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Flood Inundation Modeling using MIKE FLOOD and Remote Sensing Data

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Abstract A coupled 1D-2D hydrodynamic model, MIKE FLOOD was used to simulate the flood inundation extent and flooding depth in the delta region of Mahanadi River basin in India. Initially, the 1D model MIKE 11 was calibrated using river water level and discharge data of various gauging sites for the monsoon period (June to October) of the year 2002. Subsequently, the calibrated set up was validated using both discharge and water level data for the same period of the year 2001. The performance of calibration and validation results of MIKE 11 were evaluated using different performance indices. A bathymetry of the study area with a spatial resolution of 90m was prepared from SRTM DEM and provided as an input to the 2D model, MIKE 21. MIKE 11 and MIKE 21 models were then coupled using lateral links to form the MIKE FLOOD model set up for simulating the two dimensional flood inundations in the study area. Flood inundation is simulated for the year 2001 and the maximum flood inundation extent simulated by the model was compared with the corresponding actual inundated area obtained from IRS-1D WiFS image.

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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. For the management of floods, two types of measures, i.e., structural and non-structural may be adopted. The structural measures such as embankments, levees, spurs, etc., have not proved to be quite effective in the long run. Recently, the practice of non-structural measures such as flood risk zoning and flood forecasting are more in vogue (NNRMS, 2000). For the development of flood hazard and risk zone maps, it is essential to simulate the flood inundation in the floodplains caused by floods of different magnitudes.

In the past few years, various researchers have used the hydrodynamic modeling approach to simulate flood inundation in the floodplains (Werner, 2004; Bates *et al.*, 2005). Various numerical models have been developed for floodplain delineation/flood inundation and flow simulation which may be used as tools to delineate the floodplain zones bordering the rivers and calculate the associated risk considering hypothetical floods of various return periods. These numerical models are categorized into (a) one-dimensional (1D) models, (b) two-dimensional (2D) models, and (c) one-dimensional river flow models coupled with two-dimensional floodplain flow (1D-2D) models.

Various software, like MIKE 11 developed at the Danish Hydraulic Institute, Denmark (DHI, 1997), SOBEK-1D developed at the Delft Hydraulics, Delft (Werner, 2001) etc. have been used extensively for dynamic 1D flow simulation in rivers. The 1D models, though simple to use and provide information on bulk flow characteristics, fails to provide detailed information regarding the flow field. Hence, attempts have been made to model the 2D nature of flood-plain flow using different software like MIKE 21, DELFT-FLS and DELFT-3D. The 1D models fail to provide information on the flow field while the 2D models require substantial computer time; hence, attempts have been made to couple 1D river flow models with 2D floodplain flow models. The coupled 1D-2D models offer great advantage for real-time simulations of flooding events. Verwey (2001) and Dhondia and Stelling (2002) describe the 1D-2D model SOBEK (Rural/Urban) developed by the laboratory at Delft Hydraulics. Also, MIKE 21 has been dynamically linked to the MIKE 11 model, into a single package called MIKE FLOOD developed at the Danish Hydraulic Institute (Kjelds and Rungo, 2002; Rungo and Olesen, 2003).

In this paper, MIKE FLOOD is used to simulate the flood inundation for the delta region of Mahanadi River basin in India. Initially, the MIKE 11 model was calibrated and validated for the rivers of delta region of Mahanadi River basin and subsequently, the flood inundation was simulated using MIKE FLOOD. The model simulated flood inundation is validated using remote sensing data.

Materials and methods

Study area

Delta region of Mahanadi River basin in India forms study area (Fig. 1). It is located in the north-eastern part of coastal Orissa in India and lies between the longitudes 85° 30' E and 86° 52' E and the latitudes 19° 40' N and 20° 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. In the last five years, four severe floods have occurred in this region. 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. The flooding problem is more severe in the rivers Devi, Kushabhadra and in the downstream end of the main course of the Mahanadi River as compared to others. The catchment area upstream of the delta receives heavy rainfall during the monsoon period as a result of which all the rivers in the delta flow full and flooding occurs.

Data used

The data used in this study are the time series of daily discharge and water level of different gauging stations for the years 2001 and 2002 (Fig. 1), hourly and daily rainfall of different rain gauge stations (Fig. 1), river cross sections at different locations, topographical map and published data related to floods in the study area from different sources. At the Munduli gauging site which forms the upstream boundary of the model setup, a 3-hourly discharge data were used. These data were obtained from Central Water Commission (CWC), State Surface Water Data Centre (SSWDC) and State Water Resources Department (SWRD), Bhubaneswar. Hourly and daily rainfall data were collected from India Meteorological Department (IMD), Bhubaneswar. The river cross-sections available at different sections of the river reaches were used. Survey of India (SOI) Topomaps (73l and 73h at the

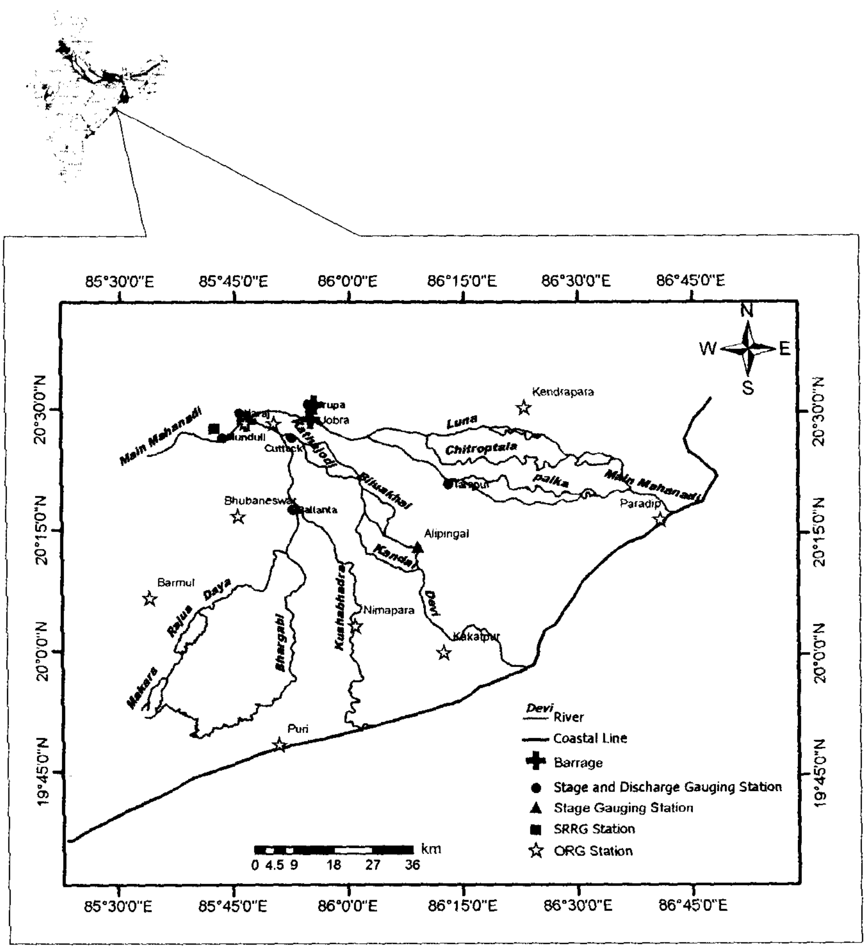

Fig. 1 Index map of the delta region of Mahanadi River basin in India.

scale 1:2,50,000) were procured from SOI, Kolkata for preparation of base map. The maps of the embankment details with elevation data at every 500 m for the entire Mahanadi delta region were obtained from SWRD. The SRTM DEM of the study area is downloaded from the website (www.csi.cgiar.org). Remote sensing data of IRS-1D WiFS pertaining to 31st July, 2001 was procured from National Remote Sensing Centre (NRSC), Hyderabad for the validation of the simulated flood inundation extent obtained from MIKE FLOOD.

Methodology

The MIKE 11 model setup was prepared to represent the entire river system in the delta region. There are seven open boundaries. All boundaries are provided with constant water levels except at two points i.e. the upstream boundary at Munduli where 3-hourly discharge data are provided and the boundary at the downstream of Birupa barrage on the river Birupa where downstream boundary is given as daily outflow time series data. As very few measured river cross sections are available, SRTM DEM extracted cross-sections were used along with the measured ones. The details of the procedure used to extract and refine the cross-sections used in the model are discussed in Patro *et al.* (in press).

The MIKE 11 model was calibrated for the year 2002 and validated for the year 2001. Initially, during calibration the Manning's n values are taken from literature (Chow, 1959) which is then modified subsequently. The model performance was assessed using different performance indices like coefficient of determination (R^2), index of agreement (d), deviation in peak (Dev.) and percentage deviation in peak (% Dev.).

The calibrated MIKE 11 model was coupled with the bathymetry of MIKE 21 model through lateral links for flood inundation simulation using MIKE FLOOD for the monsoon period of the year 2001. The MIKE 21 model contains information regarding the elevations of the floodplain, rainfall at different locations and the Manning's n values for the floodplain. An average value of Manning's n equal to 0.05 was used for the floodplain as per the land features obtained from the landuse map (Chow, 1959). The MIKE FLOOD model set up for the year 2001 is calibrated by comparing the model simulated maximum inundated extent with the actual inundation extent obtained from remote sensing data of IRS-1D WiFS.

Results and discussions

Calibration of MIKE 11 model

The MIKE 11 model was calibrated using data for the period 15th June to 15th October, 2002. During the process of calibration, the local and global values of Manning's n were adjusted to bridge the gap between the observed and simulated water levels as well as discharges at the gauging stations. The calibrated Manning's n values are given in Table 1. The performance indices for different discharge and water level gauging sites are presented in Tables 2 and 3, respectively. Tables 2 and 3 show that the d values vary from 0.92 to 0.98 while the R^2 values vary from 0.86 to 0.95 except at Tarapur where the values are 0.77 and 0.57, respectively. The % Dev. in peak values are less than around 7. These suggest that the model performs reasonably well during calibration.

Figures 2 and 3 show the comparison of observed and simulated discharges and water levels, respectively at the four gauging sites Balianta, Naraj, Cuttack and Tarapur. It is observed from Fig. 2 that there is a reasonably good agreement between the observed and simulated discharges at Naraj and Balianta gauging sites whereas at stations Cuttack and Tarapur there is close agreement of peak values while there are differences during low flow period. At Cuttack during low flow period simulated

Table 1 Calibrated Manning's n for MIKE 11 set up during calibration for the year 2002

Manning's n values	Rivers and their chainages (m) in the Delta Region of Mahanadi river basin				
	Daya (0.0-56042.0)	Devi (22427.0-89376.3)	Kandal (0.0-21402.9)	Biluakhai (0.0-12696.3)	Main Mahanadi (27720.0-115935.8)
Local n values	0.045	0.043	0.039	0.040	0.037
Global n values			0.050		

Table 2 Performance indices for different discharge gauging stations during calibration for the year 2002

Performance indices	Name of the discharge gauging stations			
	Balianta	Cuttack	Naraj	Tarapur
R^2	0.93	0.92	0.95	0.86
d	0.98	0.93	0.97	0.92
Dev. in peak (m^3/s)	67.68	191.09	-651.37	-41
% Dev. in peak (%)	6.65	2.5	-3.92	-2.17

Table 3 Performance indices for different water level gauging stations during calibration for the year 2002

Performance indices	Name of the water level gauging stations			
	Balianta	Cuttack	Naraj	Tarapur
R^2	0.91	0.88	0.89	0.57
d	0.97	0.95	0.95	0.77
Dev. in peak (m)	0.05	-0.22	0.01	-0.1
% Dev. in peak (%)	0.30	-1.06	0.04	-1.16

discharge values are higher than the observed ones which may be due to the presence of a barrage at Naraj which is not considered in the present study. Currently, most of the barrage gates are not operational and for some of the gates which are operational the data are not available. Hence, these structures are not considered in this study. The lower observed discharge at Cuttack gauging station may be due to the storage upstream of Naraj barrage during the start of monsoon period or just after a prolonged low flow period. But due to the absence of the barrage in the model setup, the supposedly stored water upstream of Naraj adds to the discharge values of Cuttack station, thus increasing the simulated discharges. But during severe floods the gates are fully raised presenting a condition of natural river flow as if there is no barrage and this results in good model performance during peak flows. On the other hand at Tarapur though there is a close agreement between the observed and simulated peak discharge values, however, during low flow the simulated values are higher. Due to unavailability of discharge distribution data as well as limited number of water level and discharge gauging stations in the region, it was not possible to ascertain the reasons for the discrepancies. Figure 3 shows that there is a very close agreement of observed and simulated water levels at Naraj, Balianta and Cuttack whereas there are differences between the observed and simulated values at Tarapur which may be because of the use of SRTM derived cross-sections at several locations. However, at all the gauging stations the peak discharge and the water level are preserved which is critical in flood modeling studies.

Validation of MIKE 11 model

The MIKE FLOOD model was used to simulate the flood inundation for the monsoon period of the year 2001 using the calibrated MIKE 11 coupled with the MIKE 21 setup. The simulated flood inundation

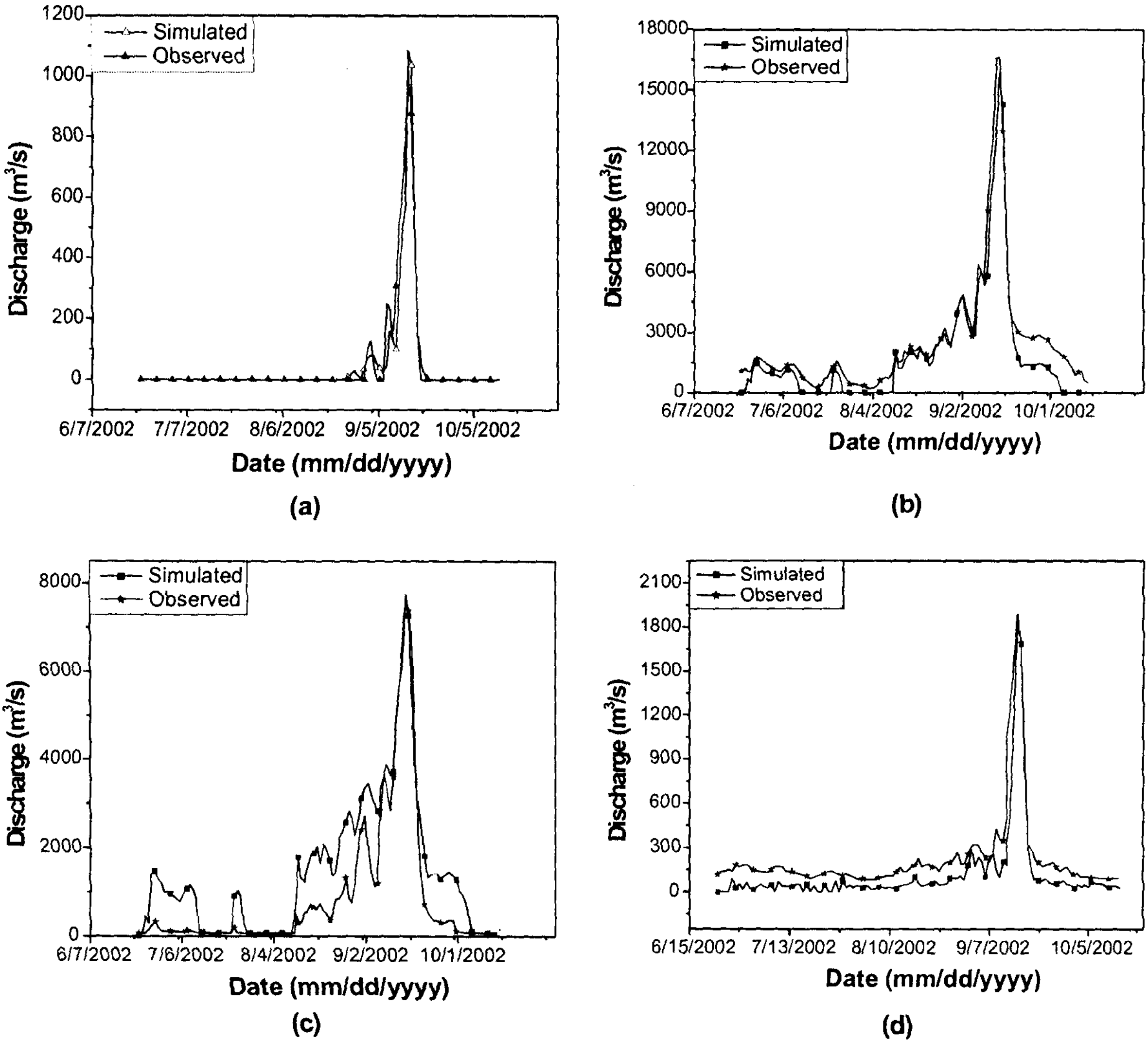

Fig. 2 Comparison of observed and simulated discharges at (a) Balianta, (b) Naraj, (c) Cuttack and (d) Tarapur during calibration for the year 2002.

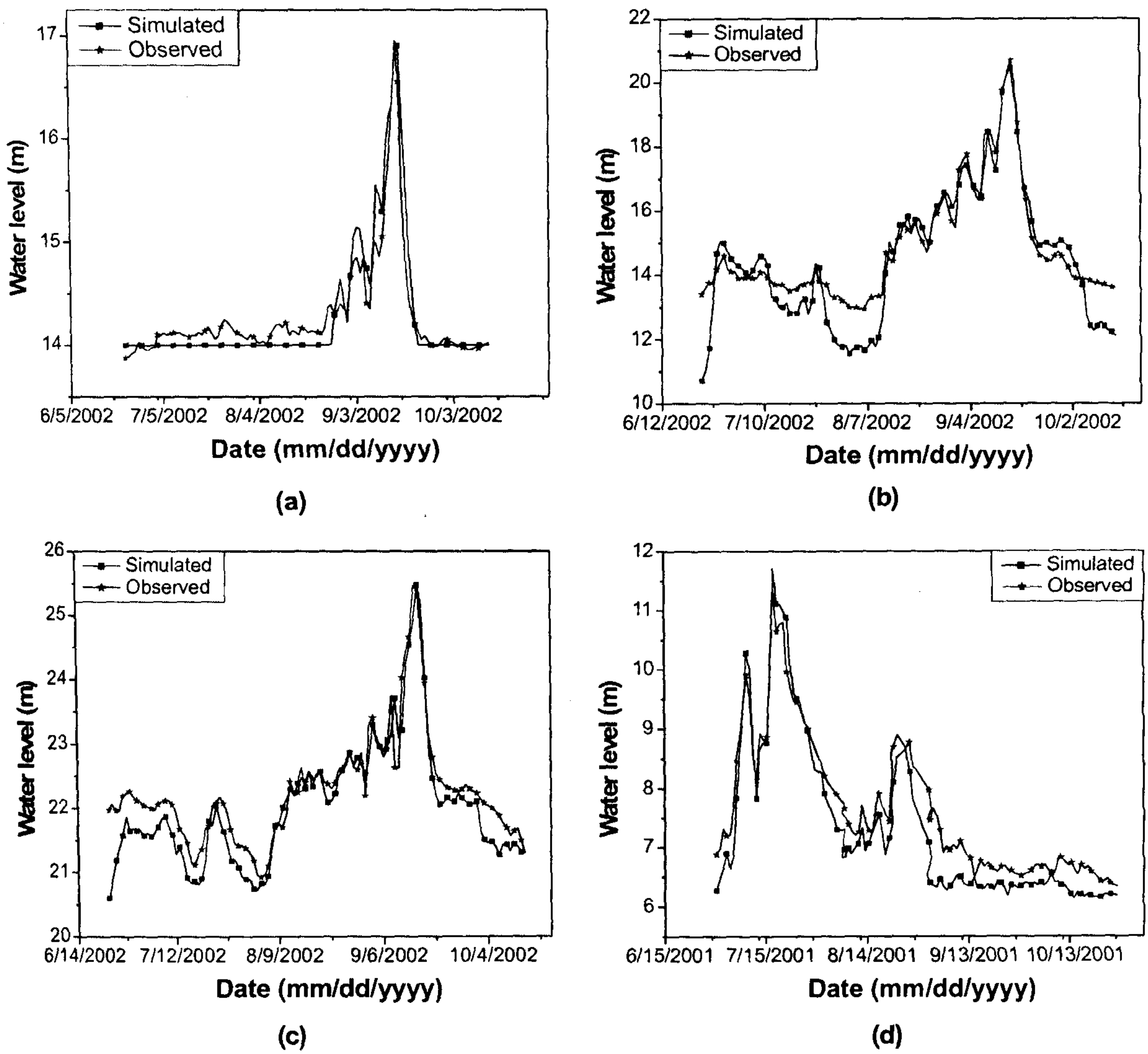

Fig. 3 Comparison of observed and simulated water levels at (a) Balianta, (b) Cuttack, (c) Naraj and (d) Tarapur during calibration for the year 2002.

extent obtained from MIKE FLOOD was compared with the actual flood inundation obtained from remote sensing data.

The calibrated setup of MIKE 11 is validated for the monsoon period of the year 2001. The performance indices for the discharge and water level gauging sites are presented in Tables 4 and 5, respectively. It is observed from these tables that the d values vary from 0.95 to 0.99 while the R^2 values vary from 0.94 to 0.99 except at Alipingal where the values are 0.88 and 0.64, respectively. The % Dev in peak values are less than around 7 except at Cuttack where the peak discharge deviation is around 14. This shows that the calibrated model performs reasonably well during validation. Figures 4 and 5 show the comparison of observed and simulated discharges and water level, respectively at different gauging stations. It is observed from these figures that there is a reasonably good agreement between the observed and simulated discharges as well as water levels at all the gauging sites particularly during peak flows.

this time flood inundation spreads towards the tail end of Bhargabi, Daya, Devi, Kushabhadra and Makara rivers. The severely affected districts are Kendrapara, Puri, Jagatsinghpur and Cuttack.

Comparison of simulated inundation extent with Remote sensing data

The WiFS image of IRS-1D dated 31st July 2001 was

Table 4 Performance indices for different discharge gauging stations during validation for the year 2001

Performance indices	Name of the discharge gauging stations			
	Balianta	Cuttack	Naraj	Tarapur
R^2	0.98	0.97	0.99	0.94
d	0.99	0.99	0.99	0.98
Dev. in peak (m^3/s)	-314.38	-2545.13	238.3	5.11
% Dev. in peak (%)	-6.91	-13.52	0.62	0.07

Table 5 Performance indices for different water level gauging stations during validation for the year 2001

Performance indices	Name of the water level gauging stations			
	Balianta	Cuttack	Naraj	Tarapur
R^2	0.95	0.96	0.95	0.64
d	0.95	0.98	0.96	0.88
Dev. in peak (m)	-0.80	0.82	0.36	0.12
% Dev. in peak (%)	-3.87	2.94	3.17	0.93

Flood inundation simulation using MIKE FLOOD

The flood inundation is simulated using MIKE FLOOD for the monsoon period of the year 2001 using an average value of Manning's n equal to 0.05 for the floodplains as stated earlier. The model simulation shows that flooding starts from 8th July with an areal extent of 212.71 km^2 and the areal extent was maximum at 1206.09 km^2 on 23rd July. It is observed that the initiation of flooding in the delta is caused at the tail end of Chitrotpala - Mahanadi joining i.e. Dasmouza island area. High water levels are found near Marshaghai, Kendrapara. During

classified using unsupervised classification in ERDAS Imagine 8.5 to obtain the actual flood inundated area (Fig. 6). From the Fig. 6, it is seen that flooding occurs in the rivers Mahanadi, Chitroptala, Devi, Bhargabi and Khushabhadra. The classified WiFS image of 31st July 2001 was compared with the simulated flood inundated area of the same date obtained from MIKE FLOOD (Fig. 7). The flood inundated areas in the extreme north side shown in the WiFS classified image are in the Brahmani-Baitarani river system which is not considered in the present study. Also, the water spread area in the south-west corner of the image is not due to flood inundation but is in fact the Chilka lake. Thus, excluding these portions, the flood inundation extent obtained from the WiFS image is 1547.31 km^2 while the corresponding simulated flooding extent is 1162.88 km^2. The difference in the flood inundation extent may be due to the presence of a few escapes in the downstream areas of the rivers which have not been considered in the MIKE FLOOD model but causes flood inundation. However, it is seen that there is a close agreement between the model simulated flood inundation and the actual flood inundated area obtained from WiFS image in the downstream end of the Main Mahanadi river near the Dasmouza island. The flooding in this area

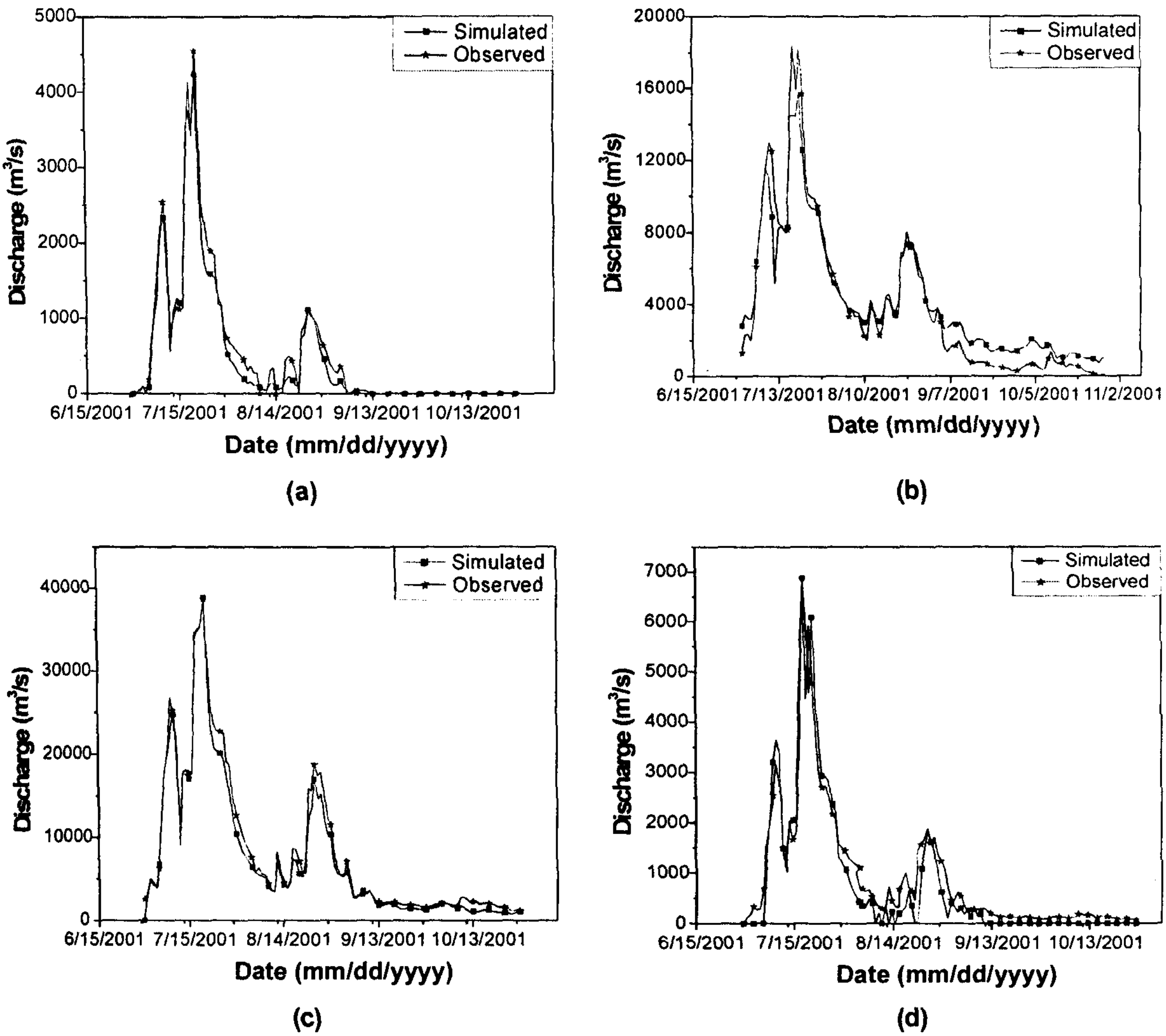

Fig. 4 Comparison of observed and simulated discharges at (a) Balianta, (b) Cuttack, (c) Naraj and (d) Tarapur during validation for the year 2001.

occurs due to the absence of a portion of the embankment as well as low lying topography. In this region, the simulated flood inundation extent is found to be 633.68 km^2 while the actual inundation obtained from WiFS image is 685 km^2 which shows a close agreement between the observed and simulated flood inundated areas. The depth of flooding varies from 0.5 to 5 m.

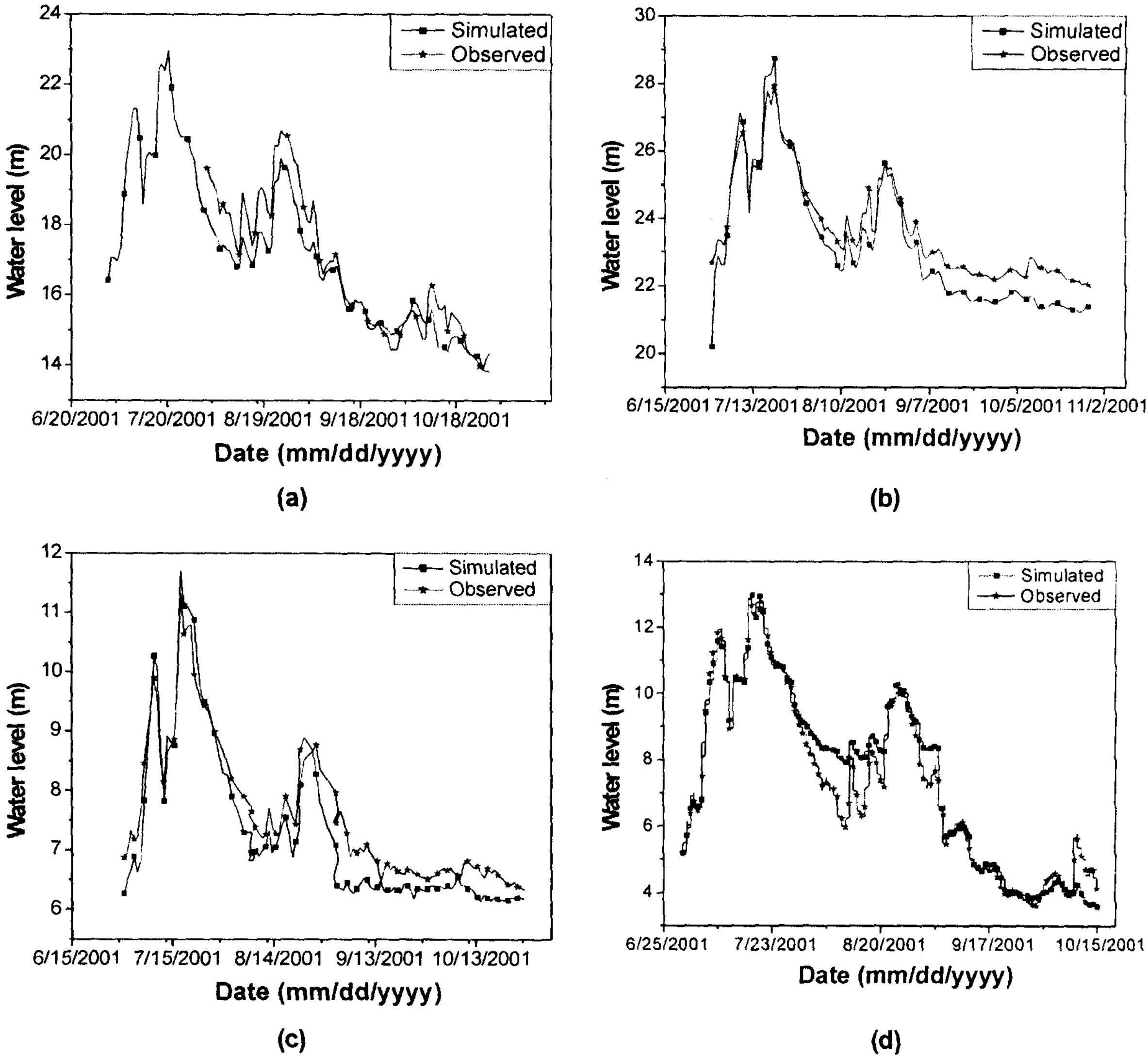

Fig. 5 Comparison of observed and simulated water levels at (a) Cuttack, (b) Naraj, (c) Tarapur and (d) Alipingal during validation for the year 2001.

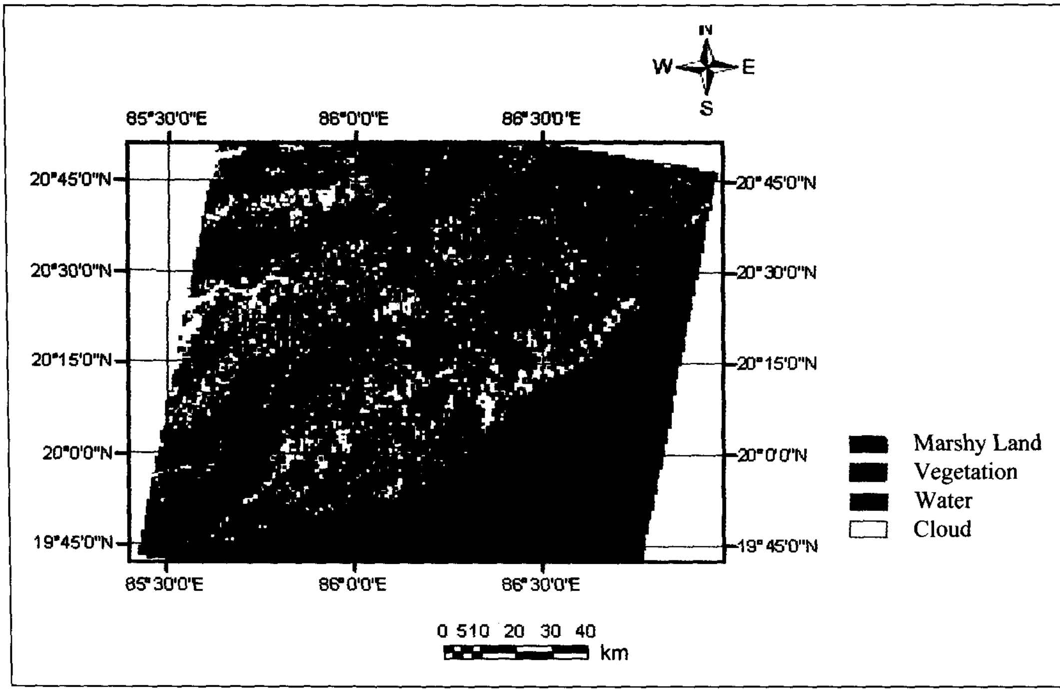

Fig. 6 Flood inundated area in unsupervised classified WiFS image of 31st July, 2001.

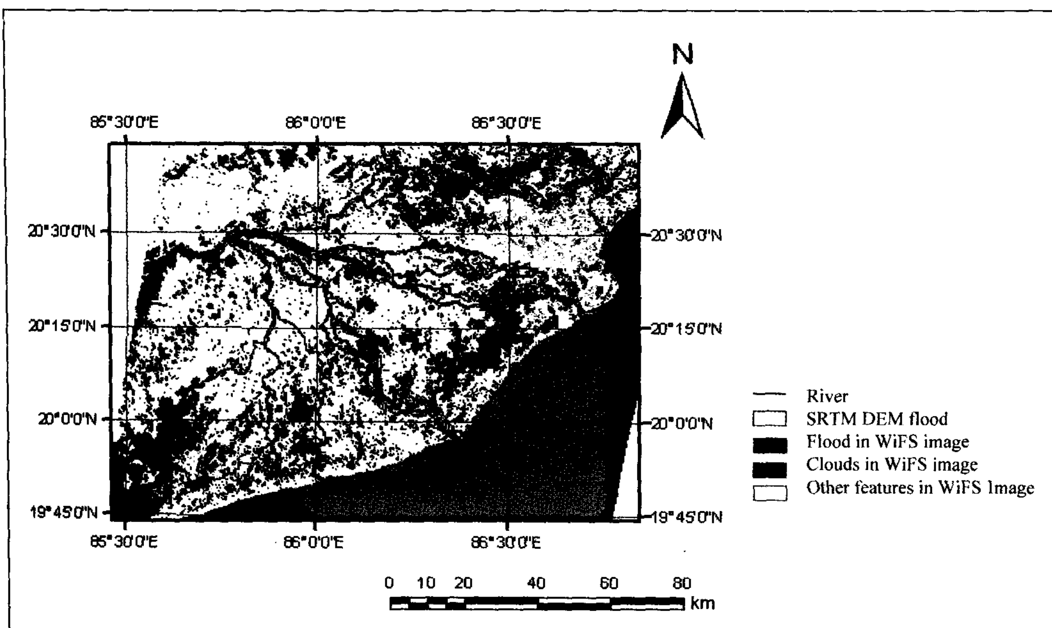

Fig. 7 Comparison of flood inundated areas obtained from MIKE FLOOD and WiFS data.

Conclusions

The present study aimed at calibrating and validating a coupled 1D-2D hydrodynamic model, MIKE FLOOD for simulating the flood inundation extent and flooding depth in the delta region of Mahanadi River basin in India. The calibration and validation results of MIKE 11 show that the model performs quite satisfactorily in simulating the river flow for the delta region of Mahanadi river basin. The calibrated local values of friction coefficients (n) range from 0.037-0.045 and the global value is found to be 0.05. The performance of the coupled 1D-2D hydrodynamic model, MIKE FLOOD in simulating the flood inundation extent was also found to be satisfactory. The simulated flood inundation pattern using MIKE FLOOD is in reasonable agreement with the observed pattern of flood inundation obtained from the remote sensing imagery. The differences in model simulated water levels as well as the inundated areas may be attributed to the fact that in the present study the details of structures like barrages etc, their regulations, escapes in the downstream end of the rivers, road and railway networks and canal as well as drainage network were not considered. Incorporation of these elements is expected to improve the results. The calibrated and validated MIKE FLOOD model may be used to simulate the flood inundation extent and flooding depth in the floodplains caused by floods of different magnitudes in the delta region of the Mahanadi River basin for development of flood hazard and risk zone maps.

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