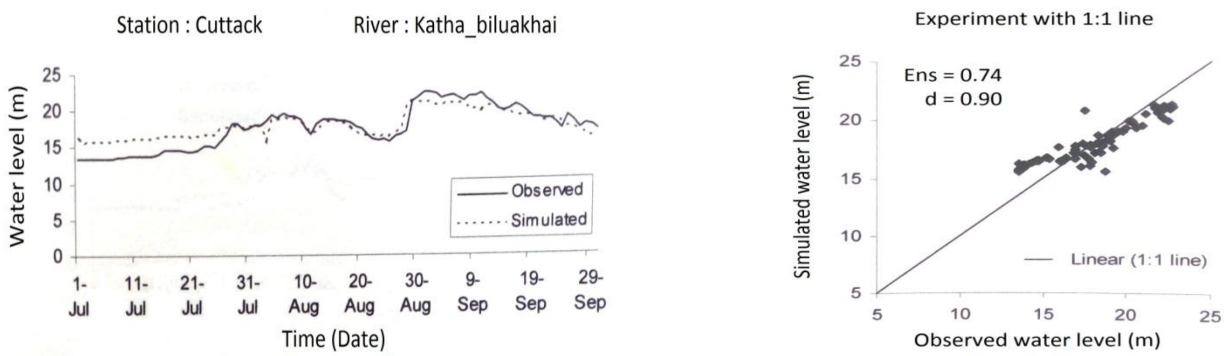

Fig.13: Comparision of observed and simulated water level at Cuttack gauging site during validation period 2003

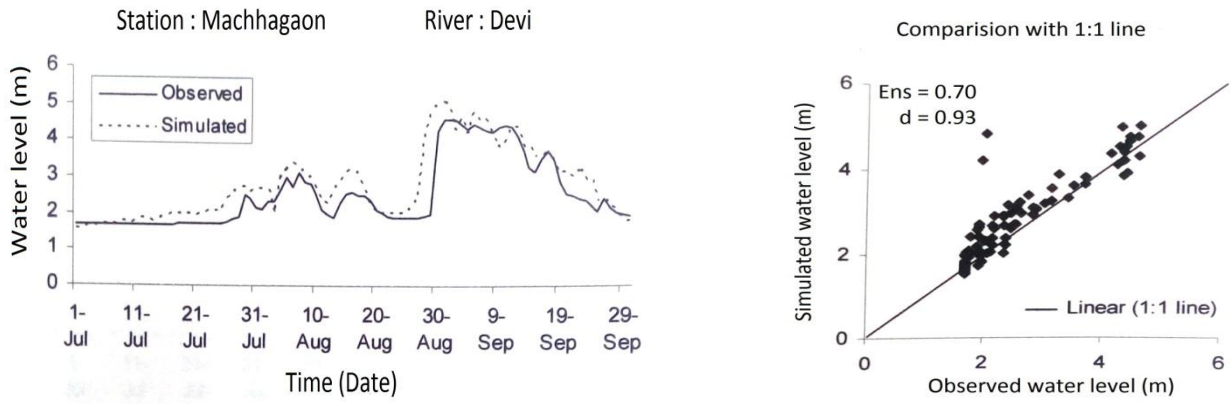

Fig.14. Comparision of observed and simulated water level at Machhagaon gauging site during validation period 2003

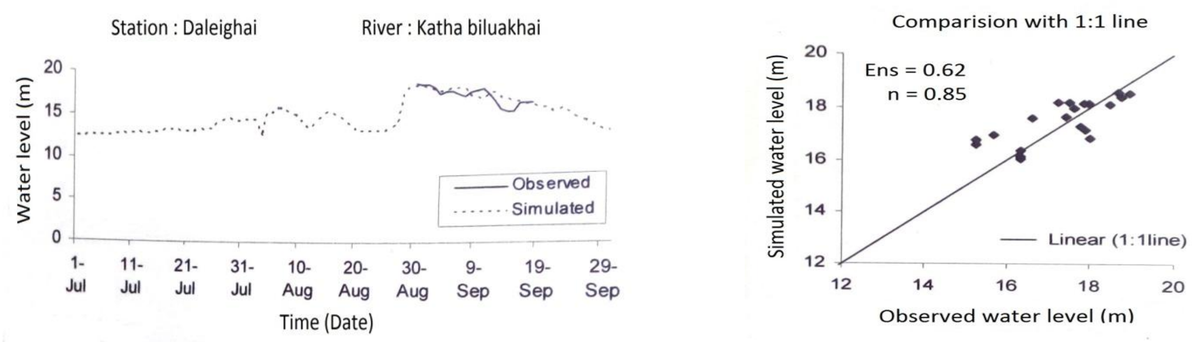

Fig.15. Comparision of observed and simulated water level at Daleighai gauging site during validation period 2003

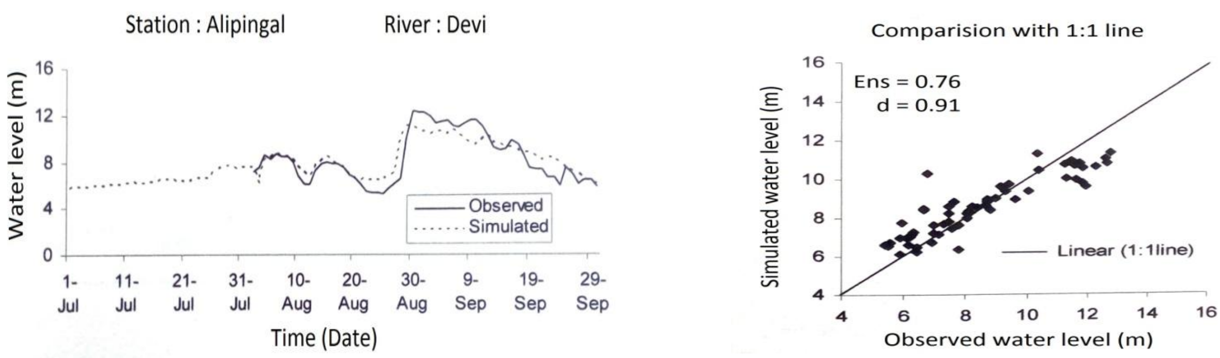

Fig.16. Comparision of observed and simulated water level at Alipingal gauging site during validation period 2003

In case of 2002, there was a gradual rise in peak values whereas there was a sudden rise in the peak values at all locations for the year 2003 (Fig. 10 to 16), which led to flooding in the year 2003. Reasonably good values of d (index of agreement) were obtained for all locations. The performance of the MIKE11 model was found to be reasonably good during validation. Thus, the calibration and validation results of MIKE11 show that the freely available SRTM DEM-extracted river cross-sections could be used in hydraulic models to simulate stage and discharge hydrographs for the rivers of Mahanadi delta region (Vijay *et al.* 2007).

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