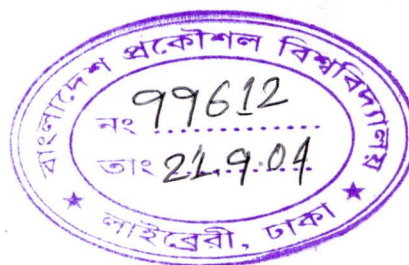


HYDRODYNAMIC SIMULATION OF THE RIVER JAMUNA

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August 2004



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HYDRODYNAMIC SIMULATION OF THE RIVER JAMUNA

A thesis submitted by

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In partial fulfillment of the requirements for the degree
of
Master of Science in Engineering (Water Resources)

**Department of Water Resources Engineering
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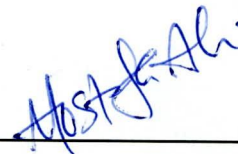
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CERTIFICATE OF RESEARCH

This is to certify that the thesis on "Hydrodynamic simulation of the river Jamuna" has been performed by Mohammad Mostafa Ali and neither this nor any part thereof has been submitted elsewhere for the award of any other degree or diploma.



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Countersigned by the Supervisor



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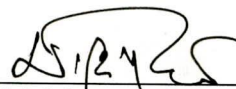
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ABSTRACT

This research deals with the morphological analysis of Jamuna river using finite element method. RMA2, a hydrodynamic model and SED2D, a sediment transport model, have been used to simulate the morphology of the Jamuna. Models have been applied using SMS (Surface-water Modeling System) environment, which gives the pre- and post- processing options for input and output data.

The finite element mesh has been developed using LANDSAT image of the 17th November 2000. Initial bed elevations for the nodes of the mesh have been composed from the scattered survey data of April 2001 by BIWTA. Once the mesh and bathymetry have been obtained, the models are ready thereby to incorporate boundary conditions, initial conditions and material properties.

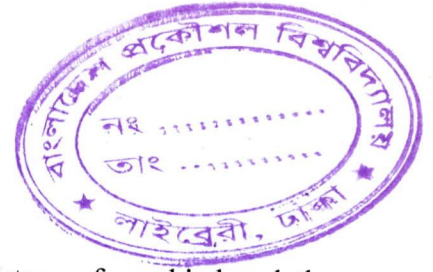
The hydrodynamic model developed in this study has been satisfactorily calibrated and validated against the observed water surface elevations at Aricha for 2001 and 2002, respectively. Sediment model has also been calibrated using measured bathymetry by BIWTA with the simulated bathymetry of 23rd August 2001. The model has been validated with the measured bathymetry of November 2002 and November 2003. Sediment rates at Baruria have been generated from the SED2D model and compared with the FAP-24 data (FAP, 1996).

Results reveal that erosion takes place in the outer bend of the meandering Eastern anabranh. In Western anabranh, severe deposition has been observed near the confluence due to backwater effect of Jamuna-Ganges flow. Velocity reduction in the confluence significantly diminishes their sediment transport capacity, and hence inducing deposition. Three morphological years have shown much similar type of erosion/deposition patterns, which occur mainly in August and September of each year. An investigation, using surveyed bathymetries from 1996 to 2003, shows that the 1998 flood initiates drastic changes in its Western anabranh near Nagarbari, which indeed may have an impact on the shifting of flow more towards left bank at Naradaha. These observations of measured data are further substantiated by the results obtained from the present simulation models.

To find a suitable location for ferry ghat and also for a sustainable navigable channel, three options have been investigated. Existence of a deep pocket near Naradaha motivates this study to take those options and among them Option 2, which is a dredging option in the upstream channel connecting upper segment of the deep pocket, has appear to show very little deposition compared to other options. Thus the option in question presents a prospective alternative for developing a sustainable ferry route.

Chapter 1

Introduction



1.1 General

Rivers play an important role in molding the history of mankind and the environment around them. These rivers sustain life by providing adequate supply of water for drinking, washing, agriculture, navigation and all other necessary purposes. But due to frequent changes in the alluvial rivers of Bangladesh, fortune always does not favor living close to the river banks. The rivers often cut the banks and gradually engulf the houses, trees and agricultural lands by devouring large areas. On the contrary, due to deposition, the navigational routes are to be readjusted often with new courses. The change of course of the river not only poses problems to lives, but also in the country to seek redress the behavior of these alluvial rivers, is of immense importance to be understood.

The alluvial rivers are considered as natural channel in which bed and bank material consists of sediment deposited by streams. Thus alluvial rivers are the products of processes produced by the interaction between flowing water and moving sediment. The channel flows generally characterize themselves as either meandering or braided. Before becoming stable, the channels undergo various dynamic actions like variation in flow rate and thereby causing erosion/deposition which changes the slope gradient, cross-section and ultimate plan-form. The rivers, at their origin usually in high mountain regions, have high gradients and scour down the bed to keep them narrow in width. But in the plains, as they reach down the stream, they find ample scope to widen their flow widths because of formation of bars and thus become braided in nature. Meandering bends are also noticeable.

Certain problems arise when they pass through alluvial plains. The rivers in alluvial plains carry sediment loads of various types from upper reaches. This load is augmented by the local addition of sediment from scouring bed and banks. The surface run-off even adds some more sediment into the channel discharge. The discharge also varies from season to season and year to year, the highest being even higher than 100,000 cumecs and the lowest being around 2500 cumecs for Jamuna river (Thorne et al., 1993). This varying discharge contributes largely towards erosion and deposition. The erosional activities devour banks, create scour holes and change

the ultimate plan-form of the channel and thus add more sediment to it. The depositional activities include creation of bars in the channel, which ultimately influence the flow directions within the channel and thus force plan-form to change further. A braiding nature channel then evolves. Braided rivers pose engineering problems in bridges, harbors, roads and railway constructions and protection of bank lines etc. So it is needed to understand the physical processes of erosion and deposition in braided channel.

Jamuna is one of the greatest rivers in the world ranking fifth in terms of discharge (mean flow 20,000 cumecs) and eleventh in terms of drainage area (666,000 sq. km), is happened to be a braided alluvial river (Thorne et al. 1993). The peak flows during late July or early August cause over-bank spilling. These prevailing circumstances cause erosion either at banks or in the bars and a depositional activity in the channel. Bifurcation of channels and meander growths are the natural fluvial phenomena occurring in the channel. However, development of large bars and deposition in main navigational channels are posing major problems.

Different aspects of the morphological behavior of the Jamuna river were studied by a large number of researchers over the past decades: Coleman (1969), Bristow (1987), Alam and Hossain (1988), Klaassen et al. (1988), Klaassen and Vermeer (1988a, 1988b, 1988c), Hossain (1992), Thorne et al. (1993), Mosselman (1994), Hoque (1999), BIWTA (2003) etc.

Most of the previous studies are based on field studies, analytical studies, application of remote sensing/GIS and application of finite difference models. This research deals with the morphological analysis of Jamuna river using finite element method. The basic concept of the finite element method is that any continuum can be approximated by a discrete model composed of a set of piecewise smooth functions named basis functions, which are defined over a finite number of sub-domain called element. Element-wise integration gives a series of linear algebraic equations, from which unknowns are solved. It differs from the finite difference method as these elements can vary widely in size and shape easily, it can accommodate both triangular and rectangular elements and it can easily represent any complex geometry. Refinement of mesh at specific location and dynamic placing of grid are other special features of finite element method. Also many researchers showed that (e.g., Price et al., 1968; Thacker, 1978a), finite element method requires fewer nodes and lesser computational time compared to the finite difference method for one-dimensional

problem. It can be stated that finite element method is ideally suited for modeling two-dimensional flow over a complex topography. In this study RMA2 and SED2D programs under SMS environment, which are finite element programs for hydrodynamic and sediment transport respectively, are used to simulate the flow field and morphology of the river Jamuna. In this study morphological processes of Jamuna river has been examined and also effects of some engineering interventions are scrutinized using SMS.

SMS (Surface-water Modeling System), which gives options for pre- and post- processing of input and output data, has been used to generate model mesh, bathymetry, boundary conditions and other parameters in a common environment. SMS gives various tools to minimize errors for the creation of mesh. Basic data files required to run RMA2 and SED2D are developed using SMS environment. Binary solution files can be easily observed using post-processing tools provided in SMS. These tools are very helpful for interpreting the results.

1.2 Scope and importance of mathematical modeling

It is not practical, nor possible to measure all river processes continuously and simultaneously. Field data represents the physical reality of the existing processes in the river. But whatever the detail and frequency of surveys, the representation will always be discrete in space and time, especially during the monsoon period when the rate of change of bed level is high, the bathymetry in general is not expected to be in equilibrium with local flow conditions. In this case measurements of sediment concentrations at certain location would depend on local flow conditions, but also on conditions upstream and on the flow history. Field surveys with the purpose of understanding the processes would then include very large amount of information. Collection and analysis of data would be a very costly and time-consuming task. In that respect mathematical modeling is an alternative tool to understand the detail physical processes in nature.

Mathematical modeling has been introduced as a tool to interpret the information provided by the field data in an integrated way. The mathematical model enables interpolation and extrapolation in space and time based on the observations from the field and on the understanding of the physical processes and their interaction to the extent that this has been incorporated in the model. The mathematical model further makes it possible to take into account conditions of non-equilibrium. As

mathematical models have their limitations, they cannot stand alone. Results should be assessed critically against field/laboratory data to assure that misleading conclusions are not drawn from a poorly designed and calibrated mathematical model.

The RMA2 and SED2D finite element models that developed by U.S. Army Corps of Engineers have been applied to model depth-averaged two-dimensional flow conditions, sediment transport and morphological developments in the river Jamuna.

1.3 Objectives of the study

The key features, to which this study limits itself, are as follows:

- Water surface elevation and depth variation with a flood hydrograph.
- Sediment concentration variation with time.
- Erosion or deposition of bed material and possible locations
- Erosion or deposition in bank and possible locations.
- Bed level changes with time.

The main outcome of the present study is to improve the understanding of the river processes with the aid of finite element model. The model will be calibrated using computed values with the observed values from the field. The following processes will be simulated after several runs using two or more years of consecutive hydrographs:

- To identify the channels, which are vulnerable for navigational purposes during the low flow season.
- Erosion or deposition in main channels during monsoon season.
- Possible bed level changes in main channels due to erosion or deposition.
- Possible measures to find a sustainable navigable channel.
- To find a sustainable location for construction of ferry ghat.

1.4 Organization of the report

The first chapter of the study gives a brief presentation of the morphological processes of the braided rivers. It emphasizes the need of mathematical tools for analyzing the phenomenon. It also includes the objectives of the present study.

The second chapter gives a short account of previous studies and literature available in the domain in question. Numerical methods: finite difference and finite element methods are also illustrated with their merits and demerits.

The third chapter describes SMS (Surface-water Modeling System) in details. Different pre- and post- processing tools associated with different models: GFGEN, RMA2 and SED2D are also explained here.

The fourth chapter comprises a brief description of the models developed under this study. The logical development of steady, unsteady and sediment transport models have been presented. The calibration and validation processes using different parameters are shown at the end of this chapter.

The fifth chapter presents the results of the model and its application to the engineering interventions.

Finally the study comes to its last episode in chapter six by drawing conclusions and recommendations for the future study.

Chapter 2

Literature Review

2.1 General

Various previous studies have been reviewed under this chapter. The governing equations describing two-dimensional surface water flow in the horizontal x-y plane are presented here for ready reference. Two common methods, finite difference method (FDM) and finite element method (FEM), to solve the governing equations are described with their relative merits and demerits. Previous studies on the river Jamuna using mathematical model, and physical model, in Bangladesh as well as outside Bangladesh, are described in this chapter. A review of characteristics of Jamuna river by different researchers are also presented here.

2.2 Characteristics of Jamuna/Brahmaputra river

Flowing on an easterly course through the Assam valley, with the Himalayan range to the north and the Meghalaya mountains to the south, the Brahmaputra river turns south at the Indian township of Dhuburi and crosses the border in Nunkhawa to enter the flood plains of Bangladesh. The mainstream today flows all the way south till the confluence with the Ganges river some 240 km from where it crossed the border. However after 80 km, at Bahadurabad the river changes its name into Jamuna. The distributory at that location is now called 'Old Brahmaputra', but it used to be the main river until a major shift took place and the Jamuna became the main stream.

All along its course, the land is cultivated by a population principally living in numerous small villages and settlements, which are scattered along the banks. Only a few townships are located immediately on the riverbank. Most of the cities are found in a distance of 30 to 50 km from the riverbank like Rangpur and Bogra to the west and Jamalpur to the east. Furthermore it is estimated that 300,000 persons are living on the more or less permanent islands or chars in the river.

The discharge is principally fed from snowmelt of the Himalayas. But in the wet season the rainfall in Assam contributes significantly to the discharge. Tributaries are found on the west bank only. A major tributary is the Teesta river which flows in south-east direction over a distance of 250 km from the Himalayas range to its confluence with Jamuna, just south of the border with India. Smaller tributaries are there like Dudkumar and Dharla rivers. The other purely rain-fed tributaries on the

west bank are Bangali river, Ghagat river (Manos regulator), Hurasagar river, Karatoya and Gohala river (Baral river). The distributaries like Old Brahmaputra and Daleshwari rivers are on the east bank.

The Jamuna is an alluvial and non-tidal river with a slope of 8 to 6 cm/km and an annual average discharge of 20,000 m³/s, was recorded in 1988. The usual average peak discharge is in the order of 55,000 m³/s, with a minimum of 43,100 m³/s, and peaks of 100,000 m³/s in 1998-1999 (Fig.2.1). The dominant discharge for the Jamuna at Bahadurabad was found to vary between 36,000 m³/s and 38,500 m³/s. An average value of dominant discharge for the Jamuna may be taken to be 38,000 m³/s (Hossain,1992). The difference between the highest and the lowest water level in one year may amount to 6 m to 8 m between Nunkhawa and Aricha.

The width of the river between the banks ranges between 6 km and 18 km. The wider sections have large islands or chars. They are flooded during the peak of the flood when also a part of the discharge is spilled in the floodplain. The hydrographs in subsequent years vary in peak discharge level but the level changes are more or less identical for the various periods characterized as follows:

November - February	gradually falling levels
February till mid-March	minimum levels, hardly changing
March	some rise of levels
April - June	rapidly rising levels
Early July till mid-October	maximum levels, changes up and down.

A typical hydrograph of yearly flow variation is shown in Fig. 2.2.

With decreasing discharge, starting around September and reaching its lowest in January, the permanent islands, the chars, fall dry again and gradually also the surrounding sandbanks and flat plain.

Current velocities during flood are measured with an average of 2 m/s in the northern part and 1.75 m/s in the southern part, but maximum velocities up to 4 m/s have been reported in some locations. During low water the current velocities decrease to 1.5 to 1.0 m/s.

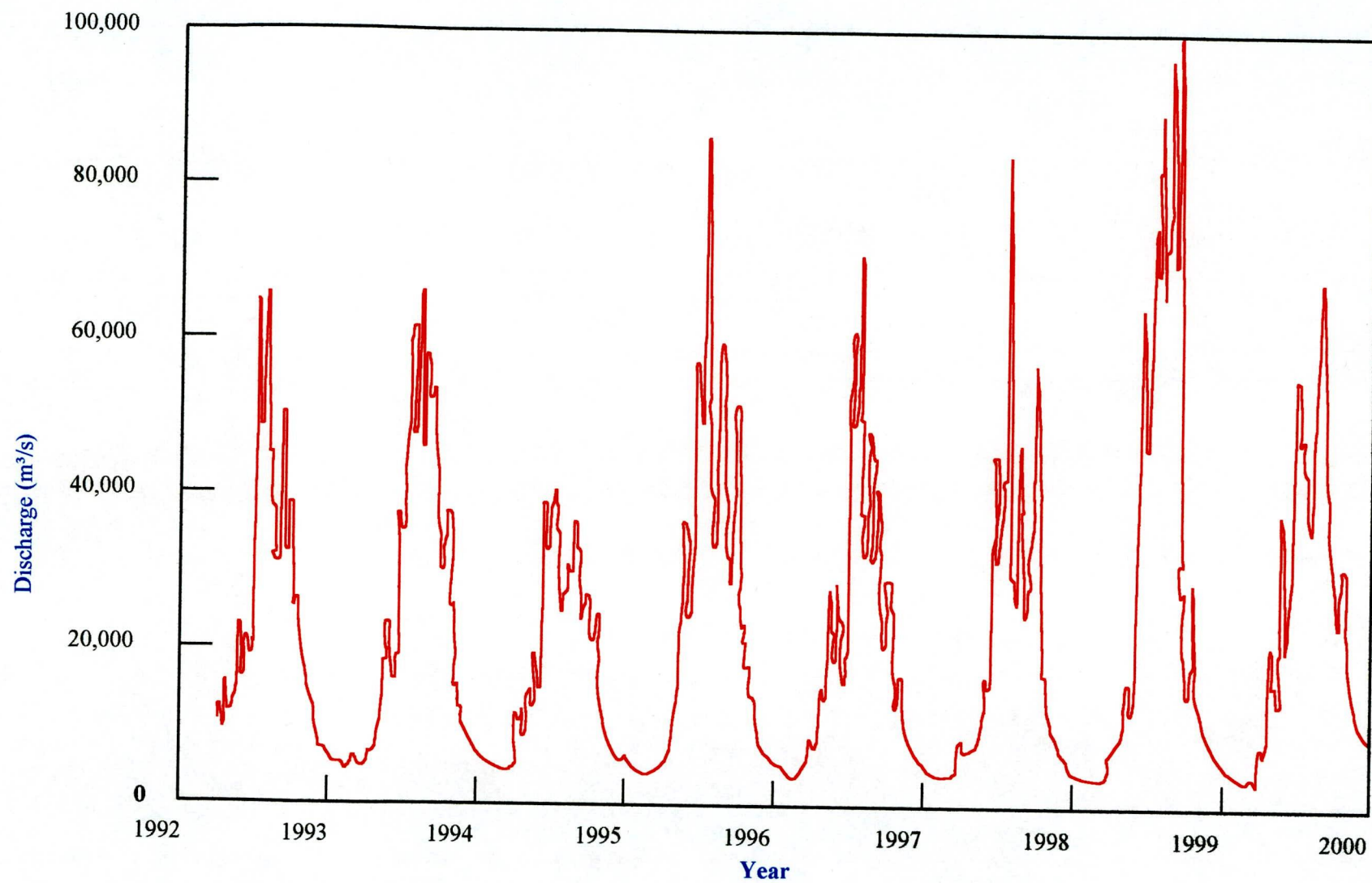


Fig. 2.1: Annual discharge through the Jamuna River

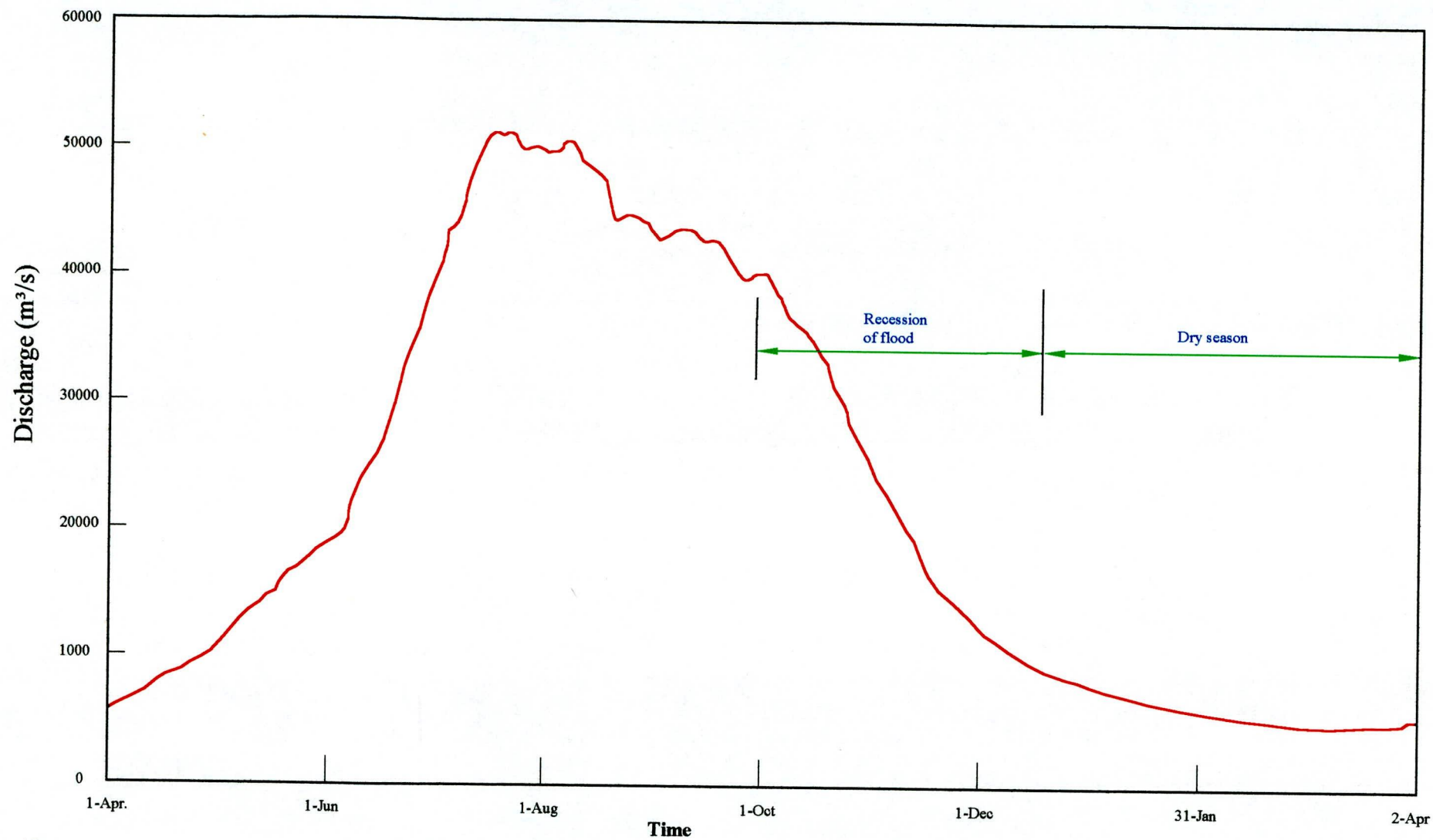


Fig. 2.2 Typical discharge hydrograph of the Jamuan river at Bahadurabad

Bank erosion is more serious than flooding. The rate of erosion reaches such a level that whole settlements are swept away and many square kilometers of farmland with roads and embankments disappear. Although bank erosion always was in the history of the river it seems that currently the main attack is concentrated on the west bank, thus causing the river gradually to shift westward.

A result of increased erosion is that traditionally navigable branches are suddenly closed whereas others have opened up; the landing places and their infrastructure disappear or become inaccessible. When erosion is normal, shifting of the navigable route is a constant threat to port facilities. The braided channels shift frequently, sometimes within a day, and during that process the least available depth may be reduced considerably.

The minimum depth required for the navigable channel all along the Jamuna is reported to be 1.8 m (6.0'). With 0.5 m (1.5') keel clearance, the depth of water required for ferry operation is 2.3 m. But due to emerge of shoals haphazardly, this minimum draft is very often not available.

Among the available literatures the pioneering work on the Jamuna river was by Coleman (1969) on the scientific investigation of river morphology in Bangladesh. Later a large number of publications (Bristow, 1987; Klaassen and Vermeer, 1988a, 1988b; Klaassen et al., 1988; Klaassen and Masselink, 1992; Thorne and Russel, 1993 etc.) were made and those are mainly related to the different studies on the Jamuna related to the river engineering works (bridge, floodplain management, bank protection) or flood protection. In the following paragraphs the various morphological aspects of the Jamuna river by the available literature and studies are discussed.

Based on Lacey's (1930) regime relation on channel dimensions, Klaassen and Vermeer (1988) found the following relations for second order channels in the Jamuna river:

$$h = 0.23Q^{0.32} \quad (2.1)$$

$$B = 16.1Q^{0.53} \quad (2.2)$$

where Q = bankfull discharge (m^3/s), B bankfull width and h = the average depth at bankfull condition. The estimation of width and depth were made by using the BWDB standard cross-section, generally surveyed in the lean season.

Klaassen and Vermeer (1988), derived relations for at-a-station, considering different levels for different discharges and corresponding water surface widths and

average depths from BWDB measured cross-sections. The discharge in an individual channel was estimated as given for regime relations. The at-a-station relations (Klaassen and Vermeer, 1988) are as follows:

$$h = 0.56Q^{0.23} \quad (2.3)$$

$$B = 18.9Q^{0.51} \quad (2.4)$$

Due to the higher variability of flow condition in a natural river, the bed forms generally differ from the classification given by Simons and Richardson (1966) and van Rijn (1984). However, Coleman (1969) was the first who provided the data on the bed forms in the Jamuna river, which can be distinguished as follows:

Ripples	:	Typical height is 0.2 to 0.5 m.
Mega ripples	:	Typical height is 1 m and celerity is 120 m/day.
Dunes	:	Typical height is 5 m and celerity is 60 m/day.
Sand Waves	:	Typical height is 10 m and celerity is 200 m/day.

The study on bed form and bed roughness in the Jamuna river was also conducted by Klaassen et al. (1988a). The study was based on field data of bed form, historical discharge and cross-sectional data measured by BWDB. The occurrence and dimensions of bed forms were found directly from field investigation. The resistance to flow was estimated by the following two approaches. One was based on BWDB's discharge measurement, where Chezy's C was computed as follows:

$$C = \frac{Q}{B(h)^{\frac{3}{2}} i^{\frac{1}{2}}} \quad (2.5)$$

where Q = discharge (m^3/s), B = width (m), and h = water depth (m) are all measured data during discharge measurement, and i = water surface slope is being estimated.

The other approach was based on at-a-station relations for width and depth as a function of discharge derived by Klaassen and Vermeer (1988a) (Eqs. 2.3 and 2.4), for the Jamuna river and using the BWDB standard cross-section measurements. Using the coefficient and exponents of B and h , the Chezy's C was expressed as follows:

$$C = 0.126 \frac{Q^{0.14}}{i^{\frac{1}{2}}} \quad (2.6)$$

It has been found that in the Jamuna river fine fractions of sediment are dominating, i.e., approximately 66 percent of the total volume of transport. Most of the previous studies (Alam and Hossain, 1988; Hossain, 1992 etc.) estimated the total sediment transport (fine + coarse fraction) in the Jamuna river based on BWDB-measured data and related to the discharge of the river in a form, which is as follows:

$$S_t = aQ^b \quad (2.7)$$

where S_t is the total sediment (bed material) transport, Q is the discharge and 'a' and 'b' are the coefficient and exponent of the discharge respectively.

Alam and Hossain (1988) compared the total suspended sediment transport in the Jamuna river using different sediment transport predictors and found better agreement with the Hossain (1985) predictors. They considered the water surface width as the width of the river, and depth as flowarea÷width and velocity as the discharge÷flowarea.

Using BWDB 1968-70 sediment transport data in the Jamuna river, Klaassen and Vermeer (1988c) found a relation for total bed material transport as:

$$S_t = 4.5 \times 10^{-6} Q^{1.38} \quad (2.8)$$

where S_t = total bed material transport (m^3/s). Bed load transport is included here estimating from dune tracking as 10 percent of suspended bed material transport. Using at-a-station relations (Eqs. 2.3 and 2.4), they convert Engelund-Hansen equation for total bed material transport into:

$$S_T = \frac{0.01}{D_{50}} i^{3/2} \frac{Q^2}{Bh^{1/2}} \quad (2.9)$$

where the total bed material transport S_T in m^3/s is estimated. Extensive field investigation shows that D_{50} is 0.18 mm and i is 7×10^{-5} .

The riverbed erosion and deposition in the Jamuna River was first studied by Coleman (1969). He found that due to high sediment load the erosion-deposition in the riverbed is extremely high and the processes are very complicated. His study was mainly based on the shifting of the thalweg, which is always associated with erosion and deposition in the riverbed, by comparing cross-sectional profiles measured

several times in a year at a certain section of the river, and by comparing each cross-section measured in two successive lean seasons at different locations in the river.

Coleman (1969) found that the thalweg shifting during the flood discharge is very high (500 to 1000 m) and erratic. The scouring of bed is about 15 to 20 percent of the flood flow area during the rising limb of the flood. Although the erosion and deposition in a cross-section is quite high (5 to 8 m) within a year, no significant changes of the overall balance between erosion and deposition were observed.

The observation of Bristow (1987) from satellite images also suggested that the yearly volume of erosion and deposition in the Jamuna is the function of the high discharge and the duration of discharge. Bristow subdivided identified depositional areas from satellite images into four categories: addition to bars, lateral accretion to the bank, new mid channel bars and channel abandonment. Each types of deposition results into the other types of erosion, say for example abandonment of an old channel is the subsequent result of the formation of a new channel. Formation of a new medial bar results in the widening of a channel by bank or bar erosion.

Furthermore, different studies (Klaassen and Masselink, 1992; Klaassen and Vermeer, 1988) on the Jamuna River shows that the channel processes in the Jamuna are quite rapid and generally associated with erosion and deposition in the riverbed. In such a quickly responding river with comparatively low bed load transport, whose processes of sediment transport, i.e., the bed, near-bed or suspended load transport activate the changes of riverbed left a question to model morphological processes of the river. The abandonment of large channels and the developing of new channels in a few years only are common features in the Jamuna River. Klaassen and Masselink (1992) found that three types of processes are related to the channel shifting processes, viz., bar-induced shifting, development of cutoff and outer bend channels in bends. Among these, the development of the cutoff in the channel shifting process happens quit often in the Jamuna River.

Klaassen and van Zanten (1989) analytically studied the cutoff processes in meandering channels. Their study was based on the ratio of the sediment supply from the offtake into the cutoff channel and the sediment transport capacity of the channel. They found that the most important parameter is the *cutoff ratio* (X), which they defined as the ratio of the length of the channel and the length of the cutoff channel. Later study by Klaassen and Masselink (1992) based on the analysis of satellite images in the Jamuna River, found that for cutoff the ratio as they suggested is 1.25.

The cutoff ratio in the Jamuna river is very low in comparison to the meandering river, where the cutoff ratio of 5 to 30 is common, suggesting that cutoff occurs very quickly in the Jamuna river.

Coleman (1969) first studied the bank erosion rate of the Jamuna River by analyzing old maps and he identified the types of bank failure. Two types of bank failure generally occur in the Jamuna River: liquefaction and flowage of material, and shearing away of bank materials. The former type of bank failure can occur below the low water level or in the zone of low and high water level. Generally they occur during the receding of flood discharge. Receding rates of water level directly influence the rate of failure. The most common process of bank failure in the Jamuna river is due to shearing, caused by flow attacking the bank or over steepening the bank by a thalweg approaching the bank. However, the bank erosion and accretion rates provided by Coleman (1969) at an interval of 5 to 8 km apart, for two different periods, 1944-1952 and 1952-1963 based on the analysis of three maps, showed that the bank erosion rate was erratic and varied from 0 to 800 m/year. Taking the bank accretion as zero, the average bank erosion rates of the Jamuna river based on Coleman (1969) are presented in the table below.

Table 2.1 The average bank erosion rate of the Jamuna river

Bank	Average bank erosion rate (m/year)	
	Period	
	1952-1963	1944-1952
Left	43	118
Right	67	177

By analyzing satellite images Thorne et al. (1993) estimated the bank erosion rate of the right bank of the Jamuna river for the period of 1973-1992. They estimated bank erosion at an interval of 500 m apart and averaged the erosion rate for 10 km. The average bank erosion rate for the period 1973-1992 varies from 0 to 160 m/year and the average erosion rate is about 80 m/year. They found that for a shorter time-scale the bank erosion rate increases, and the average bank erosion rate is higher for a higher flood discharges. They also found that catastrophic events of bank erosion (> 350 m/year) generally occur for short duration, 2 to 4 years and this erosion took

place at the outer bank of the curved channels. Thorne and Osman (1988) attempted to predict the bank erosion rate for the right bank of the Jamuna river for different time scales and different locations, extrapolating the previous results.

Klaassen and Masselink (1992) studied the bank erosion rate of the curved channels in the Jamuna river by analyzing the satellite images from 1976 to 1987. As the Jamuna river is a braided river, the various braided channels having different discharges, width and radius of curvature are usually active in eroding the bank at different places. They found that in the Jamuna river the bank erosion is generally associated with the rotation and extension of bend rather than translation.

The confluence scour that occurs at the downstream of confluences of two channels, such channels may either be two separate rivers or two braided channels of a braided river. The confluence scour is characterized as an elongated reach of relatively high depth in the middle of the combined downstream channel.

Klaassen and Vermeer (1988c) studied the confluence scour of the Jamuna river. Their study is mainly based on the study of Ashmore and Parker (1983) on the confluence scour in the gravel bed river by using the previous hydrographic surveys of Bangladesh Inland Water Transport Authority (BIWTA) and special surveys in relation to the feasibility study for the Jamuna bridge. They estimated the discharge of the different confluence anabranches with the help of at-a-station relation (Eq. 2.4). They also obtained a relation between relative scour depth and θ for the Jamuna river as follows:

$$\frac{h_{cs}}{h} = 1.292 + 0.037\theta \quad (2.10)$$

It was observed that the maximum scour depth in the Jamuna is slightly smaller than the Ashmore and Parker (1983).

The changes of the Jamuna river are often very rapid and the process is quite chaotic in nature. Based on the recent understanding of the processes of the Jamuna river, Klaassen et al. (1993) attempted to develop a model for plan-form changes of the Jamuna river. Their study was performed by using a continuous series of satellite imagery from 1973 to 1993. They observed that there are a number of limitations in making a deterministic model for the plan-form changes of the Jamuna river. The main problems they encountered are in determining the initial conditions, boundary conditions and also in the formulation of the predictive model. Therefore, instead of a deterministic approach Klaassen et al. suggested a stochastic approach for modeling

the plan-form changes of the river. The components to their models are: channel migration, mid-channel bar formation, behavior of bifurcated channels and migration of confluences and bifurcations. They observed that for a shorter time scale the model can predict the plan-form with a fair accuracy providing the indication of a few possible developments of plan-form. But as the prediction time increases, the number of possible developments increases as well, whereas the accuracy of the prediction reduces.

Present study area is located from 465000 to 485000 Easting and 625000 to 655000 Northing of Jamuna–Ganges confluence, 7 km upstream of Ganges river from its confluence and 5 km downstream of Padma river from its confluence. As the morphological process is pronounced in monsoon, simulation is taken for the period from June to October of the years 2001, 2002 and 2003. The total 30 km reach of the Jamuna River consists of large and small chars. Two branches of Jamuna are separated by a large island, which is only submerged during very high flood, otherwise, remains dry. To reduce the computational time, the large middle island is excluded from the simulation grids. A satellite image of the study area along with mesh of the model is shown in Fig. 2.3.

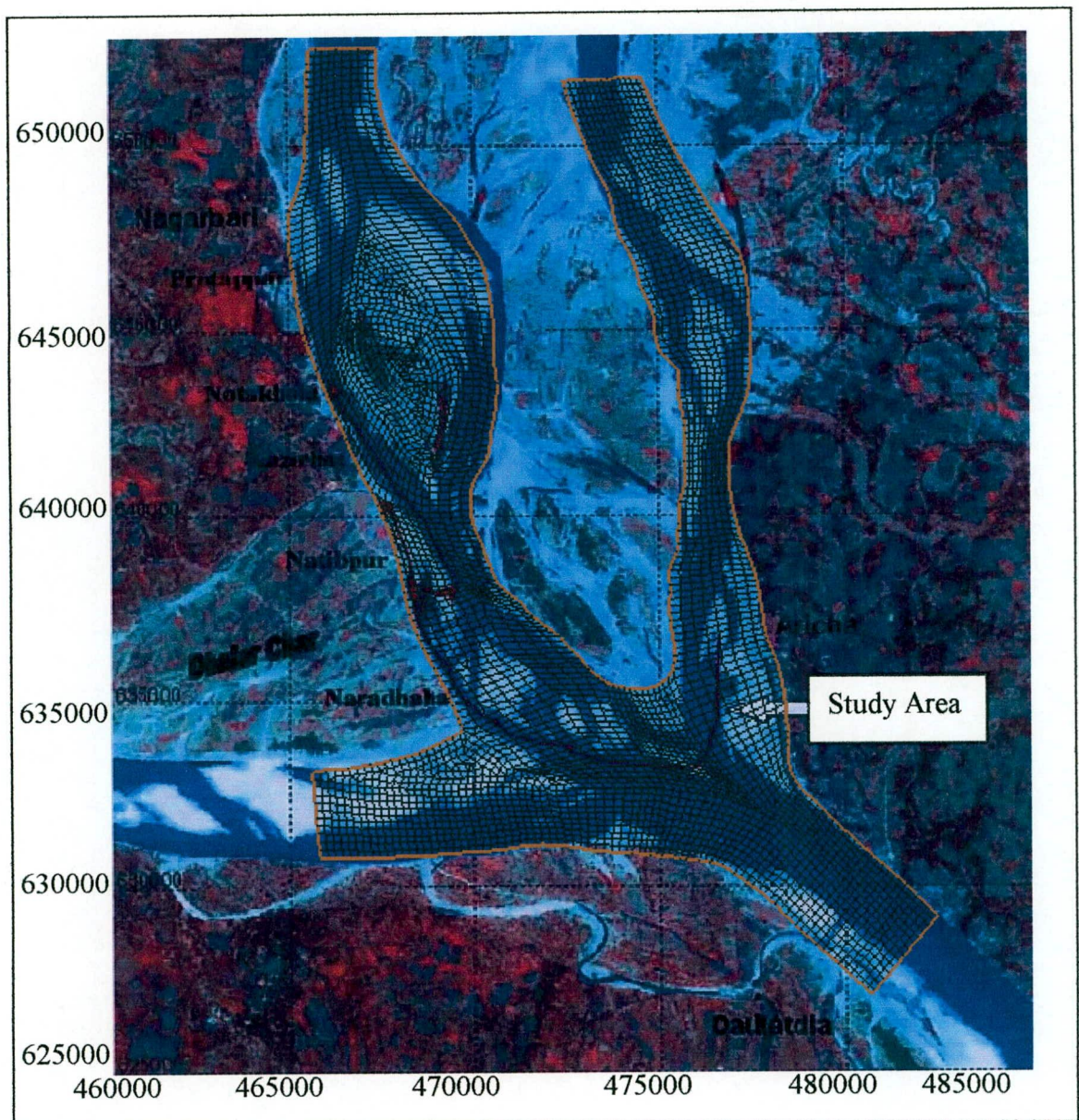


Fig. 2.3 Satellite image of the study area

2.3 Governing equations for two-dimensional surface-water flow

Several related sets of equations have been used to describe steady and unsteady two-dimensional surface-water flow in the horizontal x-y plane. The most basic formulation consists of three nonlinear partial-differential equations, one for conservation of momentum in the x-direction, one for conservation of momentum in the y-direction and one for conservation of mass (Pritchard, 1971).

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + g \frac{\partial H}{\partial x} + g \frac{\partial z_o}{\partial x} - 2\omega V \sin \phi -$$

$$\frac{1}{\rho H} \left[\frac{\partial}{\partial x} (H \tau_{xx}) + \frac{\partial}{\partial y} (H \tau_{xy}) + \tau_x^s - \tau_x^b \right] = 0 \quad (2.11)$$

$$\frac{\partial U}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + g \frac{\partial H}{\partial y} + g \frac{\partial z_o}{\partial y} + 2\omega U \sin \phi$$

$$- \frac{1}{\rho H} \left[\frac{\partial}{\partial x} (H \tau_{yx}) + \frac{\partial}{\partial y} (H \tau_{yy}) + \tau_y^s - \tau_y^b \right] = 0 \quad (2.12)$$

and

$$\frac{\partial H}{\partial t} + \frac{\partial}{\partial x} (H U) + \frac{\partial}{\partial y} (H V) = 0 \quad (2.13)$$

where,

x, y = Cartesian coordinates in the positive east and north directions, respectively;

t = time;

U, V = depth-averaged velocity components in the x and y-directions, respectively;

H = total depth of water;

z_o = bed elevation;

ρ = density of water (assumed constant);

ω = magnitude of the angular velocity of the earth;

ϕ = latitude;

g = gravitational acceleration;

$\tau_{xx}, \tau_{xy}, \tau_{yx}, \tau_{yy}$ = components of depth-averaged effective stress tensor,

τ_x^s, τ_y^s = components of surface stress (wind) in the x and y-directions, respectively;

and

τ_x^b, τ_y^b = components of bottom stress (friction) in the x and y-directions, respectively.

Eqs. 2.11 through 2.13 are commonly referred to as the "shallow-water equations," and the formulation given in the equations is referred to as the "primitive formulation." These equations are obtained from the three-dimensional Reynolds

equations for turbulent flow by integrating with respect to the water depth under the assumption of hydrostatic pressure and by making simplifying assumptions regarding the nonlinear terms.

The first three terms of Eqs. 2.11 and 2.12 are inertial force terms, the first of the three representing temporal acceleration and the second and third representing convective acceleration. The fourth and fifth terms represent the pressure force due to the water-surface gradient. The sixth term represents the Coriolis force, an inertial force describing the effect of the earth's rotation. The seventh and eighth terms represent the combined effect of viscous stresses, Reynolds stresses, and momentum transfers due to the vertical velocity distribution (Wang and Connor, 1975; Lean and Weare, 1979). The ninth and tenth terms represent surface and bottom stresses, respectively.

Eq. 2.13 states that the change in storage in an infinitesimally small control volume accounts for the net flux of mass into or out of the control volume.

2.4 Numerical methods

A model is a simplified representation of a complex process or phenomenon. A model when uses quantitative or mathematical expression to describe the system behavior is called a mathematical model. A mathematical model contains three important components: variables, governing equations and parameters. A mathematical model can be approximated as 1-D, 2-D, and 3-D. One-dimensional model is simple and widely used where variations along longitudinal direction are of interest. If variations over the topography are pronounced, 2-D model should be used in that case. Where the secondary currents are dominating, a 3-D model is the only solution. In all these models two major methods are used to solve the governing partial differential equations: the finite difference method (FDM) and the finite element method (FEM).

2.4.1 Finite difference method (FDM)

The finite difference method is a numerical technique of solving the differential equations in which the derivatives are replaced by finite difference quotients so that the governing differential equations are converted to a set of algebraic finite difference equations. This equation can be solved numerically on the computer.

The different ways in which derivatives and integrals are expressed by discrete functions are called finite difference schemes. These schemes can be classified into explicit schemes or implicit schemes. The implicit schemes permit numerical solutions over large time steps but require the solution of large sets of simultaneous algebraic equations at each time step. On the contrary, explicit schemes are easy to understand and formulate but require small time steps in order to maintain stability.

Finite difference approximations

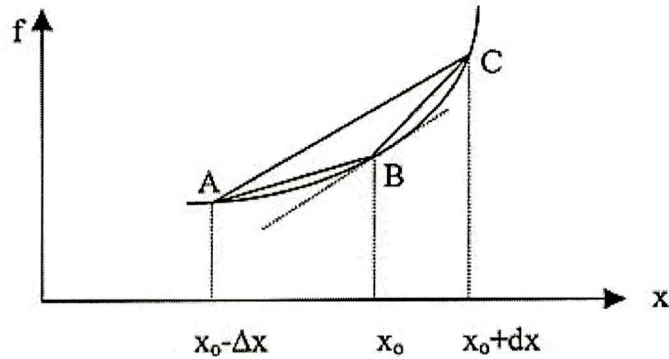


Fig. 2.4 Graphical representation of finite difference approximations

Referring to the above figure, the different approximations for the first-order ordinary derivatives are as following:

$$\text{Forward finite difference} \quad \left. \frac{df}{dx} \right|_{x=x_0} = \frac{f(x_0 + \Delta x) - f(x_0)}{\Delta x} \quad (2.14)$$

$$\text{Backward finite difference} \quad \left. \frac{df}{dx} \right|_{x=x_0} = \frac{f(x_0) - f(x_0 - \Delta x)}{\Delta x} \quad (2.15)$$

$$\text{Central finite difference} \quad \left. \frac{df}{dx} \right|_{x=x_0} = \frac{f(x_0 + \Delta x) - f(x_0 - \Delta x)}{2\Delta x} \quad (2.16)$$

While both the backward and forward finite difference approximations are first-order accurate, the central finite difference approximation is referred to as second-order accurate. It is clear from the Fig. 2.4 that the central difference approximation is more accurate than the forward or backward finite difference approximations.

Now let us consider finite difference approximations for partial derivatives. For a function $f(x, t)$, we may divide the x - t plane into a grid as shown in Fig. 2.5. To

refer to different variables at these grid points, we will use the number of the spatial grids as subscript and that of the time grids as superscript. For example, the flow depth y at the i th spatial grid point and k th time grid point is denoted by y_i^k . The known time level is denoted by superscript k and the unknown time level by $k+1$. If the computations progress from one step to the next, the procedure is referred to as a *marching procedure*. Most of the phenomena described by hyperbolic partial differential equations are solved by using marching procedure. The conditions specified at time $t = 0$ are referred to as the *initial conditions*. The conditions specified at the channel ends are called end, or *boundary conditions*.

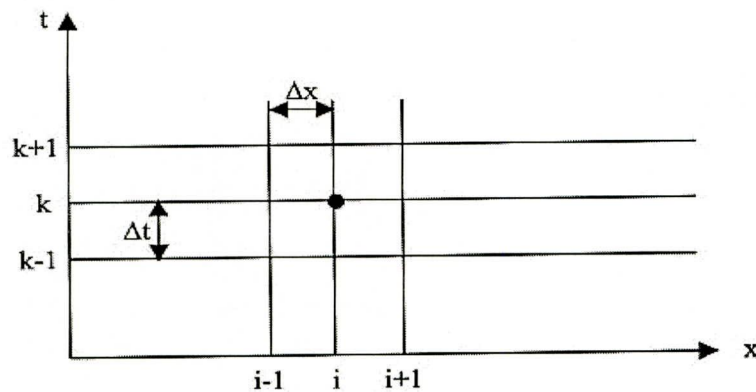


Fig. 2.5 Finite difference computational grid

There are several possibilities for approximating the partial derivatives. The spatial partial derivatives replaced in terms of the variables at the known time level are referred to as the explicit finite differences, whereas those in terms of the variables at the unknown time level are called implicit finite differences. Some typical finite difference approximations for the spatial partial derivative, $\frac{\partial f}{\partial x}$ at the grid point (i, k) are as follows:

Explicit finite differences

Backward:
$$\frac{\partial f}{\partial x} = \frac{f_i^k - f_{i-1}^{k+1}}{\Delta x} \quad (2.17)$$

$$\text{Forward: } \frac{\partial f}{\partial x} = \frac{f_{i+1}^k - f_i^{k+1}}{\Delta x} \quad (2.18)$$

$$\text{Central: } \frac{\partial f}{\partial x} = \frac{f_{i+1}^k - f_{i-1}^{k+1}}{2\Delta x} \quad (2.19)$$

Implicit finite differences

$$\text{Backward: } \frac{\partial f}{\partial x} = \frac{f_i^{k+1} - f_{i-1}^{k+1}}{\Delta x} \quad (2.20)$$

$$\text{Forward: } \frac{\partial f}{\partial x} = \frac{f_{i+1}^{k+1} - f_i^{k+1}}{\Delta x} \quad (2.21)$$

$$\text{Central: } \frac{\partial f}{\partial x} = \frac{f_{i+1}^{k+1} - f_{i-1}^{k+1}}{2\Delta x} \quad (2.22)$$

Many other finite difference approximations are possible if the values at three or more grid points, instead of just two grid points, are used.

2.4.2 Finite element method (FEM)

The finite-element method is a numerical procedure for solving the differential equations encountered in problems of physics and engineering. Although it was originally devised to analyze structural systems, the finite-element method has developed into an effective tool for evaluating a wide range of problems in the field of continuum mechanics.

The fundamental concept of the finite-element method is that any smooth quantity can be approximated by a discrete model composed of a set of piecewise-smooth functions, which are defined over a finite number of sub-domains called *elements*. The piecewise-smooth functions are called *interpolation*, *shape*, *trial*, or *basis functions*. These are described in terms of the values of the smooth quantity at a finite number of points in its domain, and are typically polynomials of at most the third or fifth degree. The points at which the quantity is defined are called *nodes* and are usually located along the element boundaries, where adjacent elements are considered to be connected, although some nodes may be positioned in the element interiors.

The nodal values of the quantity being modeled along with the selected interpolation functions completely describe the variation of the quantity within each element. For the finite-element solution of the problem, the nodal values become the unknowns. The behavior of the solution throughout the assemblage of elements is described by the interpolation functions once the unknown nodal quantities are found.

Once the finite-element model has been established (i.e., once the elements and their interpolation functions have been chosen), the derivation of the element equations may be achieved by *direct methods*, *variational methods*, or *weighted-residual methods*.

2.4.2.1 Variational approach

In this method, the problem of finding a solution of the governing differential equation is replaced by an equivalent variational problem that consists of finding a known function that extremizes a certain integral quantity, subject to the prescribed boundary conditions. Such an integral is called a functional. A general expression for this functional, U over a one-dimensional domain R is given by

$$U = \int_R F \left(x, u, \frac{\partial u}{\partial x}, \frac{\partial^2 u}{\partial x^2}, \dots \right) dx \quad (2.23)$$

within each sub-domain, the unknown function u is approximated by trial function $\hat{u}$,

$$\hat{u} = \sum_{j=1}^{N^e} \phi_j(x) u_j \quad (2.24)$$

where, $\phi_j(x)$ are linearly independent functions, known as basis functions;

The total functional, U

$$U = \sum_{e=1}^m U^e \quad (2.25)$$

$$\text{where, } U^e = \int_{R^e} f \left(x, \hat{u}, \frac{d\hat{u}}{dx}, \frac{d^2\hat{u}}{dx^2}, \dots \right) dx \quad (2.26)$$

Applying nodal compatibility,

$$U = U(u_1, u_2, u_3, \dots, u_n) \quad (2.27)$$

After assembly of all elements, the global matrix equation takes the form

$$[C]\{u\} = \{F\} \quad (2.28)$$

$$\text{where, } [C] = \sum_{e=1}^m [C]^e \quad (2.29)$$

and

$$\{F\} = \sum_{e=1}^m \{F\}^e \quad (2.30)$$

2.4.2.2 Method of weighted residuals

The weighted residual methods are general methods that can be applied in cases where direct and variational methods do not work. In these methods, the desired function, say $u(*)$ is replaced by a finite series approximation, $\hat{u}(*)$.

$$u(*) \approx \hat{u}(*) = \sum_{j=1}^{N^e} u_j \phi_j(*) \quad (2.31)$$

where, $\phi_j(*)$ are denoted as basis functions. The basis functions are chosen to satisfy all the boundary conditions. Substitution of $\hat{u}(*)$ in the partial differential equations of the general form

$$Lu(*) - f = 0 \quad (2.32)$$

results in a residual, R

$$R(*) = L\hat{u}(*) - f \quad (2.33)$$

the objective that the residual is minimized by introducing N^e weighting functions, $W(*)$.

$$\int_U \int_V R(*) W_i(*) dV dU = 0 \quad i = 1, 2, \dots, N^e \quad (2.34)$$

Based on the selection of the weighting functions, $W(*)$, the method of weighted residuals may be classified into the following three approaches: *Galerkin*, *Collocation*, and *Sub-domain* methods.

i. Galerkin method

The method results into Galerkin method when the weighting function is chosen to be the basis function.

$$\int_U \int_V R(*) \phi_i(*) dV dU = 0 \quad i = 1, 2, \dots, N^e \quad (2.35)$$

In this case, $R(*)$ and $\phi_i(*)$ are orthogonal to each other and the residual is forced to zero.

ii. Sub-domain Method

In the sub-domain method the weighting function is chosen to be unity in the sub-domain V_i and zero elsewhere.

$$\int_U R(*) W_i(*) dU = 0 \quad i = 1, 2, \dots, N^e \quad (2.36)$$

where, $W_i = 1, (x, y, z)$ within V_i
 $= 0, (x, y, z)$ outside V_i

The integration is less tedious in this method than the Galerkin method because of simplicity of the $W_i(*)$ function.

iii. Collocation method

Collocation method is the simplest of the method of weighted residuals to implement. The weighting function, W_i is chosen here to be the dirac delta, that is,

$$W_i = \delta(x - x_i) \quad (2.37)$$

The dirac delta function has the following important property

$$\int_U \int_V a(*) \delta(x - x_i, y - y_i, z - z_i, t - t_i) dV dt = a|x_i, y_i, z_i, t_i \quad (2.38)$$

Thus, the orthogonality constraints for the collocation method are

$$\int \int_{UV} R(*) \delta_i(*) dV dU = 0 \quad i = 1, 2, \dots, N^e \quad (2.39)$$

The residual vanishes at each collocation points (x_i, y_i, z_i, t_i) . Hence, the accuracy of this method depends heavily on the location of the collocation points.

2.4.2.3 Historical development of FEM

The finite element method was originally developed by aircraft structural engineers in the 1950's to analyze large systems of structural elements in the aircraft. Turner et al., (1956) presented the first paper on the subject, followed by Clough(1960) and Argyris(1963), among others. Application of the FEM to non-structural problems such as fluid flows and electromagnetism was initiated by Zienkiewicz (1965), and applications to wider problems of interest in nonlinear mechanics was contributed by Oden (1972).

The close relationship of finite element analysis to the classical variational concept of the Rayleigh-Ritz method (Rayleigh, 1877; Ritz, 1909) or the weighted residual methods modeled after the well known method of Galerkin (1915) has established the FEM as an important branch of approximation theory. After that various authors have contributed to the development of the mathematical theory of finite elements. Among them are Babuska and Aziz (1972), Ciarlet and Raviart (1972), Aubin (1972), Oden and Reddy (1976) etc.

2.4.2.4 Advantages and disadvantages of FEM over FDM

The main advantage of the FEM is its ability to handle irregular boundaries and grid refinement. The finite difference solutions have grids with square corners, straight edges and mostly equal grid spacing. As the finite element method is based on the concept of discretization of elements, it can accommodate both triangle and rectangle elements. Using the triangle elements any complex geometry can be easily represented. In FEM, uses of only rectangle elements produces "stair-shape" boundary. This can be illustrated with the Fig 2.6.

These elements can also vary widely in size and shape. Variable grid size and refinement to any interested area, where changes take place rapidly, (near edges and corners) can be easily handled by the FEM in comparison to FDM.

Another advantage of the FEM is that it can handle boundary conditions involving derivatives very easily. In finite difference, this type of boundary condition

is approximated by using special devices such as non-centered difference equations or fictitious external grid points.

Price et al. (1968) showed that the FEM requires fewer nodes and less computation time than the FDM to achieve comparable accuracy in solving the one-dimensional convection-diffusion equation with a trapezoidal-rule scheme.

Thacker (1978a) showed that finite-element solutions are more accurate than finite-difference solutions in solving the equations of one-dimensional gravity-wave motion where both the depth and the grid are variable.

Although FEM has potential advantages, in two-dimensional and three-dimensional problems it requires more computation time. As matrices generated by FEM are much more complex than those generated by FDM, it has large bandwidth and less sparse which cost huge space in computer disk and reduce the speed of the computation. Also extensive manpower is required to prepare input and output data if pre-and post-processing software is not available.

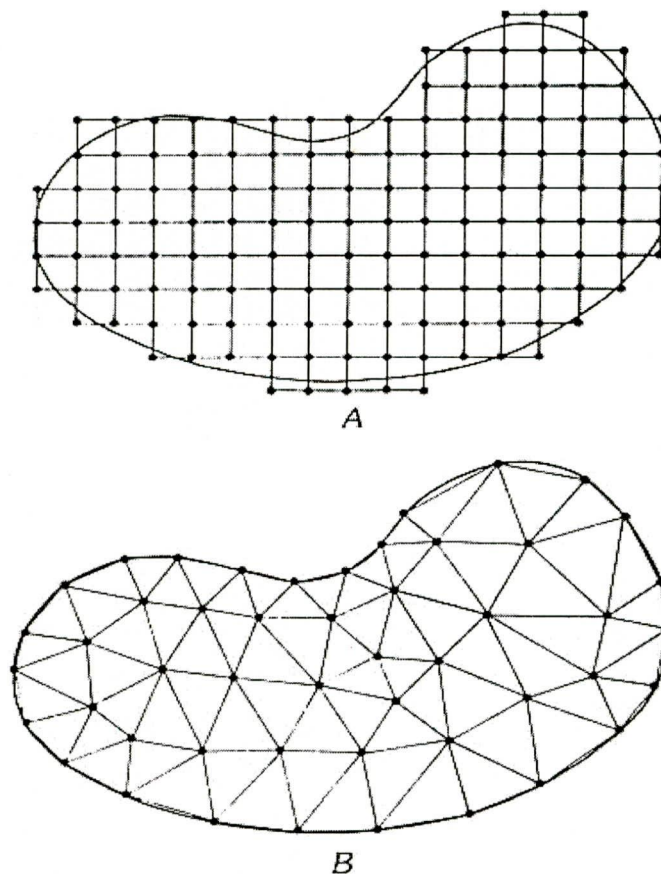


Fig. 2.6 Finite-difference and finite-element discretizations: (A) Typical finite-difference grid, and (B) Typical finite-element grid.

2.5 Various hydrodynamic and sediment models

Various 1-D, 2-D and 3-D hydrodynamic and sediment models are in use throughout the domain of literature. All these are either finite difference or finite element models. Short descriptions for few of them are presented below.

- i. HEC Model Series, including HEC-UNET, HEC-6, and HEC-RAS, is a set of one-dimensional models of river hydrodynamics and sediment transport provided by the U.S. Army Corps of Engineers.
- ii. RMA Model Series, together with the SED-2D model, is a set of one-, two-, and three-dimensional models of hydrodynamics, sediment transport and water quality. The RMA models are finite element models. This model can be run with 1-D elements, has significant computational efficiency. It has the capability of addressing certain control structures, but not all the structures envisioned for the ponds. The models are in the public domain. RMA is supported by the SMS preprocessing and display suite.
- iii. MIKE Model Series together comprises a very extensive set of finite difference models in one-, two- and three dimensions. Most of the MIKE models (MIKE-11, MIKE-21, MIKE-12 and MIKE-3) use a rectangular, potentially nested, grid. Modules exist to cover hydrodynamics, sediment transport, water quality, and wave generation/transformation. MIKE-21C is a newer one which uses curvilinear grid. Finite element version (MIKE-FM) is also in ongoing processes.
- iv. DELFT Model Series together comprises a set of finite difference models in two, and three dimensions. They include hydrodynamics, wave generation/transformation, water quality and sediment transport with dynamic bed morphology. The models use a curvilinear orthogonal grid. DELFT2D and DELFT3D are commercially available from Delft Hydraulics.
- v. TELEMAC Model Series comprises a set of two- and three-dimensional finite element models of hydrodynamics, with modeling of salinity provided by WQ-2D and WQ-3D, and sediment transport by SUBIEF. The models use irregular triangular grids. TELEMAC and the associated models are commercially available from H.R. Wallingford, U.K.
- vi. GEMSS consists of a three-dimensional finite difference hydrodynamic, water quality, and sediment transport model, with a curvilinear orthogonal grid. The model uses the same basic hydrodynamic model (GLLVHT) as CE-QUAL-

- W2. The model is developed by J.D. Edinger Associates. Model development and application are possible only through a cooperative agreement with the developers.
- vii. TRIM is a two-dimensional finite-difference hydrodynamic model. There is a version of this model, UnTRIM, that uses an irregular grid which has not been used very widely except by the developer. TRIM is developed by, and available from, the USGS, although model documentation and software support is limited.
 - viii. CH2D / CH3D are two- and three-dimensional finite difference models of hydrodynamics, salinity, and sediment transport. The models use a curvilinear orthogonal grid. It can be used together with CE-QUAL-ICM to model water quality. CH2D / CH3D are developed and maintained by the U.S. Army Corps of Engineers. However, the software is not freely available to users outside the U.S. Army Corps of Engineers. Model development and application are possible through a cooperative agreement with the Waterways Experiment Station or other branches within the Corps.
 - ix. ADCIRC is a two- and three-dimensional finite element hydrodynamics model using an irregular grid and provided by the U.S. Army Corps of Engineers. ADCIRC is supported by the SMS preprocessing and display suite.
 - x. CE-QUAL-W2 is a two-dimensional finite difference hydrodynamic and water quality model, with a rectangular grid. The model can be run in a vertical or horizontal plane, so that it can simulate deep, narrow channels as well as large water bodies. The model is provided by the U.S. Army Corps of Engineers.
 - xi. WASP is a very extensive water quality model provided by the EPA. The focus of this modeling suite is on water quality (e.g., eutrophication kinetics, and toxic chemicals bound to sediments) rather than on hydrodynamics. WASP can be applied in one, two or three dimensions. It imports the hydrodynamics from another model; it is often used in concert with the one-dimensional DYNHYD model or the three-dimensional EFDC model (these are relatively simple hydrodynamic models). The model is commercially available at a relatively low cost.
 - xii. CORMIX, which is a three-dimensional hydrodynamic and water quality model developed specifically to describe plume dispersion, for example at wastewater outfall pipes. It is commercially available.

- xiii. Three-dimensional groundwater flow models include GMS, MODFLOW, and MOC-3D, all provided by the U.S.G.S.

In Table 2.2 the capabilities of the above model suites are systematically summarized.

Table 2.2 Content of available model suites

Type of Model	Characteristics of Numerical Model(s)	HECUNET, HEC-6, HEC-RAS	RMA-2, -4, -10, -11, SED-2D	MIKE-11, -21, -21-3, -FM-C	TRIM, UnTRIM	DELFT2D, DELFT3D	TELEMAC	CH2D, CH3D, ICM	WASP	ADCIRC	CE-QUAL-W2	GEMSS (GLLVHT)
General	Numerical Solution Method	FE	FE	FD ¹	FD	FD	FE	FD	FE	FE	FE	FD
	Numerical Grid Type	NA ²	IR	RE ¹	RE ⁷	CU	IR	CU	NA ³	IR	RE	CU
	General Model Availability	F	\$	\$\$	L	\$\$	\$\$	L	\$	\$	F	L
Hydrodynamic Model	Water Levels and Velocity	■	■	■	■	■	■	■	■	■	■	■
	Wetting and Drying	■	■	■	■	■	■	■	■	■	■	■
	Evaporation and Precipitation	□	■	■	□	■	■	■	□	□	□	■
	Control Structures	■	■	■	□	■	■	□	□	■	□	■
	Temporal Variation (Unsteady Flow)	■ ⁴	■	■	■	■	■	■	□	■	■	■
	Spatial Variation (2-D Modeling)	□	■	■	■	■	■	■	□	■	■	■
	1-D / 2-D Model Integration	□	■	■	□	□	□	□	□	□	□	■
Wave Model	Vertical Stratification (3-D Modeling)	□	■	■	■	■	■	■	□	■	■	■
	Wind-Generated Waves	□	□	■	□	■	■	■	□	□	□	□
Sediment Transport Model	Wave-Current Interactions	□	■	■	□	■	■	■	□	■	□	■
	Cohesive Processes	■ ¹	■	■	□	■	■	■	□	□	□	■
	Bed Load Transport	■	□	■	□	■	■	■	□	□	□	■
	Wind-Driven Wave Resuspension	□	■	■	□	■	■	■	□	□	□	■
	Source / Sink Terms	□	■	■	■	■	□	■	□	□	□	□
	Dynamic Bed Morphology	■	□	■	□	■	□	■	□	□	□	□
	Channel Migration	□	□	■	□	□	□	□	□	□	□	□
Water Quality Model	Solute Transport (Advection-Diffusion)	■	■	■	■	■	■	■	■	■	■	■
	Particle Tracking	□	■	■	□	■	□	■	■	□	□	■
	Heavy Metals (Absorption-Desorption)	□	□	■	□	■	□	□	■	□	□	□
	Temperature Model	■	■	■	□	■	□	■	■	□	■	■
	Biochemical Processes	■	■	■	□	■	□	■	■	□	■	■
	Groundwater Modeling	□	□	□	□	□	□	□	□	□	□	□

Key:

FE Finite Element	FD Finite Difference	CU Curvilinear orthogonal
RE Rectangular	UN Unstructured	F Public Domain
\$ Available at low cost	\$\$ Relatively high cost	L Limited availability (coop agreement, etc.)
■ Addressed	■ Partially Addressed	□ Not Addressed

Notes:

1. Curvilinear grid for MIKE-21C, and finite element for MIKE-FM
2. Not Applicable (1-D model)
3. The WASP model can take input hydrodynamics from a number of other models
4. Unsteady flow and sediment transport are not available simultaneously
5. Channel migration is available as a specialized module, not integrated with other morphologic modules
6. CE-QUAL-W2 can be run in a 2-D or a 1+1-D mode
7. Irregularly shaped finite difference grid for UnTRIM

2.6 Previous studies

Jamuna, the largest river of Bangladesh, is characterized as a braided one. Every year the widening of the river, bank erosion, development of large bars and deposition in main navigational channels, are happened to be the major problems. Various studies were conducted in the past to understand the behavior of the river Jamuna. These studies are mainly consisting of analytical, physical and mathematical modeling in nature. Some of those studies are briefly described below.

2.6.1 Studies using various two-dimensional mathematical models

Following invent of high speed computers nowadays, mathematical models are extensively used for the simulation of the natural processes all over the world. In Bangladesh several studies on hydrodynamics and sediment transport were conducted for some major rivers.

2.6.1.1 2-D mathematical modeling in Bangladesh

A morphological model of Jamuna river at Jamuna bridge site was developed in 1995. The model was done by IWM (Institute of Water Modeling) using MIKE-21C, which is a two-dimensional finite difference curvilinear grid model for simulating hydrodynamic and sediment transport in vertically homogenous flow. The model covered a reach, extending 20 km upstream to 10 km downstream approximately from bridge site. Bathymetry and hydrological data of the year 1994 were used in the model. Simulation of the hydrodynamics for pre-bridge and post-bridge conditions was carried-out for the entire monsoon period of 1994. Changes from pre- to post bridge conditions have been extracted. The morphological model was run for one and a half month. The results showed that water level had increased by 0.5 m at the upstream of guide bund due to bridge construction.

Two-dimensional model of Ganges river for Pakshey bridge project was developed in 1999 by IWM and DHI (Danish Hydraulics Institute). The simulation was developed using FESWMS-2DH model (version 3.0). FESWMS-2DH is an acronym for finite element surface water modeling system for two-dimensional flow in a horizontal plane. It is a computer program to perform two-dimensional hydraulic modeling of rivers, floodplains and highway crossings. Main objectives of the study were to find the impacts of the new bridge and river training works on the existing Hardinge bridge, river training works and the downstream irrigation intake canal and

also to evaluate the expected morphological changes in the river regime due to proposed bridge. The model was run only for steady-state condition using 100-year and 500-year peak discharges. It had been found that under the above design flood events, both velocity and unit discharge along the Hardinge guide bunds decreased due to presence of Pakshey bridge.

In 2003, two models had been developed at IWM for finding a suitable location of ferry ghat for BIWTA (Bangladesh Inland Water Transport Authority). For these two models: one is a 30 km long and another one is a 200 km long reaches, where Jamuna-Ganges confluence had been included for both to study the erosion-deposition pattern in the confluence region. The key feature of the study was to find a sustainable channel, which should have the minimum navigational depth round the year. The short-model is used to evaluate the engineering interventions and the long-model is used to simulate long-term bed level changes along the navigational routes (BIWTA, 2003).

Feasibility study for the Gorai River Restoration Project (GRRP) for augmenting dry season flow through the Gorai offtake had been taken-up by the Government of Bangladesh (GoB) in 1997. A two-dimensional morphological model had been developed for simulating the hydraulic and morphological processes in the Gorai offtake to study the feasibility of undertaking Gorai river restoration work. A quasi-steady flow calculation was carried-out for the morphological calculation using MIKE-21C of DHI Water and Environment. A helical flow module was used to calculate the streamline curvature generated secondary flows. The sediment transport computed are composed of bed-load and suspended load. For the bed-load calculation, the effects of the helical flow and bed slope were accounted through the direction of bed-shear stress and direction of the bed-slope. The model was calibrated and validated at the offtake with extensive data collected for three consecutive monsoons from 1998 to 2000. Both Chezy's roughness (depth invariant) and depth variant roughness were used in the study.

Halcrow (2002) reviewed the morphological processes of the Jamuna river at Pabna Irrigation Rural Development Project (PIRDP). Halcrow proposed riverbank protection based on the morphological studies of the area. Three reaches of the bank had been identified as susceptible to different degrees of erosion, and then the sites were being prioritized to allow the introduction of a staged intervention program for

protecting the vulnerable bank reaches. A 4 km reach of bank line within PIRDP showed immediate need for protection.

2-D hydraulic model and morpho-dynamic model are developed by IWM in 1998 under the Meghna Estuary Study. The Meghna Estuary Study has covered an area of the lower Meghna from Chandpur town up to the Bay of Bengal. The model has been developed using MIKE-21. The dominant hydraulic and morphological conditions and processes in the study area are studied through regional and detailed local 2-D models. To determine the dynamic behavior of the entire estuary system, computations are carried out under different hydrodynamic conditions during low and monsoon seasons. Neap tide and spring tide, current velocity and sediment transport patterns and wave conditions are assessed in that study. The results of these computations give qualitative and quantitative information about the spatial and temporal variations of the water level, current velocity, discharge as well as sediment transport and the rate of sedimentation and erosion.

Houqe (1999) has studied the fluvial processes of the braided Jamuna in its 73.65 km reach including confluence with the Ganges using application of remote sensing and GIS. Using eleven sets of LANDSAT satellite images from 1973 to 1996, he studied the bank erosion, meander travel, bar formations of Jamuna river and migration of Jamuna-Ganges confluence. Analysis of the processed data revealed that formation of bars caused channel bifurcation and created anabranches which together increased the total width of the Jamuna from 7 km to 12 km over the study period. The anabranches thus created either lost or gained width gradually. The one losing width ultimately becomes only a remnant allowing the bar to merge with the flood plain. The channel developed an oscillatory nature which caused erosion at the bank and the bar developing a meander. He also revealed that the confluence has undergone an oscillation due to the movement of the Ganges and formation of bars in the Jamuna. This movement is estimated as 12 km within the study period.

2.6.1.2 2-D mathematical modeling works outside Bangladesh

Great deals of works have been done all over the world using mathematical models. Region-wise a niche market has been developed for different models. In North America normally RMA series (under SMS) models are in great use for different research and consultancy services. Under European Union it has been found that the DELFT series models that developed by Delft Hydraulics Laboratory, and

MIKE series models developed by Danish Hydraulics Institute are in greater command not only in Europe but also in some developing countries like Bangladesh, India, Africa and some southeast Asian countries. Some of the reputed models that have been used internationally for various studies and projects are described briefly below.

A two-dimensional hydrodynamic model of the St. Clair-Detroit river had been developed by U.S. Army Corps of Engineers in 2002. The model was developed to compute flow velocities and water levels as part of a source-water assessment of public water intakes. RMA2, a finite element model had been used to develop the model with 13,783 quadratic elements defined by 42,036 nodes. Seven steady-state scenarios were used to calibrate the model by adjusting parameters associated with channel roughness in 25 material zones. Calibration results denoted close agreement between simulated and expected flows and water levels at gaging stations of the major channels.

A hydrodynamic and sediment transport model was developed in support of a feasibility study for a port construction project in Dharma river, Orissa, India. The proposed port had to be at the mouth of the Dharma river in the Bay of Bengal. This would require development and maintenance of a 19 km long navigational channel, and also a dike to divert Dharma river flow into the navigational channel to minimize the maintenance dredging requirements. Tidal circulation and sediment transport were modeled using RMA2 and SED2D. The study result reflected that construction of the new navigational channel and the port would not likely to result in increased deposition of river borne sediments. The new channel would function as, if not better than that, the existing natural channel, and would only require dredging in some parts. The study also suggested that the proposed dike would not cause a backwater effect on Dharma river and the project was feasible.

Two-dimensional model was used as part of the Missouri river bank stabilization and navigation, fish and wildlife mitigation project. The project goal was to evaluate the creation of shallow water habitat by using constructed structure along the canalized section of the Missouri river in Nebraska. Model was build for each site using the surface water modeling system of RMA2-WES and SED2D WES to estimate morphology. The model had been calibrated under the established HEC-RAS model of the Missouri river.

To study the meander migration and scour of the Roer river, a model had been developed by Delft hydraulics for the Dutch Water Board. The main goal of the project was to determine the migration velocity and migration development of the meander bends, and the depth and velocity of the bed erosion of the Roer at the location of tunnel. With the 1-D hydraulic and morphological model system SOBEK, calculations were carried out to determine the large-scale morphological development and the flood scour of the Roer at the tunnel location.

In order to demonstrate the impact of sediment supply on the morphology of Tenryuu river (Japan), downstream of the Akida dam, Delft Hydraulics developed a two-dimensional model using the Delft2D-River system. The activities included 2-D schematization, extending the model system with the 'Aishida' and Michiue sediment transport equations, hydraulic and morphological evolution of supplied sediment volume.

Two-dimensional model was developed to examine the morphological effects and changes in navigability of the Waal River due to lowering of groynes. This model was developed with the help of Delft2D-River packages.

2.7 Physical model studies

A physical model study was done in 2003 by the Department of Water Resources Engineering, BUET for the confluence of Ganges-Jamuna river to find suitable alternative locations for BIWTA ferry ghats. Bathymetry data of April 2001 and August 2001 were used to represent the river geometries of lean and flood periods. Test runs were conducted for both rising and falling stages of flow conditions. The horizontal and vertical scales in the first phase of the test runs were chosen as 1:400 and 1:60 respectively for geometric similarity. In the second phase these were 1:500 and 1:60 respectively. For dynamic similarity Froudian rules were applied. The model bed was filled up with river sand of $d_{50} = 0.15$ mm. The sand in the model was similar to prototype sand. Considering bank-full flow and high flow conditions, the morphological behavior in the major channels were evaluated.

A study on the bifurcation analysis by RRI (1993) showed that the deviation angle of a channel from the upstream channel direction is more important than the cutoff ratio. The study of RRI (1993) was based on the analysis of satellite images. To derive a predictive model on the plan-form changes they made extensive analysis on the channel abandonment in the bifurcation.

Chapter 3

Surface-water Modeling System

3.1 General

SMS is a comprehensive environment for one-, two-, and three-dimensional hydrodynamic modeling. SMS is used as a pre- and post-processor for surface water modeling, analysis, and design. It includes tools for:

- managing, editing and visualizing geometric and hydraulic data; and
- creating, editing and formatting mesh/grid data for use in numerical analysis.

The finite element mesh, finite difference grid, or cross section entities along with associated boundary conditions necessary for analysis may be specified and edited within SMS and saved to model specific files. These files are used to perform the hydrodynamic, contaminant migration, sediment transport or other desired analyses. The numerical models create solution files that contain the water surface elevations, flow velocities, contaminant concentrations, sediment concentrations or other functional data at each node, cell, or section. SMS reads this data and generates profiles and cross sectional plots, two-dimensional vector plots, drogue plots, color-shaded contour plots, time variant curve plots, and dynamic animation to enhance understanding and interpretation of numerical solutions.

3.2 Models

SMS Interfaces specifically designed to facilitate the utilization of several numerical models comprise the modules of SMS. These numeric models will compute a variety of information applicable to surface water modeling. The principle application has been hydrodynamic modeling. This involves the calculation of water surface elevations and flow velocities for shallow water flow problems and support both a steady-state and dynamic modeling. Additional applications include the modeling of contaminant migration, salinity intrusion, sediment transport (scour and deposition), wave energy dispersion, wave properties (directions, magnitudes and amplitudes) and various others. Supported models include:

- United States Army Corps of Engineers (USACE)
 - Engineer Research and Development Center (ERDC)
 - TABS-MD (GFGEN, RMA2, RMA4, RMA10, SED2D-WES)

- ADCIRC
- CGWAVE
- STWAVE
- HIVEL2D
- CH3D
- Hydrologic Engineering Center (HEC)
 - HEC-RAS
- Federal Highway Administration (FHWA)
 - FESWMS-Flo2DH
- Independent/Commercial Licenses
 - M2D
 - Generic 2D Finite Element Interface
 - Generic 2D Finite Difference Interface

Among these models, GFGEN, RMA2 and SED2D are of our concern and discussed elaborately in the later sections of this chapter.

3.3 GFGEN

It is the Geometry File GENeration program. GFGEN's purpose is to create geometry and finite element mesh files for input to the TABS-MD modeling system programs. It performs routine mesh diagnostics, reordering, and plotting (optional).

3.3.1 Capabilities of GFGEN

- a. Read node and element data and construct a finite element computational mesh for use by other programs in the TABS-MD modeling system.
- b. Identify errors and potential errors in the constructed mesh.
- c. Renumber the mesh, omitting unused nodes and/or element numbers.
- d. Fit curved element sides to land boundaries and interior element sides may be specified.
- e. Develop an elemental solution order that permits the most efficient operation of models using the mesh.
- f. Provide a nodal cross reference and statistics summary.
- g. Create a binary data file that contains the mesh information and geometry in a format suitable for use by other TABS-MD programs.

3.3.2 Types of elements

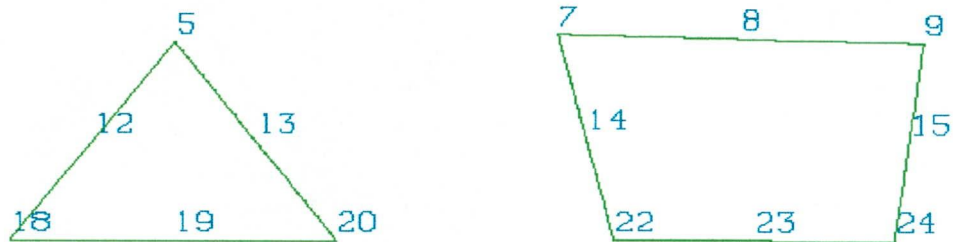
GFGEN is capable of handling many different types of elements within the same computational finite element mesh. The types of elements fit into three basic categories:

- a. Two dimensional elements (2-D).
- b. One dimensional elements (1-D).
- c. Special elements (transitions, junctions, and control structure elements).

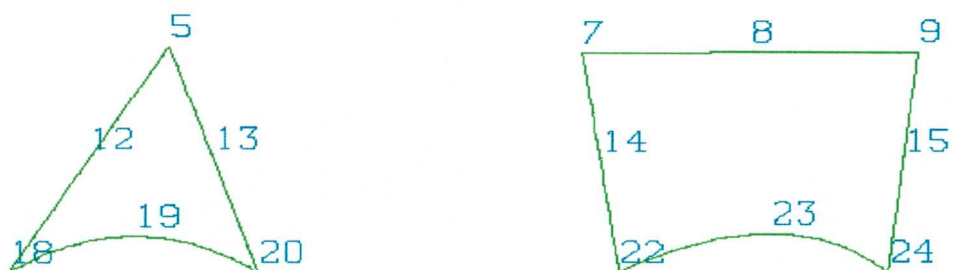
Elements may have either straight or curved edges.

3.3.2.1 Two-dimensional elements

Two-dimensional elements may be three sided with six nodes or four sided with eight nodes. Fig. 3.1 illustrates the basic triangle and quadrilateral shapes for two-dimensional elements. There are three/four corner nodes at the vertices and three/four mid-side nodes on the sides. If the element is straight, the mid-side node is exactly halfway between the two corners. However, if an edge of the element is curved the mid-side node of that edge needs to fall within the middle third of the distance between the two corners to meet the criterion of well formed.



a. Straight 2D elements.



b. Curved 2D elements.

Fig. 3.1 Well formed two-dimensional elements

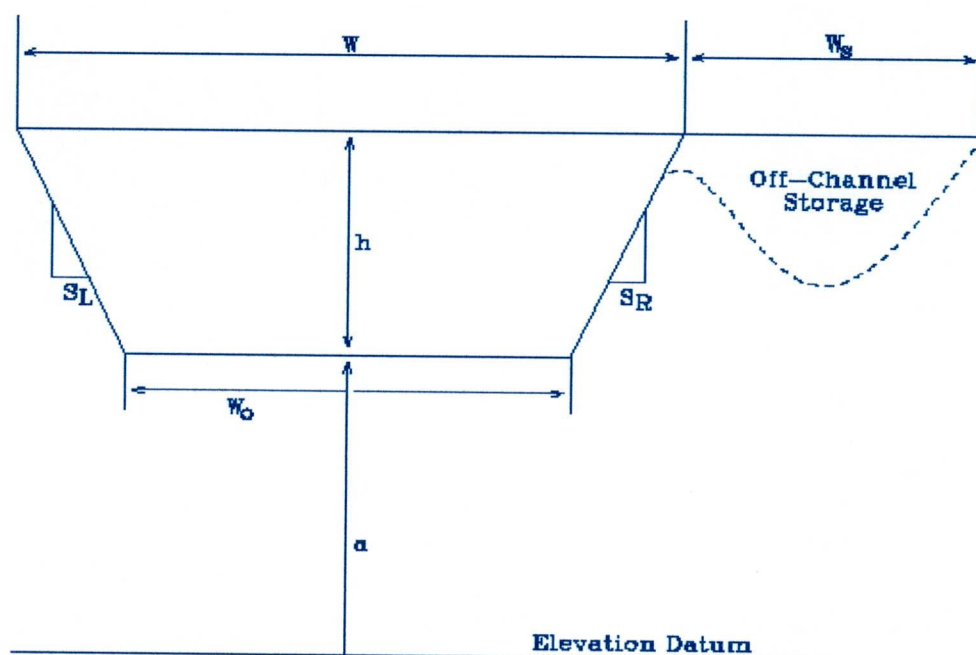
3.3.2.2 One-dimensional elements

The basic one-dimensional element is composed of two corners and one mid-side node. Parts *a* and *b* of Fig. 3.2 illustrate a basic straight and curved one-dimensional element. As depicted in part *c* of Fig. 3.2, the numerical model's governing equations for 1-D elements are based on a trapezoidal cross-section with side slopes and off-channel storage. The user may assign the width (W), slopes (S_L and S_R), and off-channel storage (W_s) within GFGEN (GNN or GWN cards) or wait and include that information within the numerical model run.



a. Straight 1D element

b. Curved 1D element

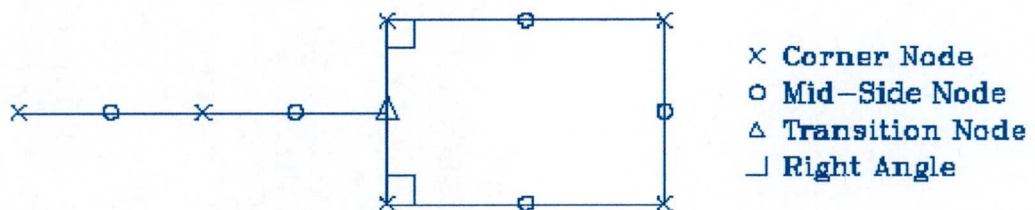


c. 1-D Trapezoidal cross-section diagram

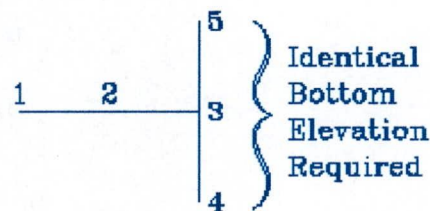
Fig. 3.2 Well formed one-dimensional elements

3.3.2.3 Special elements

- i. **Transitional element:** A transitional element is a special 1-D element that is required for connecting a 2-D element with a 1-D element. Part *a* of Fig. 3.3 illustrates a 1-D element transition to a 2-D element. The transition element has 5 nodes and is shaped like the letter T. The angles between the transition side of the 2-D element and the adjacent 2-D element sides should be close to 90 degrees, otherwise leakage will occur along those sides.



a. Function of a transition element.



b. The nodal connection of a transition element.

Fig. 3.3 Transition element

- ii. **Junction element:** A junction element is a special 1-D element that is used to describe the proper characteristics where three or more 1-D elements intersect. GFGEN is capable of handling three to eight *branching channels* within a junction. A junction element is composed of collocated corner nodes at the junction end of all 1-D elements that connect into the junction. Fig. 3.4 illustrates a junction formed by nodes 3, 4 and 7.

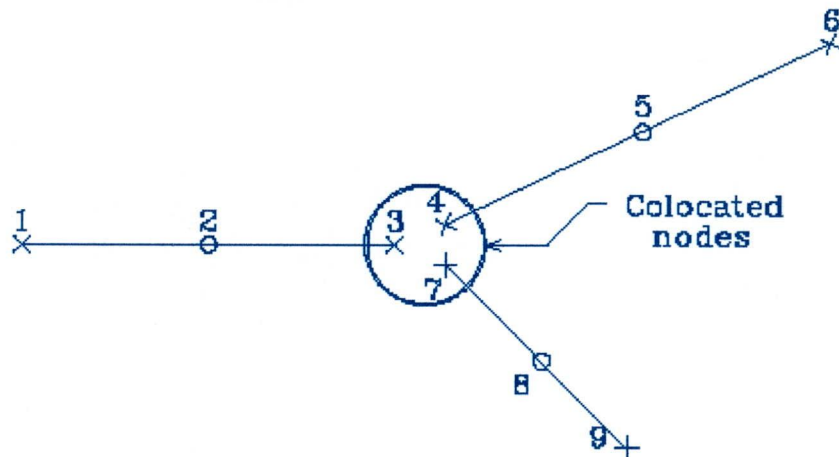


Fig. 3.4 Junction element

- iii. **Control structure element:** A control structure element is a special 1-D element that is used to simulate weirs, gates, etc. The control structure has two colocated corner nodes connecting two 1-D elements.

3.3.2.4 Problem elements

To obtain a good and stable solution it is needed to avoid problematic elements. GFGEN and SMS has the capabilities to identify these elements. There are several categories of issues, which lead to problem elements. These include:

- a. Poor aspect ratio
- b. Erroneous element connections
- c. Mid-side nodes violating the middle third rule
- d. Slope rule error
- e. Needle-like corners
- f. Element edge overlap

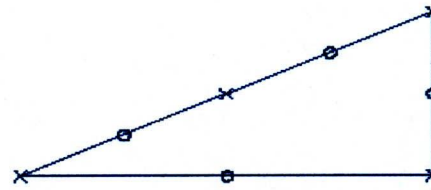
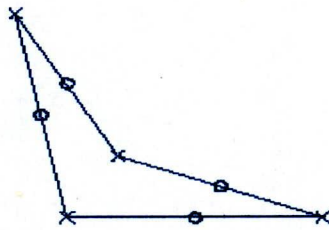
Parts *a* through *c* of Fig. 3.5 illustrates some of the problems, which may occur with straight elements. Fig. 3.6, parts *a* through *c*, illustrates problems, which may occur with curved elements.



a. Poor length to width aspect ratio.

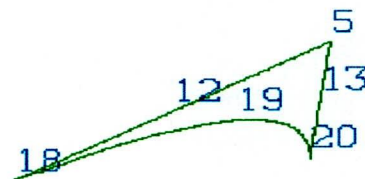
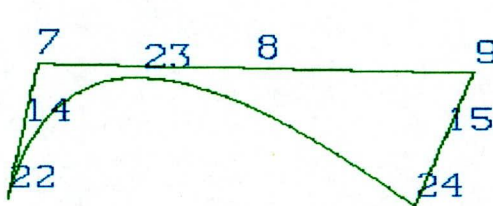


b. Needle-like corner.

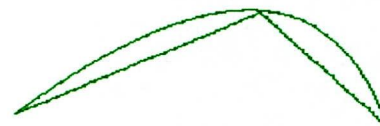
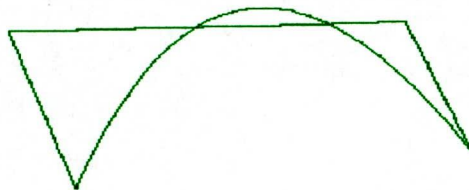


c. Boomerang or 4-sided triangle shapes.

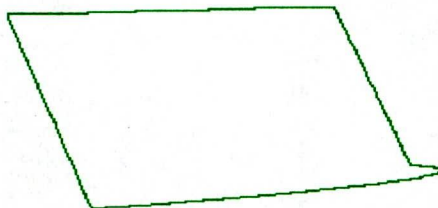
Fig. 3.5 Problem straight elements



a. "Middle third rule" violation.



b. Curved side overrun.



c. "Slope rule" violation.

Fig. 3.6 Problem curved elements

3.4 RMA2

RMA2 is a two-dimensional depth averaged finite element hydrodynamic model. It computes water surface elevations and horizontal velocity components for subcritical, free-surface flow in two-dimensional flow fields.

RMA2 computes a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows. Friction is calculated with the Manning's or Chezy's equation, and eddy viscosity coefficients are used to define turbulence characteristics. Both steady and unsteady state (dynamic) problems can be analyzed.

3.4.1 Applications of RMA2

The program has been applied to calculate water levels and flow distribution around islands; flow at bridges having one or more relief openings, in contracting and expanding reaches, into and out of off-channel hydropower plants, at river junctions, and into and out of pumping plant channels; circulation and transport in water bodies with wetlands; and general water levels and flow patterns in rivers, reservoirs, and estuaries.

3.4.2 Capabilities of RMA2

RMA2 is a general purpose model designed for far-field problems in which vertical accelerations are negligible and velocity vectors generally point in the same direction over the entire depth of the water column at any instant of time. It expects a vertically homogeneous fluid with a free surface. RMA2 has the following capabilities:

- Identify errors in the network.
- Accept either English or standard SI units. (version 4.27 or higher)
- Restart (Hot start) the simulation from a prior RMA2 run and continue.
- Simulate wetting and drying events.
 - Adjust for wetting and drying by element.
 - Account for marsh porosity wetting and drying (wetlands).

- Account for effects of the earth's rotation.
- Apply wind stress involving frontal (storm) passages.
- User selectable turbulent exchange coefficients, Manning's n-values, temperature, etc.
 - or, user selectable equations for automatic dynamic assignment of Manning's n-value by depth (version 4.28 or higher).
 - or, user selectable Peclet number for automatic dynamic assignment of turbulent exchange coefficients (version 4.28 or higher).
- Model up to 5 different types of control structures.
- Compute flow across continuity check lines.

3.4.3 Limitations of RMA2

RMA2 operates under the hydrostatic assumption, meaning accelerations in the vertical direction are negligible. It is two-dimensional in the horizontal plane. It is not intended to be used for near field problems where vortices, vibrations, or vertical accelerations are of primary interest. Vertically stratified flow effects are beyond the capabilities of RMA2.

RMA2 is a free-surface calculation model for subcritical flow problems. More complex flows where vertical variations of variables are important should be evaluated using a three-dimensional model, such as RMA10.

3.4.4 Governing equations

The generalized computer program RMA2 solves the depth-integrated equations of fluid mass and momentum conservation in two horizontal directions. The forms of the solved equations are:

$$\begin{aligned}
 h \frac{\partial u}{\partial t} + hu \frac{\partial u}{\partial x} + hv \frac{\partial u}{\partial y} - \frac{h}{\rho} \left(E_{xx} \frac{\partial^2 u}{\partial x^2} + E_{xy} \frac{\partial^2 u}{\partial y^2} \right) + gh \left(\frac{\partial a}{\partial x} + \frac{\partial h}{\partial x} \right) + \frac{gun^2}{(1.486h^{1/6})^2} \\
 + (u^2 + v^2)^{1/2} - \zeta v_a^2 \cos \psi - 2h\omega v \sin \phi = 0
 \end{aligned}
 \tag{3.1}$$

$$h \frac{\partial v}{\partial t} + hu \frac{\partial v}{\partial x} + hv \frac{\partial v}{\partial y} - \frac{h}{\rho} \left(E_{yx} \frac{\partial^2 v}{\partial x^2} + E_{yy} \frac{\partial^2 v}{\partial y^2} \right) + gh \left(\frac{\partial a}{\partial y} + \frac{\partial h}{\partial y} \right) + \frac{gvn^2}{(1.486h^{1/6})^2} + (u^2 + v^2)^{1/2} - \zeta v_a^2 \cos \psi + 2h\omega v \sin \phi = 0 \quad (3.2)$$

$$\frac{\partial h}{\partial t} + h \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) + u \frac{\partial h}{\partial x} + v \frac{\partial h}{\partial y} = 0 \quad (3.3)$$

where,

- h = depth, m
- u, v = velocities in the Cartesian directions, m/sec
- x, y = Cartesian coordinates, m
- t = Time, sec
- ρ = density of fluid, Kg/m³
- a = Elevation of bottom, m
- E = eddy viscosity coefficient, Pascal-sec
 - for xx = normal direction on x axis surface
 - for yy = normal direction on y axis surface
 - for xy and yx = shear direction on each surface
- g = acceleration due to gravity, m/sec²
- n = Manning's roughness n -value, m^{1/6}
- ζ = empirical wind shear coefficient
- v_a = wind speed, m/sec
- ψ = wind direction
- ω = rate of earth's angular rotation, rad/sec
- ϕ = local latitude.

Eqs. 3.1, 3.2 and 3.3 are solved by the FEM using the Galerkin method of weighted residuals. The elements may be one-dimensional lines, or two-dimensional quadrilaterals or triangles, and may have curved (parabolic) sides. The shape functions are quadratic for velocity and linear for depth. Integration in space is performed by Gaussian integration. Derivatives in time are replaced by a nonlinear finite difference approximation. Variables are assumed to vary over each time interval in the form:

$$f(t) = f(0) + at + bt^c \quad t_0 + \leq t < t_0 + \Delta t \quad (3.4)$$

which is differentiated with respect to time, and cast in finite difference form. Letters a, b, and c are constants.

The solution is *fully implicit* and the set of simultaneous equations is solved by Newton-Raphson non-linear iteration. The computer code executes the solution by means of a *front-type solver*, which assembles a portion of the matrix and solves it before assembling the next portion of the matrix.

3.4.5 Element types supported

RMA2 is capable of supporting different types of elements within the same computational finite element mesh. As shown in GFGEN, the types of elements fit into three basic categories are:

- Two-dimensional elements
- One-dimensional elements
- Special elements
 - Transition elements
 - Junction elements
 - Control structure elements

3.5 SED2D

SED2D is a two-dimensional depth averaged finite element sediment model. It computes bed level changes, sediment concentrations, bed shear stress and water depth for a given period of time. It needs hydrodynamic solutions over the area from any other model.

3.5.1 Applications of SED2D

SED2D-WES can be applied to clay or sand bed sediments where flow velocities can be considered two-dimensional in the horizontal plane. It is useful for

both deposition and erosion studies, and to a limited extent, for stream width studies. The program treats two categories of sediment: 1) non cohesive, which is referred to as sand herein; and 2) cohesive, which is referred to as clay.

3.5.2 Capabilities of the program

Either steady-state or transient flow problems can be analyzed. The exchange of material with the bed can be calculated or suppressed. Default values may be used for many sediment characteristics or these values may be prescribed by input data. Either the smooth wall velocity profile or the Manning's equation may be used to calculate bed shear stress due to currents. Shear stresses for combined currents and wind waves may be calculated.

3.5.3 Limitations of SED2D

Both clay and sand may be analyzed, but the model considers a single, effective grain size during each run. Therefore, a separate model run is required for each effective grain size. Fall velocity must be prescribed along with the water surface elevations, x-velocity, y-velocity, diffusion coefficients bed density, critical shear stress for erosion, erosion rate constants, and critical shear stress for deposition.

The program does not compute water surface elevations or velocities; these data must be provided from an external calculation of the flow field. For most problems, a numerical model for hydrodynamic computations, RMA2-WES, is used to generate the water surface elevations and velocities. An implicit assumption of the SED2D-WES model is that the changes in the bed elevation due to erosion and/or deposition do not significantly affect the flow field. When the bed change calculated by the model does become significant and the externally calculated flow field supplied by the user is no longer valid, then the SED2D-WES run should be stopped, a new flow field calculation should be made using the new channel bathymetry generated by SED2D-WES, and the SED2D-WES run should be restarted with the new flow field as input.

3.5.4 Conceptual basis of SED2D

The program is based on the following conceptual model:

- a. Basic processes in sedimentation can be grouped into erosion, entrainment, transportation, and deposition.
- b. Flowing water has the potential to erode, entrain, and transport sediment whether or not sediment particles are present.
- c. Sediment on the streambed will remain immobile only as long as the energy forces in the flow field remain less than the critical shear stress threshold for erosion.
- d. Even when sand particles become mobile, there may be no net change in the surface elevation of the bed. A net change would result only if the rate of erosion was different from the rate of deposition - two processes which go on continuously and independently.
- e. Cohesive sediments in transport will remain in suspension as long as the bed shear stress exceeds the critical value for deposition. In general, simultaneous deposition and erosion of cohesive sediments do not occur.
- f. The structure of cohesive sediment bed changes with time and overburden.
- g. The major portion of sediment in transport can be characterized as being transported in suspension, even that part of the total load that is transported close to the bed.

3.5.5 Theoretical basis

The derivation of the basic finite element formulation is presented in Ariathurai (1974) and Ariathurai et al. (1977) and summarized below. There are four major computations:

- a. Suspended sediment concentration using convection-diffusion equation with a bed source term
- b. Bed shear stress
- c. Bed source quantity
- d. Bed model

3.5.5.1 Convection-diffusion equation

The basic convection-diffusion equation is presented in Ariathurai, et al. (1977),

$$\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y} = \frac{\partial}{\partial x} \left(D_x \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left(D_y \frac{\partial c}{\partial y} \right) + \alpha_1 c + \alpha_2 \quad (3.5)$$

where,

c = concentration, kg/m³

T = time, sec

u = flow velocity in x-direction, m/sec

v = flow velocity in y-direction, m/sec

D_x = effective diffusion coefficient in x-direction, m²/sec

D_y = effective diffusion coefficient in y-direction, m²/sec

α_1 = a coefficient of the source term, sec⁻¹

α_2 = equilibrium concentration portion of the source term, kg/m³/sec.

This equation is then cast into the finite element form using quadratic shape functions, N ,

$$\begin{aligned} \sum_{j=1}^{NE} \iint_{\Omega_j} \left[N_j \left\{ Q + u \frac{\partial \hat{C}}{\partial x} + v \frac{\partial \hat{C}}{\partial y} - \alpha_1 \hat{C} \right\} + \frac{\partial N_j}{\partial x} D_x \frac{\partial \hat{C}}{\partial x} + \frac{\partial N_j}{\partial y} D_y \frac{\partial \hat{C}}{\partial y} \right] dx dy \\ + \sum_{i=1}^{NL} \int_{\zeta} N_j q_i^s d\zeta = 0 \end{aligned} \quad (3.6)$$

where,

NE is the total number of elements; N is the quadratic shape functions; $Q = (\partial \hat{C} / \partial t) + \alpha_2$ for the transient problem; $\hat{C}$ = the approximate concentration in an element as evaluated from shape functions and nodal point values of c ; NL is the total number of boundary segments; ζ is the local coordinate; q_i^s is the flux from source on boundary i .

The transient equation is expressed as

$$[T] \frac{\partial \{c\}}{\partial t} + [K] \{c\} - \{F\} = 0 \quad (3.7)$$

where each element in the computational mesh contributes the following terms to the global matrix

$$[T] = \iint_D [N]^T [N] dx dy; \quad (3.8)$$

$$[K] = \iint_D \left[K_j \left\{ u \frac{\partial \hat{C}}{\partial x} + v \frac{\partial \hat{C}}{\partial y} - \alpha_1 \hat{C} \right\} + \frac{\partial N_j}{\partial x} D_x \frac{\partial \hat{C}}{\partial x} + \frac{\partial N_j}{\partial y} D_y \frac{\partial \hat{C}}{\partial y} \right] dx dy \quad (3.9)$$

(the steady-state system coefficient matrix);

$$\{F\} = - \iint_D [N]^T \{\alpha_2\} dx dy + \int_{\zeta} [N]^T \{q\} d\zeta \quad (3.10)$$

(the boundary loadings vector).

Applying the Crank-Nicholson scheme, where θ is the implicitness coefficient, gives the following equation, where n refers to the present, $n+1$ to the future time-step, and Δt the computation time interval.

$$\left\{ \frac{[T]}{\Delta t} + \theta [K]^{n+1} \right\} \{c\}^{n+1} = \left\{ \frac{[T]}{\Delta t} - (1-\theta) [K]^n \right\} \{c\}^n + \theta \{F\}^{n+1} + (1-\theta) \{F\}^n \quad (3.11)$$

3.5.5.2 Bed shear stress

Several options are available for computing bed shear stresses using

$$\tau_b = \rho (u^*)^2 \quad (3.12)$$

where, ρ is the water density; u^* is the shear velocity.

a. Smooth-wall log velocity profile,

$$\frac{V}{u^*} = 5.75 \log \left(3.32 \frac{u^* D}{\nu} \right) \quad (3.13)$$

which is applicable to the lower 15 percent of the boundary layer when

$$\frac{u^* D}{\nu} > 30 \quad (3.14)$$

where, V is the mean flow velocity; D is the water depth; ν is the kinematic viscosity of water.

b. The Manning's shear stress equation,

$$u^* = \frac{\sqrt{gVn}}{CME D^{1/6}} \quad (3.15)$$

where, g is the acceleration due to gravity; n is the Manning's roughness value; $CME = 1.0$ for metric units and 1.486 for English units (coefficient).

c. A Jonsson-type equation for surface shear stress (plane beds) caused by waves and currents,

$$u^* = \sqrt{\frac{1}{2} \left(\frac{f_w u_{om} + f_c V}{V + \frac{u_{om}}{2}} \right)} \quad (3.16)$$

where, f_w is the shear stress coefficient for waves; u_{om} is the maximum orbital velocity of waves; f_c is the shear stress coefficient for currents.

d. A Bijker-type equation for total shear stress caused by waves and currents,

$$u^* = \sqrt{\frac{1}{2} f_c V^2 + \frac{1}{4} f_w u_{om}^2} \quad (3.17)$$

3.5.5.3 Bed source quantity

The form of the bed source term, $s = \alpha_1 C + \alpha_2$, as given in Eq. 3.5 is the same for deposition and erosion of both sands and clays. Methods of computing the alpha coefficients depend on the sediment type and whether erosion or deposition is occurring.

For sand transport, the supply of sediment from the bed (i.e., the sediment reservoir) is controlled by the transport potential of the flow and availability of material in the bed. The bed source term is

$$S = \frac{C_{eq} - c}{t_c} \quad (3.18)$$

where,

S = source term

C_{eq} = equilibrium concentration (transport potential)

c = sediment concentration in the water column

t_c = characteristic time for effecting the transition.

There are many transport relations for calculating C_{eq} for sand size material. The Ackers-White (1973) formula was adopted for this model because according to SED2D user manual (Donnell, 1998), it performed satisfactorily in tests by WES and others (White, Milli, and Crabbe 1975; Swart 1976), because it seems to be complete, and because it is reasonably simple. The transport potential is related to sediment and flow parameters by the expressions in the following paragraphs.

The characteristic time, t_c , is somewhat subjective. It should be the amount of time required for the concentration in the flow field to change from c to C_{eq} . In the case of deposition, t_c is related to fall velocity. The following expression was adopted.

$$t_c \left\{ \begin{array}{l} C_d \frac{D}{V_s} \\ or \\ DT \end{array} \right. \quad (3.19)$$

where,

t_c = characteristic time

C_d = coefficient for deposition

D = flow depth

V_s = fall velocity of a sediment particle

DT = computation time interval.

In the case of scour, there are no simple parameters to employ. The following expression is used.

$$t_c \begin{cases} C_e \frac{D}{V} \\ or \\ DT \end{cases} \quad (3.20)$$

where,

C_e = coefficient for entrainment

For clay transport, deposition rates of clay beds are calculated with the equations of Krone (1962).

$$S = \begin{cases} -\frac{2V_s}{D} C \left(1 - \frac{\tau}{\tau_d} \right) \text{ for } C < C_c \\ -\frac{2V_k}{D} C^{5/3} \left(1 - \frac{\tau}{\tau_d} \right) \text{ for } C > C_c \end{cases} \quad (3.21)$$

where,

τ = bed shear stress

τ_d = critical shear stress for deposition

C_c = critical concentration = 300 mg/l.

Erosion rates are computed by a simplification of Partheniades (1962) results for particle by particle erosion. The source term is computed by

$$S = \frac{P}{D} \left(\frac{\tau}{\tau_e} - 1 \right) \quad (3.22)$$

where,

P = erosion rate constant

τ_e = critical shear stress for particle erosion.

When bed shear stress is high enough to cause mass failure of a bed layer, the erosion source term is

$$S = \frac{T_L \rho_L}{D \Delta t} \text{ for } \tau > \tau_s \quad (3.23)$$

where,

T_L = thickness of the failed layer

ρ_L = density of the failed layer

Δt = time interval over which failure occurs

τ_s = bulk shear strength of the layer.

3.5.5.4 Bed model

The sink-source term in Eq. 3.5 becomes a source-sink term for the bed model, which keeps track of the elevation, composition, and character of the bed. Bed change computations utilize the Crank-Nicholson weighting of the time-step contributions.

Sand beds are considered to consist of a sediment reservoir of finite thickness, below which is a non-erodible surface. Sediment is added to or removed from the bed at rate determined by the value of the sink/source term at the previous and present time-steps. The mass rate of exchange with the bed is converted to a volumetric rate of change by the bed porosity parameter.

Clay beds are treated as a sequence of layers. Each layer has its own characteristics as follows:

- a. Thickness.
- b. Density.
- c. Age.
- d. Bulk shear strength.
- e. Type.

In addition, the layer type specifies a second list of characteristics.

- a. Critical shear stress for erosion.
- b. Erosion rate constant.
- c. Initial and 1 - year densities.
- d. Initial and 1 - year bulk shear strengths.
- e. Consolidation coefficient.
- f. Clay or sand.

3.6 Modules

Modules are provided for each of the basic data types supported by SMS. There are six different modules in SMS. Switching from one module to another can be done instantaneously to facilitate the simultaneous use of several data types when necessary. This changes the relevant tools and menus. The data can be converted from one format to another. The following modules are available in SMS:

- a. 2-D mesh module
- b. 2-D boundary fitted grid module
- c. 2-D Cartesian grid module
- d. 2-D scatter point module
- e. Map module
- f. 1-D river hydraulics module

As 2-D grid modules and 1-D module are not used in this study, rest of the modules (map module, scatter module and mesh module) will be discussed in the next subsections.

3.6.1 Map module

The map module is used to manipulate four types of objects: feature objects, image objects, drawing objects and DXF objects.

- i. **Feature objects:** Feature objects in SMS have been patterned after Geographic Information Systems (GIS) objects and include points, nodes, arcs, and polygons. Feature objects can be grouped together into coverages. Each coverage defines a particular set of information. The primary use of feature objects is to construct finite element meshes, finite difference grids, or one-dimensional cross sections. The area included by the polygons defines the domain of the mesh, grid, or limit the extents of cross sections. Each polygon represents a material zone or element type. Special points can be identified in the interior of the domain as areas of particular interest. Boundary parameters such as flow and head values can also be assigned to points or arcs. SMS then generates a mesh points by filling in the interior of the polygonal zones with nodes and elements, a grid by filling in the interior of the polygonal zones with cells, or a one-dimensional model by automatically generating cross sections.

- ii. **Image objects:** Images are scanned maps or aerial photos imported in the form of TIFF or JPEG files. Images are displayed in the background for on-screen digitizing, model placement, or simply to enhance the display of a model.
- iii. **Drawing objects:** Drawing objects provide a simple method for adding annotation to a plot. Drawing objects include text, arrows, lines, rectangles, and ovals.
- iv. **DXF:** DXF objects consist of drawings imported from standard CAD packages such as AutoCAD® or Microstation®. This data may be used as background information or converted to features or scattered data for model generation.

3.6.2 Scatter module

The scatter point module is used to interpolate from groups of the scatter point. Module is used to visualize and apply various types of data. This data typically comes from surveys, digital maps, previous numerical analysis or digitization on screen. The data is stored as sets or groups of 2-D scattered data points with associated values. The most common value is bathymetry and is used to create the geometric representation of the area being modeled.

SMS applies data from scattered data sets to finite element networks or grids via interpolation. This allows poorly distributed elevation data to be assigned to a well-structured set of elements to create the bathymetry of the entire mesh. A variety of interpolation schemes are supported. SMS supports three interpolation schemes including *linear*, *natural neighbor* and *inverse distance weighted*. The module is also used to view and edit survey data.

Interpolation is useful for setting up input data for analysis codes. Generally, the data gathered from a site to be modeled varies in density. Generating a finite element mesh directly from these points would result in a very low quality mesh. Further this data does not lie in a grid for use as a finite difference grid. Interpolation allows the gathered data points to be used as background information. A base mesh or grid can be generated using the mesh module, the grid module or the map module. The actual bathymetry comes from the scattered data. SMS interpolates this data to the created mesh or grid points.

Interpolation may also be used to create data sets for one mesh from data related to another mesh of the same region. For example, we may have a mesh of a river reach for which analysis has been preformed. If a bridge is to be added to the reach, the mesh topology changes. The data from the first mesh can be converted to a scattered data set and then interpolated to the second mesh. This data may be used as initial conditions for the second mesh, or compared to results of analysis run on the second mesh using the data calculator.

A third purpose of interpolation is to create additional data sets from either observed or calculated data.

3.6.3 Mesh module

The 2-D mesh module is used to manipulate 2-D finite element meshes. A finite element mesh is defined as a network of triangular and quadrilateral elements constructed from nodes. The creation of a finite element mesh requires the user to provide bathymetric information and to define the study area extremities. Digitized or survey points can be imported to provide the bathymetry. This type of data is generally not appropriate for use as mesh nodes due to random location and distribution. The map module provides tools for defining the study area boundaries and features from which a finite element mesh can be created. SMS then interpolates the bathymetry data onto the mesh. Various tools and menu commands are provided for manipulating data. A limited number of finite element analysis models are directly supported by SMS. These include:

Hydrodynamic Models

- RMA2 (USACE-WES TABS-MD)
- FESWMS-2DH (FHWA)
- HIVEL2D (USACE-WES)

Water Quality

- RMA4 (USACE-WES TABS-MD)
- SED2D-WES (USACE-WES TABS-MD)

Coastal Modeling

- ADCIRC (USACE-WES)
- CGWAVE (USACE-WES)

Other finite element analysis models can use SMS for pre- and post- processing via the generic model interface or through the generic SMS file formats.

3.7 Post-processor

Post-processing tools inside SMS help to visualize the model solution created by running the simulation through the solver. Post-processing tools available on solution data vary based on the module. Very common tools are described in the following sub-sections.

3.7.1 2-D plots

Plots are useful for many purposes, such as extracting data from two- or three-dimensional objects, model verification and defining one-dimensional river models. Plots are created through the plot wizard. The following plot types are available:

- Computed vs. Observed
- Residual vs. Observed
- Error vs. Simulation
- Error vs. Time-Step
- Error Summary
- Time Series
- Observation Profile
- 1-D Hydraulic Cross Section
- 1-D Hydraulic Hydrograph
- 1-D Hydraulic Profile

3.7.2 Animation

Flow trace animation is a technique used to visualize vector fields in SMS. It can be thought of as dropping tiny drops of dye into a fluid field in a random distribution and watching the flow pattern created. The process can also be thought of as creating particles of zero mass, and letting the vectors in the vector field be forces pushing the particles around. The path of each particle is defined by tracing the particle. Also any time series hydrodynamic solution or sediment solution can be animated using this tool.

3.7.3 Contour plots

The scalar values in a data set represent a sampling of values from a continuous function. Contour lines of constant value created by interpolating the sample values are very useful when visualizing this function. SMS uses linear interpolation across the elements, triangles or grid cells to generate these contours. Contour display is enabled using in the display options dialog of each applicable module. Three contouring methods are available:

- a. The default method is normal linear contours and causes the contours to be displayed as piece-wise linear strings.
- b. If using the color fills between contours method, the same linear contour strings are computed but the regions between adjacent contour lines is filled with a solid color.
- c. If using the cubic spline contours method, the contours are computed in strings and drawn as cubic splines. Drawing the contours as splines can cause the contours to appear smoother.

3.7.4 Vector plots

If the vectors item in the display options dialog is toggled for display, vector plots can be generated using the active vector data set for the object. Vectors are placed at specified nodes or cells, or displayed across the mesh or grid with uniform spacing based on user defined options. The display of vectors can be controlled using the vector options dialog which is accessed through the vector opts command in the data menu or from the data browser or display options dialogs.

SMS provides four methods of filtering vectors. These include:

- Vectors above and below extremes may be turned off.
- Vectors at mid side nodes may be turned off.
- A random sampling of vectors may be used.
- Vector arrows may be displayed on a uniform grid overlaying the mesh or grid. The user specifies the density of this overlaying uniform grid in screen space.

3.7.5 Data browser

Most of the interaction with data sets is accomplished with the data browser. Data browser is used to visualize the solution files from the simulation by any model in SMS. This is also used to export the data sets and save as either ASCII or binary data sets.

3.7.6 Data calculator

The data calculator is used to perform mathematical operations on data sets and/or scalar values to create new data sets. The data calculator is also used to perform any set of mathematical operations. This creates new data sets. Such a data set would be useful for comparing the results of two separate solutions computed by a numerical model.

Chapter 4

Methodology

4.1 General

Three basic models have been used for the present study, which are a steady hydrodynamic model, an unsteady hydrodynamic model and a sediment transport model. The steady model, which has to be generated first, is used to hot-start the unsteady model. Unsteady model is used to obtain hydrodynamic solution files for sediment model and also for hydrodynamic calibration and verification processes. SED2D is an uncoupled sediment model, which requires a solution file from another model. RMA2 is used to generate the solution files for SED2D. Mesh generated under the steady model is used for all the models. Mesh generation technique is described in the next section. Both the unsteady and sediment models are run using boundary conditions of 2001. Unsteady model is calibrated using observed water surface elevation at Aricha for 2001. Sediment model is calibrated by comparing simulated sediment rating curve with the observed curve at Baruria. Then the reach-wise simulated bathymetry has been compared with the observed bathymetry of the same period. The calibration shows a good agreement with measured data for both unsteady and sediment models. If calibration does not show well matches with observed data, roughness and sediment size should change for hydrodynamic and sediment models respectively. The whole modeling process and its inter-linking has been demonstrated with a flow chart in Fig. 4.1. Once the model is calibrated adequately, it would be ready to simulate future scenarios using envisaged boundary condition of some conceivable hydrologic years.

4.2 Methodological steps

At first the study area has been defined using a 17th November 2000 LANDSAT image. The scanned image has been imported in the background using map module. The map module provides tools for defining the study area boundaries and features, from which a finite element mesh can be created. Mesh module is used to manipulate finite element meshes. The bathymetry is interpolated to the mesh nodes by scatter module. Once the mesh is generated, various parameters such as boundary conditions, material roughness, turbulence exchange coefficient, initial

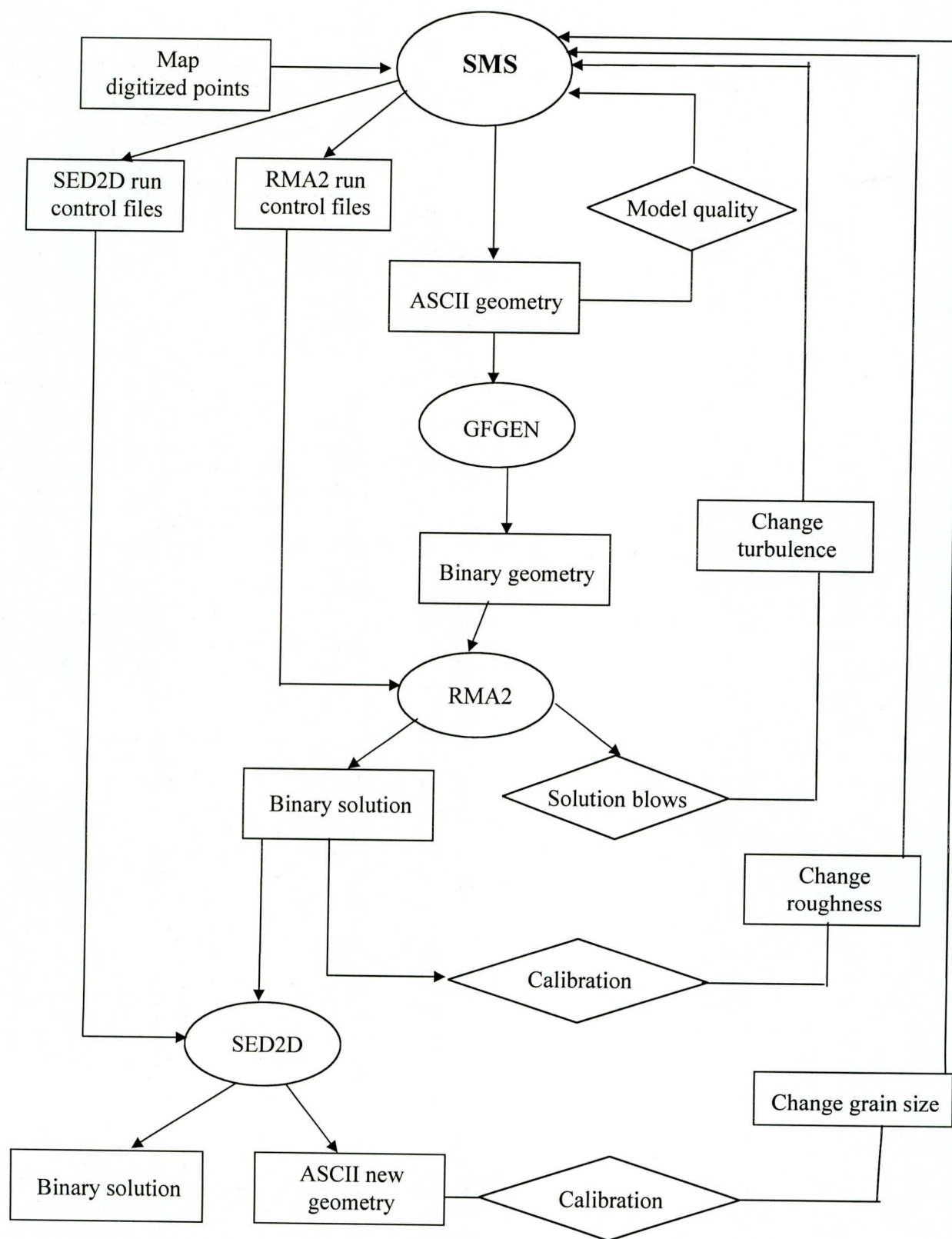


Fig. 4.1 Flow chart of the modeling process

condition, wetting/drying parameters, time-step, sediment characteristics, sediment concentrations etc. are assigned using mesh module. SMS saves all the files required to run RMA2 and SED2D models. The basic steps taken to develop the core model are delineated below.

4.2.1 Mesh generation

Steady hydrodynamic model is the core of all models. Mesh generated under this model is used for rest of the models. Mesh generation is the most important task in any finite element model application.

First the study area defined by using 17th November 2000 LANDSAT image is imported in the map module as background information. The image is registered using three points with their real coordinates. The boundaries of the model are created from the image. Boundaries are created using feature arcs in map module. A *feature polygon* is defined as an area surrounded by three or more feature arcs. These feature polygons are used to describe the different types of area in real world with different materials.

Various types of mesh can be incorporated in these polygons. Among them patch and adaptive tessellation type meshes are used in this model. Patch type mesh consists of eight-noded rectangular elements, which requires four or three feature arcs with equal number of nodes. Adaptive tessellation mesh type consists of six-noded triangular elements are used when boundaries of the polygons are not in regular shape to form patch type mesh.

After each polygon is assigned with their material type and mesh type, the real mesh has been generated with a total of 4185 elements and 12940 nodes. It has got four open boundaries. This mesh has been generated with their real coordinates only. Bathymetry of the mesh is yet to be assigned with scatter module. Before any further development, mesh quality should be checked to obtain a stable and accurate solution. This can be done within SMS environment easily. Various criteria could be checked, these include: maximum interior angle, minimum interior angle, maximum slope, maximum change of area, and ambiguous gradient. Various tools are given to minimize or remove the problematic elements from the mesh. After several iterations, mesh is finally ready to be incorporated with bathymetry data, boundary conditions, material roughness, turbulence parameters and wetting/drying parameters. The final mesh generated for the study region is shown in the Fig. 4.2

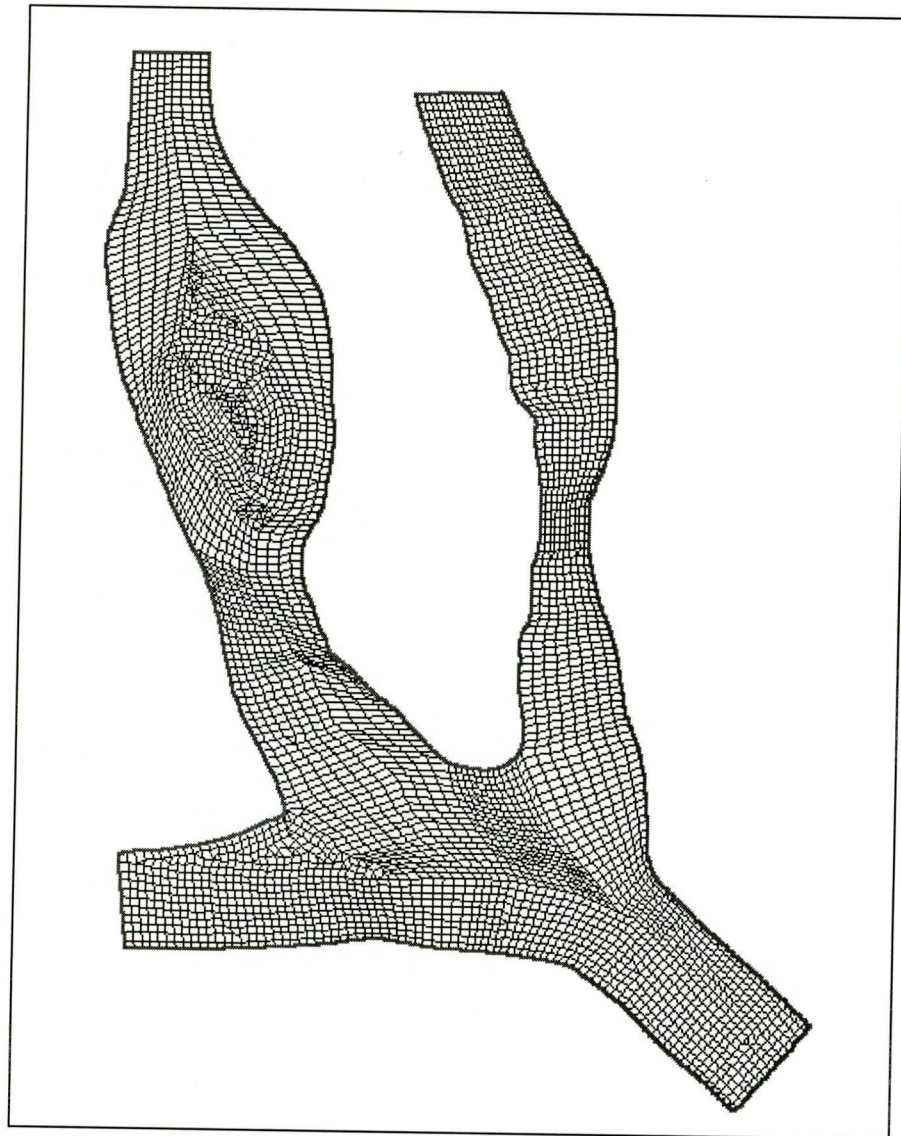


Fig. 4.2 Generated mesh into the study area

4.2.2 Bathymetry

Scattered survey data on bathymetry are interpolated to mesh nodes using scatter module. Normally bathymetry data are measured in random fashion. Mesh can be generated using these measured bathymetric points. But mesh generated in this way would not give better quality model. For this the study area has been developed with good quality meshes and then surveyed bathymetric data are interpolated into those mesh nodes. Normally linear interpolation is used but other methods are also available under SMS environment.

BIWTA lean period bathymetry charts surveyed during April 2001 has been used to set-up the initial bathymetry of the model. The distribution of measured and interpolated bathymetries is shown in Figs. 4.3(a) and 4.3 (b). Areas where data are missing, February 1999 surveyed data of BIWTA and of BWDB cross-sections as shown on to the satellite image below, have been used to fill-up the gaps.

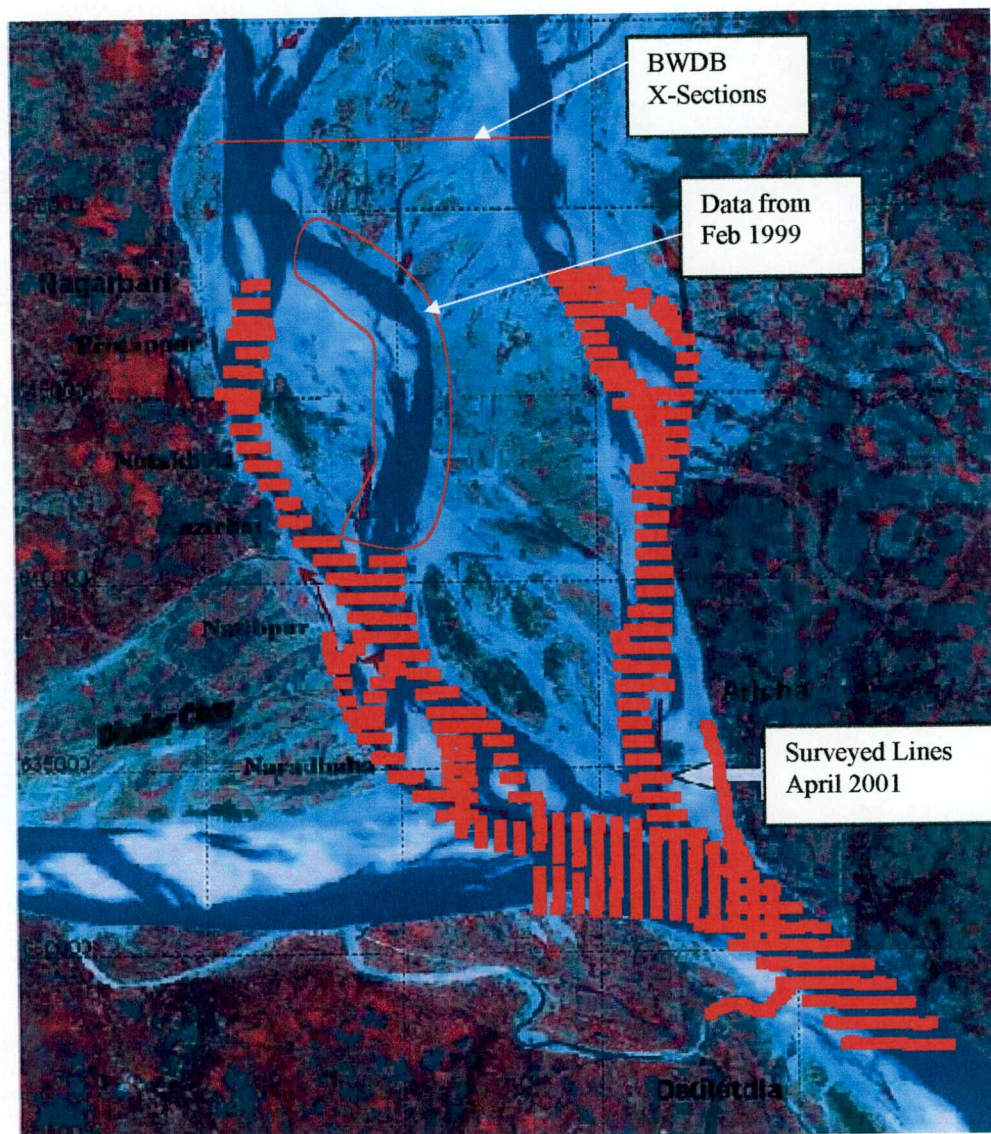


Fig. 4.3a BIWTA measured bathymetry on to the satellite image of November 2000

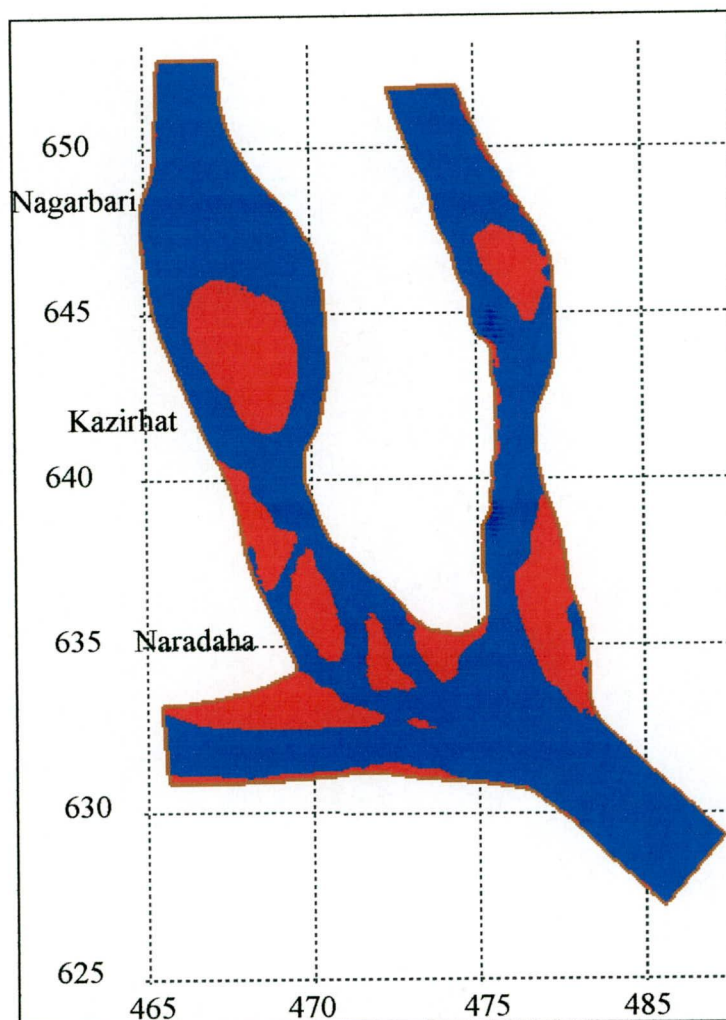


Fig. 4.3b Corresponding interpolated bathymetry based on measured data (using bed elevations of 2.0 m PWD below and above)

4.2.3 Boundary conditions

Boundary condition is an essential component for hydrodynamic modeling. Normally discharge is assigned to upstream inflow boundary and water level or rating curve to downstream boundary. The model has two discharge boundaries (northern end) in the Jamuna, one discharge boundary in the Ganges, and one water level boundary (southern end) in the Padma. In SMS environment, boundary condition can be assigned to every node or in a line of that boundary. Node-strings are lines along the boundary are used to assign boundary condition and also checks for continuity of discharge.

The rating curve at Bahadurabad has been used to generate discharge boundaries at upstream northern end. The distribution of the discharges through those two branches is generated according to their conveyance functions of the channels. Interpolated water level data from Aricha and Baruria have been applied to downstream boundary in the Padma. The discharge boundary applied to the Ganges is

calculated by subtracting the discharges through Gorai Railway Bridge from the discharges through Hardinge Bridge. The discharge and water level hydrographs of monsoon, June-October for 2001-2003, as shown in Fig. 4.4 have been taken to apply into the model as boundary conditions, and subsequent calibration purposes.

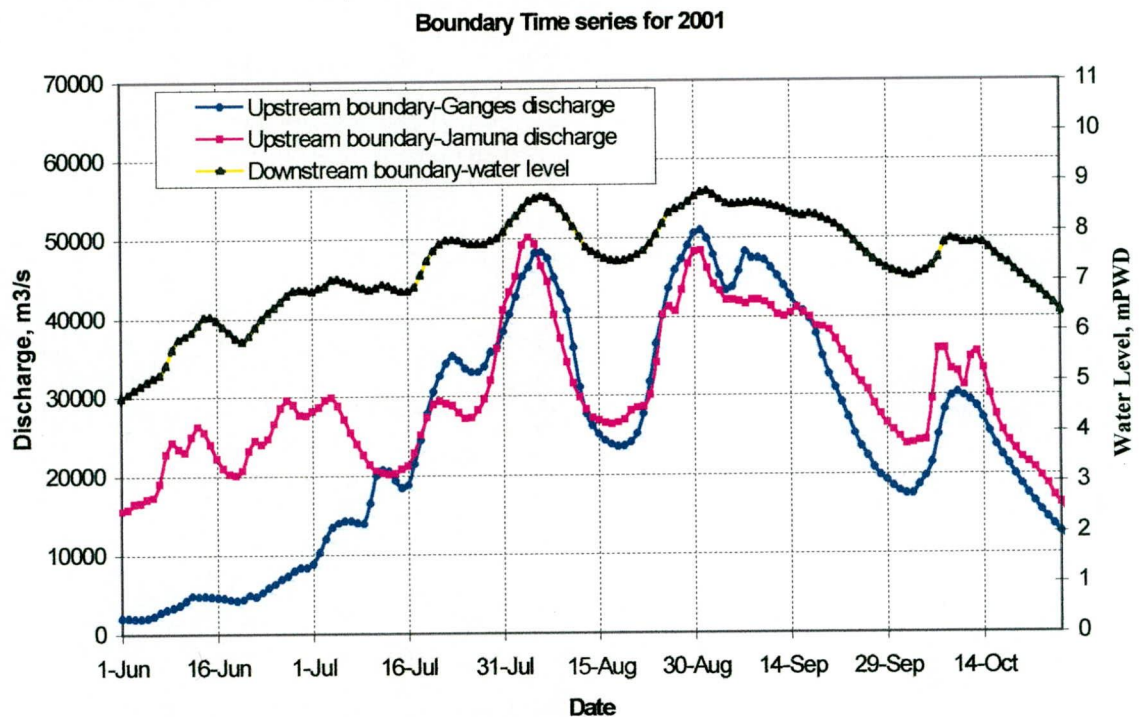


Fig. 4.4a Time series hydrographs from June to October 2001 used in the model as boundary conditions

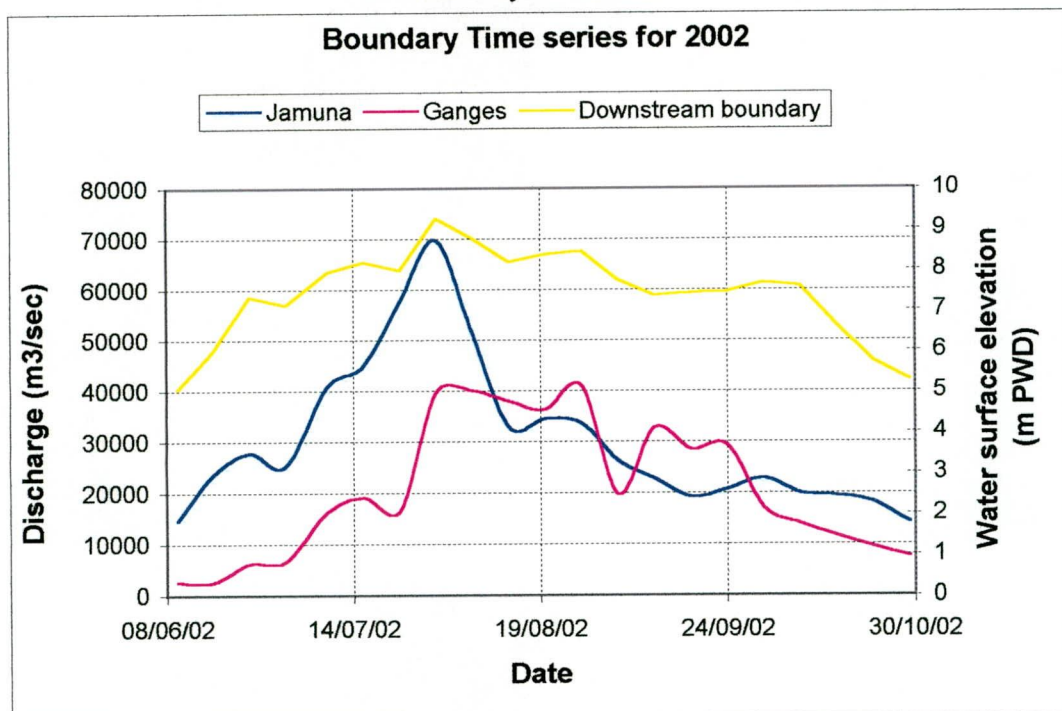


Fig. 4.4b Time series hydrographs from June to October 2002 used in the model as boundary conditions

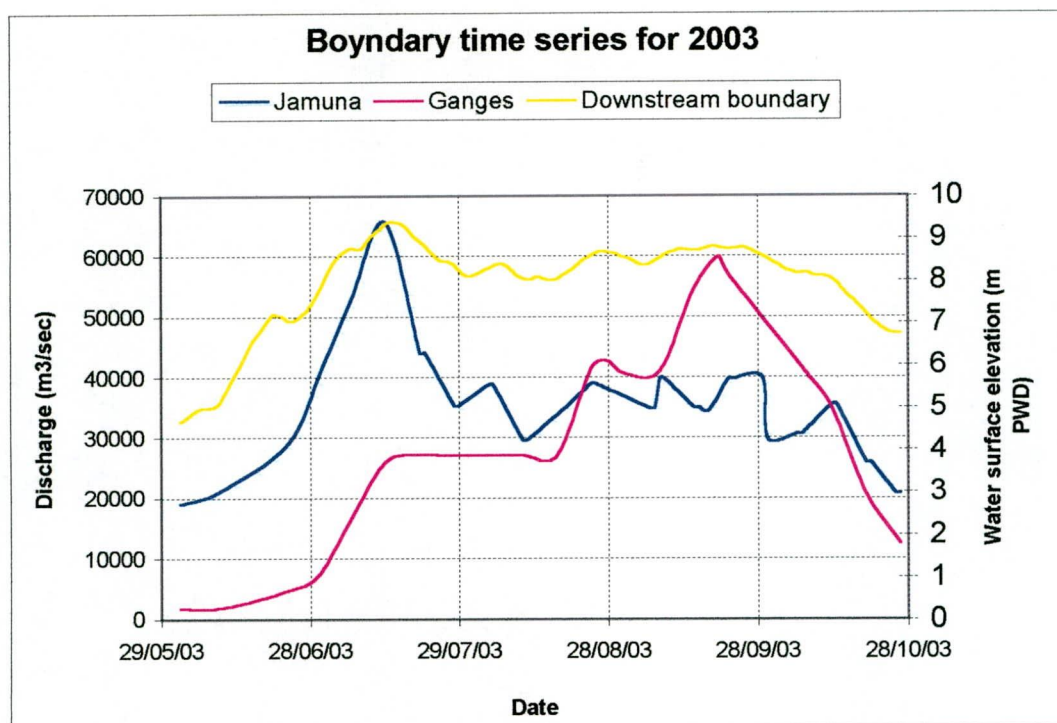


Fig. 4.4c Time series hydrographs from June to October 2003 used in the model as boundary conditions

4.2.4. Roughness parameters

Roughness is one of the primary verification tools for RMA2. Changing the bed friction provides some control over the fluid velocity magnitude and direction. Roughness can be assigned in every node or element. Different material can be defined by different values of roughness. Roughness is assigned in RMA2 by two ways:

- i. Manual roughness assignment: In this method roughness values are assigned directly in RMA2. Different materials are assigned with different single values. Values are used in all nodes associated with that element type.
- ii. Automatic roughness assignment: This method provides real adjustment of the roughness coefficient. Automatically changes the Manning's n-value of an element depending upon the depth at each gauss point. Generally deeper the water, the lower the roughness value.

For the study area initial roughness is given using Manning's roughness value. Depth varying roughness is used with the lower value of 0.025 where water depth is above 0.5 m and 0.055 is used when water depth becomes lower than 0.5 m. After calibration it has been changed to match with the observed values.

4.2.5 Turbulence parameters

All forms of numerical models require some form of stabilization. The Galerkin method of weighted residuals employed by RMA2 does not include any inherent form of stabilization other than the *eddy viscosity* term. The Galerkin formulation requires a certain amount of turbulence to achieve stability and not impair the solution.

The fluid momentum transfer due to exchanges of fluid masses moving at different speeds is called turbulence exchange. It is approximated in the governing equations by multiplying a *turbulent exchange coefficient*, E , by the second derivative of the velocity with respect to the x and y directions. The Metric units for turbulence are $\text{kg}\cdot\text{sec}/\text{m}^2$. The program allows for the exchange coefficient to be specified in a local coordinate system for each element. Although it is difficult to establish the value for E , analogy with physical conditions suggests that turbulence exchanges depend on the momentum of the fluid and the distance over which that momentum is applied, divided by the fluid velocity and the surface area of the element. Therefore, as the element size increases, E should increase, or as the velocity increases, E should increase, in order for the rate of turbulent exchange to remain constant.

Turbulent exchanges are sensitive to changes in the direction of the velocity vector. Conversely, small values of the turbulent exchange coefficients allow the velocity vectors too much freedom to change directions in the iterative solutions. The result is a numerically unstable problem for which the program will diverge rather than converge at a solution. The recourse is to continue increasing the, E , until a stable solution is achieved.

There are two basic ways to control the turbulent exchange coefficient, E :

- i. Assignment by material type: The first way to assign the turbulent exchange coefficient, E , is to assign a particular value for each individual material type with the EV card. The table below provides some representative ranges of turbulence exchange coefficient.

Table: 4.1 Turbulence coefficients for various type of problem (Donnell, 2000)

Type of Problem	E, lb-sec/ft ²
Homogenous horizontal flow around an island	10-100
Homogenous horizontal flow at a confluence	25-100
Steady-State flow for thermal discharge to a slow moving river	20-1000
Tidal flow in a marshy estuary	50-200
Slow flow through a shallow pond	0.2-1.0

- ii. Automatic assignment by Peclet number: The second way to assign the turbulent exchange coefficient, E, is to allow the model to automatically adjust E after each iteration based upon a provided Peclet number, which is based upon the unique size and calculated velocity within each element. The Peclet number defines the relationship between the velocity, elemental length, fluid density, and E. Peclet number (*P*) is recommended to be between 15 and 40. Relationship between Peclet number and turbulence exchange coefficient is:

$$P = \frac{\rho u dx}{E} \quad (4.1)$$

where:

Coefficient	English Units	Metric Units
ρ = fluid density	1.94 slugs/ft ³	1 grams/cm ³
u = average elemental velocity	fps	mps
dx = length of element in streamwise direction	ft	m
E = eddy viscosity	lb-sec/ft ²	Pascal-sec

In this study turbulence by Peclet number is used to assign the eddy viscosity. Peclet number gives the better assignment as it calculates eddy viscosity after each iteration. Peclet number of 20 is used for the whole model.

4.2.6 Initial condition

Initial conditions need to be defined for all hydrodynamic and sediment transport models. Time series boundary conditions at specified upstream and downstream ends are available at BWDB database. Other than these time series boundary conditions, discharges or water levels at all the other points of the model are generally not available. So, for defining the initial conditions at all the other points of the model, it becomes essential to run a steady hydrodynamic model with the specified boundary discharge and water level in defined upstream and downstream ends. The first steady run is a *cold-start*, used when initial water levels for nodes other than the downstream boundary are unknown. In cold-start, initial downstream water surface elevation must be provided in such a manner that all the mesh nodes of the model remain submerged, otherwise the steady solution may diverge. For simplicity, the initial water surface elevation for the whole model is assumed to be the same as the downstream water level boundary condition, and accordingly velocity is assumed to be zero at all the nodes. For the first run, initial water surface elevation is chosen much higher than the maximum bed elevation from amongst all the mesh nodes. Using special technique (revision card) downstream boundary water surface elevation is decreased gradually towards desired water level boundary condition.

For the present study, as we intend to start our simulation from 6th June 2001, the water level that has been found at 5.1 m PWD for the aforesaid time, is chosen as our desired downstream boundary. As such, 17668 m³/s and 2062 m³/s inflow boundary discharges have been found for combined Jamuna (eastern and western) and Ganges, respectively for the corresponding downstream 5.1 m PWD water level. But the initial water levels at nodes other than the downstream boundary are unknown at the corresponding initial boundary discharges. Therefore, it is desired to start the first run of the cold-start with an initial water level elevation of 12 m PWD, which is much higher than the maximum bed elevation found at 9 m PWD. Using revision card with 0.1 m decrease rate, the downstream boundary water surface elevation has been reduced to desired 5.1 m PWD. This cold-start for the present study has required more than 170 iterations to get into the solution for initial condition. Once the cold-start solution is obtained, it is used as a *hot-start* for other steady or unsteady models. The hot-start is a solution file used as an initial condition for subsequent unsteady model runs.

4.2.7 Wetting drying parameter

In the real world, there may be times where portions of an area may become devoid of water and later become wet again. This process of flooding and draining is referred to as wetting and drying. Any nodes become wet or dry respectively when water depths become higher or lower than the threshold values. RMA2 provides means like, *elemental elimination method* (DE card), *marsh porosity method* (DM card) and combination of these two (DE and DM cards) methods, to handle the events of wetting and drying processes in the simulation.

Elemental elimination (DE card) method in which an element will be removed if any nodes become dry by going below a certain depth of water and will be rewetted if all nodes become wet by going above a certain depth of water.

In marsh porosity (DM card) method, elements will never be removed. A certain flow of water will be always on the elements though the water surface elevation has gone below the bed elevation. As this method does not remove any element, there is no chance to produce any zigzag boundary which has been observed during elemental elimination method. This will reduce the chance of numerical instability.

In combination method, if all nodes become dry then an element will be removed from the solution by DE card and the element will be rewetted again if any nodes become wet. This combination method is also giving better numerical stability.

While elemental elimination method is used to simulate the wetting/drying phenomena, the dry depth, below which any nodes will be treated as dry, is given as 0.01 m and wetting depth, depth above which any node will become wet again, is given as 0.11 m. A tolerance of 0.1 m is provided to minimize the possibility of alternate drying and wetting of any node during iterations in the same time-step. Otherwise this will produce numerical instability. In marsh porosity method, if water level falls below the bed elevations of all the nodes of an element, a minimum flow (say 1 percent) has been set for the element to keep the element in the solution domain. This method basically has been used while the model is in the process of simulating the receding hydrograph. The third option combination method has not been used for the present study.

4.3 Steady hydrodynamic model

As mentioned above steady hydrodynamic model is used to develop hot-start file for unsteady model. For the steady model development, inflow discharges of $17668 \text{ m}^3/\text{s}$ (Western anabranch = $8834 \text{ m}^3/\text{s}$ and Eastern anabranch = $8834 \text{ m}^3/\text{s}$) for Jamuna and $2062 \text{ m}^3/\text{s}$ for Ganges are taken, corresponding to downstream 5.1 m PWD water level. The steady model has used a mesh that is being developed from the satellite image of November 2000 (Fig. 4.2). The bathymetry data (Fig. 4.3) that surveyed on April 2001 by BIWTA has been applied to the mesh nodes of the model for subsequent simulation. This steady solution has been obtained through cold-start run and subsequent use of revision cards as explained earlier in Article 4.2.6. Roughness and turbulence are assigned globally for all the nodes.

4.4 Unsteady hydrodynamic model

Unsteady model is developed for hydrodynamic simulation and also to create binary solution file for the sediment model. The same mesh and bathymetry, as applied under steady model, are in used. The time series boundary conditions for discharges and water levels are shown in Fig. 4.4. The boundary conditions show that the model has been run for monsoon season, starting from June till October 2001.

Selection of proper time-step is a key parameter in any hydrodynamic model. In explicit schemes time-step is restricted by stability criteria, which requires fulfillment of stringent Courant condition. But in any implicit method time-step is usually unrestricted by stability requirement, however, accuracy of the results may have an impact on selecting the time-steps. The required computational time-step may be dependent upon element sizes, strength of flows, flow patterns and the rate of change in boundary conditions. The procedure of choosing a time-step is that, we have to run a test case in which the time-step size is reduced until the solution does not change and use this interval as a time-step.

To reduce the computational time, to complete a simulation, the time-step should be as large as possible to capture the extremes of the dynamic boundary conditions and maintain numerical stability. In this study one-hour is taken as a computational interval for unsteady simulation.

Calibration has been done by comparing the computed water surface elevation with the observed water surface elevation at Aricha for 2001. And validation has been done with the observed water surface elevations at Aricha for 2002.

4.5 Sediment model

Once the calibration of the hydrodynamic model is complete, sediment model is ready for running using results obtained from hydrodynamic model. As described earlier SED2D is not coupled with hydrodynamic under SMS environment. So it requires velocity field of hydrodynamic solution from another model.

The basic assumption of SED2D is that it stops whenever the bed level changes exceed 25 percent of the water depth at any nodes in the model. Experimentation with this study shows that as the bed level does not change more than 25 percent normally in a week, the running period for hydrodynamic and sediment models have been set as one week. So the flow field generated by hydrodynamic model for a week is being supplied into the sediment model to generate updated bathymetry at the end of same one week period. However bed level changes exceeded 25 percent within the week, SED2D automatically stopped, and created an updated geometry file. A new hydrodynamic solution has been initiated with the updated bathymetry for subsequent sediment run. The whole operation has been continued until the whole time period is completed. This process has been illustrated with the flow chart in Fig. 4.5.

Initial suspended sediment concentrations have been generated using an arbitrary value of 0.23 ppt under the steady hydrodynamic solution file. These concentrations have been used as a hot-start for the unsteady sediment model. For inflow boundaries, time series suspended sediment loadings have been generated from the observed sediment-rating curves at Bahadurabad and Hardinge bridge stations. These rating curves have been shown in Fig. 4.6. However no downstream sediment data is needed for SED2D.

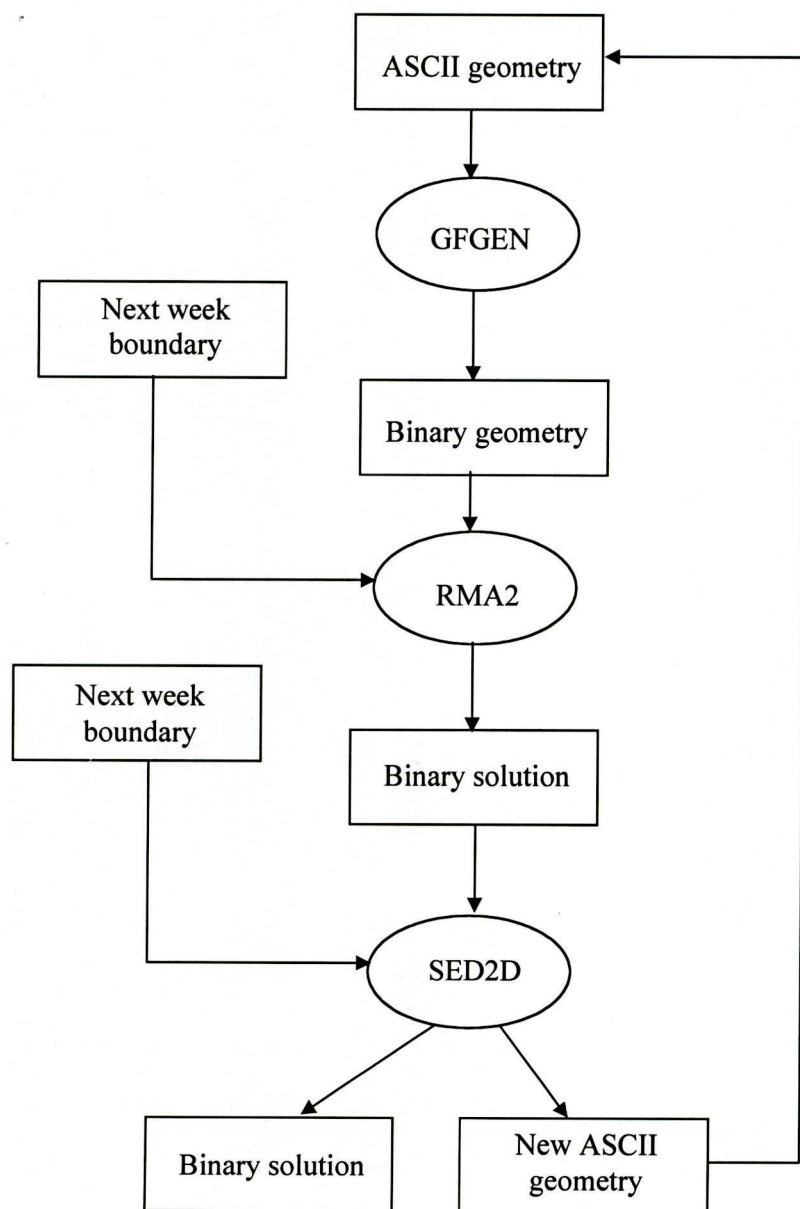
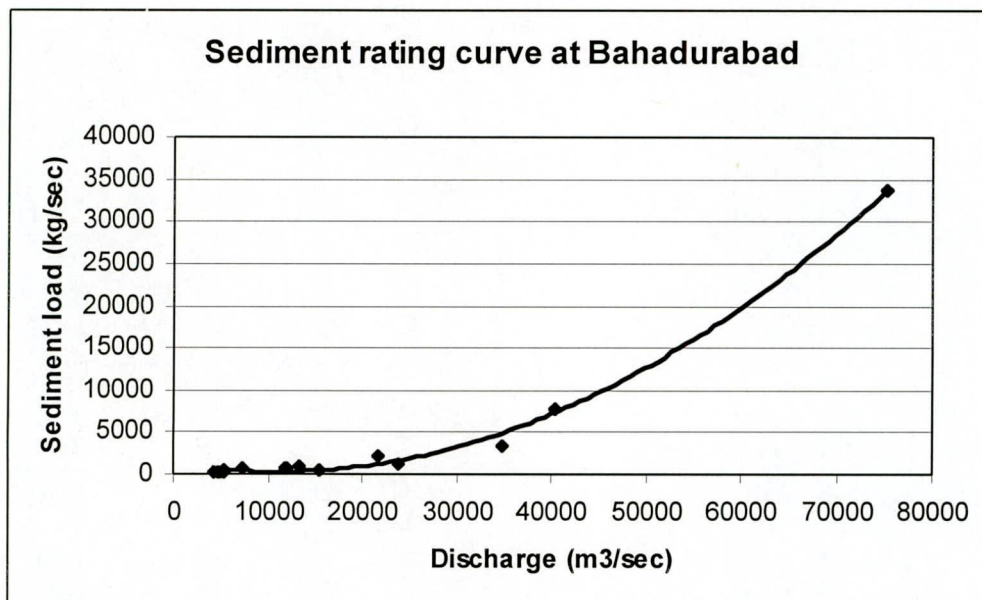
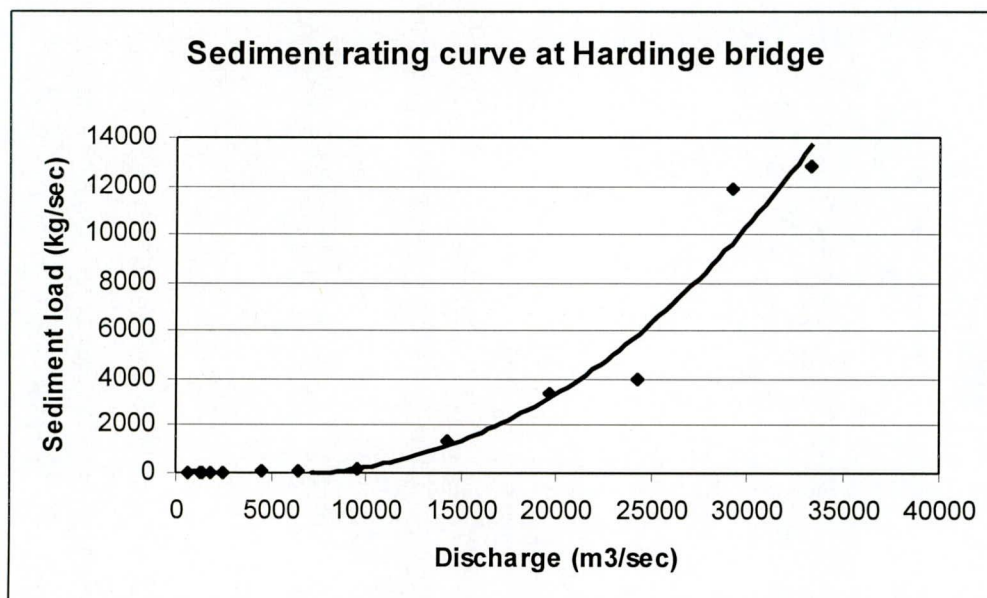


Fig. 4.5 A flow chart showing operations in sediment modeling



(a) Sediment rating curve at Bahadurabad



(b) Sediment rating curve at Hardinge bridge

Fig. 4.6 Sediment rating curves at Bahadurabad and Hardinge bridge (FAP 24, 1996)

4.6 Calibration and validation

Model calibration is an important step in the model development process. Without calibration it is unlikely that any modeling activities would produce satisfactory solutions for real world situations. Lot of uncertainties exists related to input as model geometry, boundary conditions, roughness, eddy viscosity etc., which can have momentous impact on the model solutions. Once geometry and boundary conditions have been obtained with reasonable accuracy from the field, it is common practice to set them out of preview of the calibration process. Mostly roughness and eddy viscosity are the parameters to play with to obtain an adequate match with the observed field conditions. It is possible to make educated guesses as to how these variables should be set, but better approach is to adjust these variables such that model calibrates against known observed conditions.

The RMA2 user guide suggests that geometry and study design are the most important factors for the creation of a reasonable flow model. On the other hand the parameters roughness and eddy viscosity, which are used for calibration purposes, may only account for 16 percent of the variation in their results (Fig. 4.7).

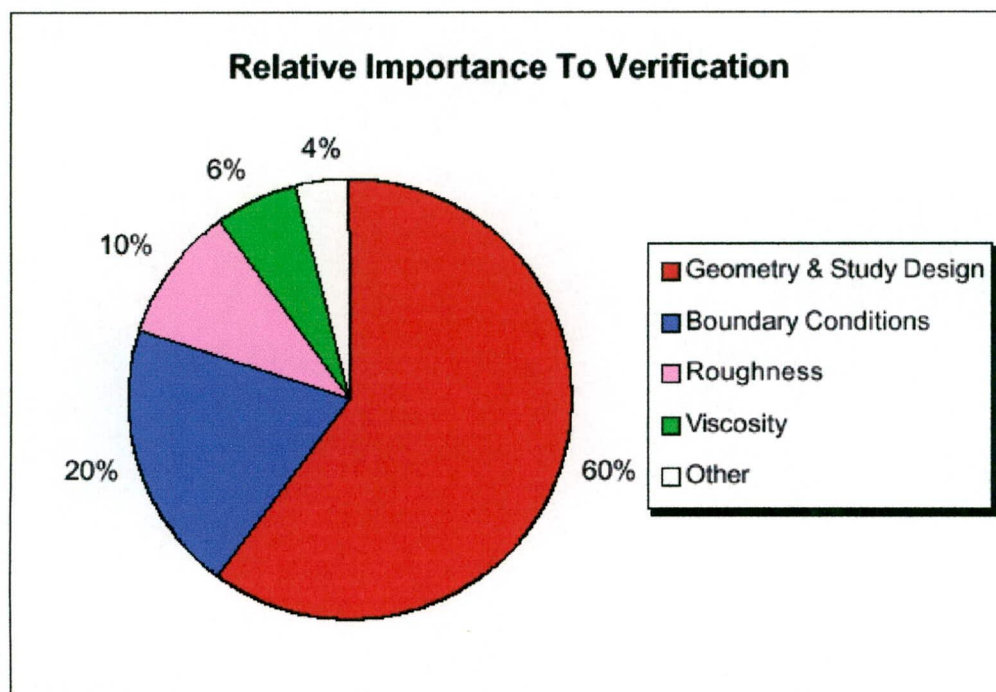


Fig. 4.7 Relative importance of user defined variables to model results
(Donnell, 2000)

SMS allows the user to input files containing point measurements of depth, velocity, or water surface elevation for model calibration. These measurements can be

compared to model estimates. SMS can graphically display a chart of computed vs. observed values or can export these data to a *comma-delimited file*. By making changes to model geometry and material parameters, the results can be adjusted to better match observed condition. If observations are available at more than one period, the model can be calibrated at one period and then validated against others.

The RMA2 user manual warns the user against assuming that model calibration and validation is a two-step process. The arguments are sound and are presented as follows: (Donnell, 2002)

1. All field data are in error, and sometimes dramatically in error. Thus, they are not an absolute standard (a necessary characteristic of calibration), and may not be even a good approximate standard.
2. Field measurements include a variety of effects that may not be reproduced in the model (for example, groundwater flow into the model).
3. Conditions often change between field surveys, mandating that coefficients should also change (for example, differences in bed forms at different flows may dictate a change in bed roughness coefficients).
4. Most natural waterways cannot be adequately characterized by two field data sets. Five or ten may be needed, but available resources usually limit the field data to a non-ideal level.
5. If the model reproduces one field data set adequately, but not the second, one may decide whether to:
 - a) Proceed with modeling, conceding an incomplete verification.
 - b) Continue adjusting/revising to obtain a balanced quality of reproduction.
 - c) Conduct a re-analysis/re-collection of field data.
6. Validation is a multi-step process of model adjustments and comparisons, leavened with careful consideration of both the model and the data. It is not a simple two-step procedure, and the term calibration should not be used.

Observed and simulated water elevations

For hydrodynamic calibration computed water surface elevations are compared with the observed water surface elevations at Aricha for June-October 2001. Calibration results showed that computed values are within ± 0.3 m (Fig. 4.8a). However, a good match in phases is observed in the figure. Results are within the 95

percent confidence band of the observed values (Fig. 4.8b). Roughness is adjusted during calibration to $n = 0.029$ when water depth is higher than 0.5 m and $n = 0.045$ when water depth is lower than 0.5 m. The computed water surface elevations are validated with observed water surface elevations for June-October 2002 as shown in Figs. 4.9a and 4.9b.

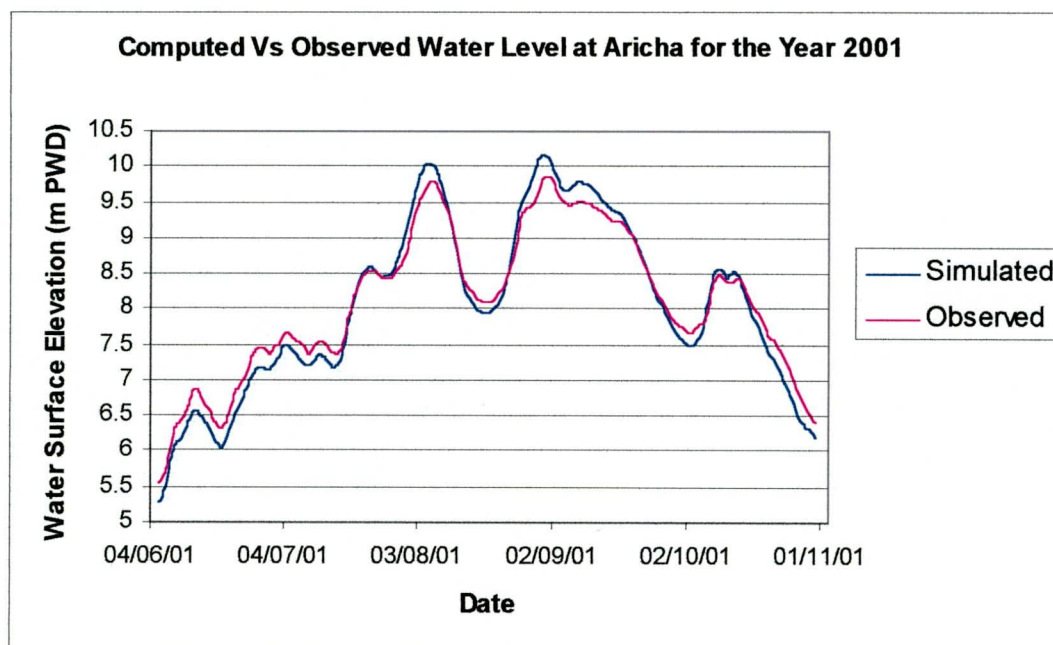


Fig. 4.8a Computed vs. observed water surface elevations for 2001 at Aricha

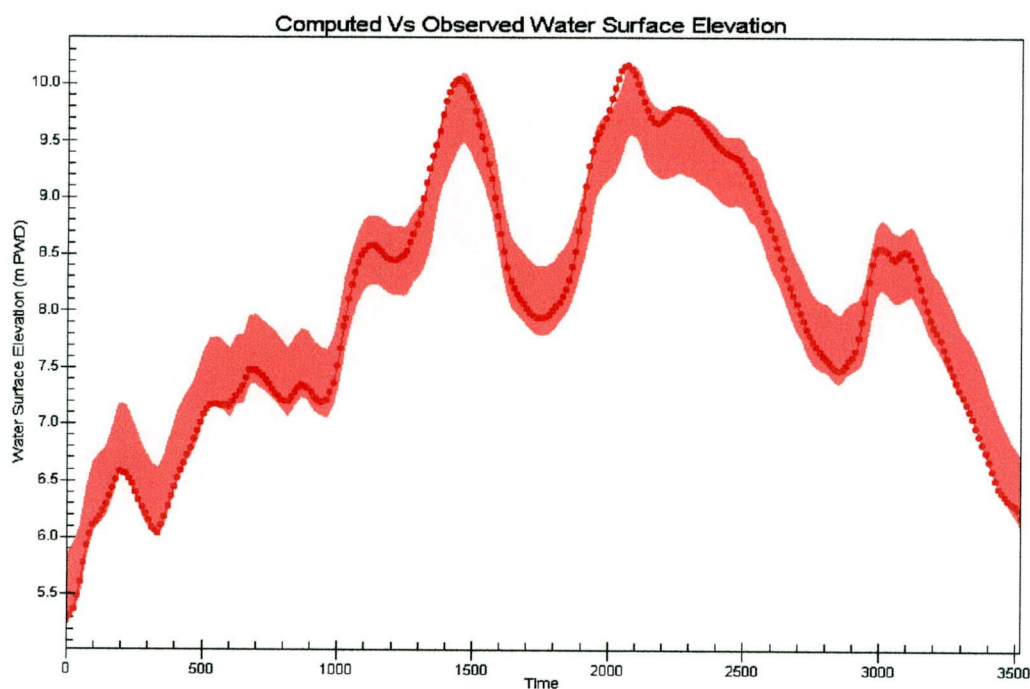


Fig. 4.8b Computed water surface elevations and 95% confidence band of observed values for 2001 at Aricha

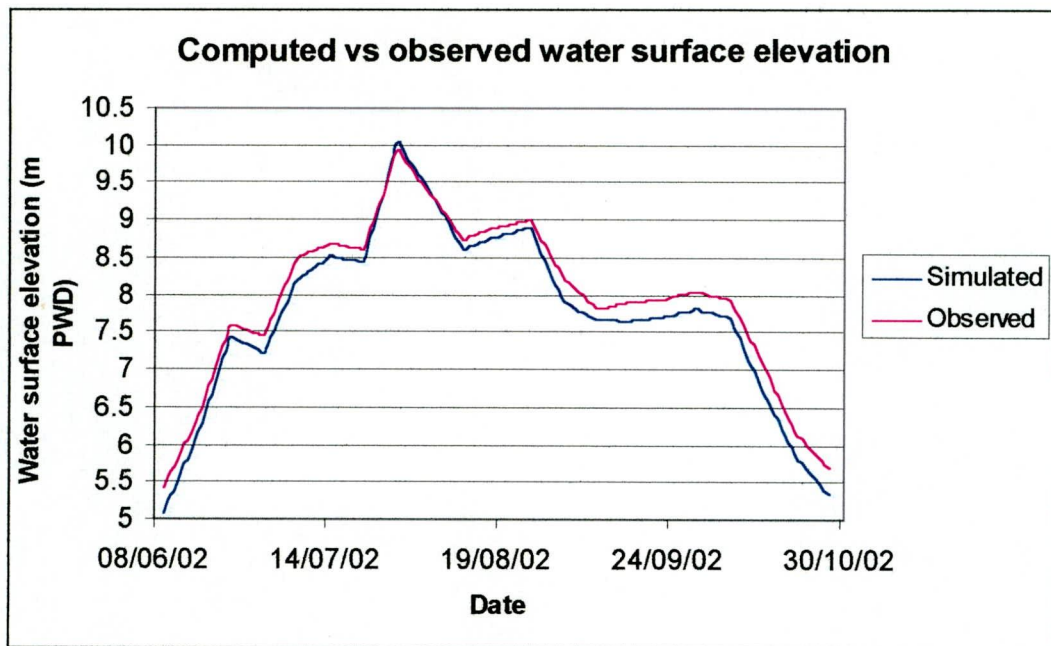


Fig. 4.9a Computed vs. observed water surface elevations for 2002 at Aricha

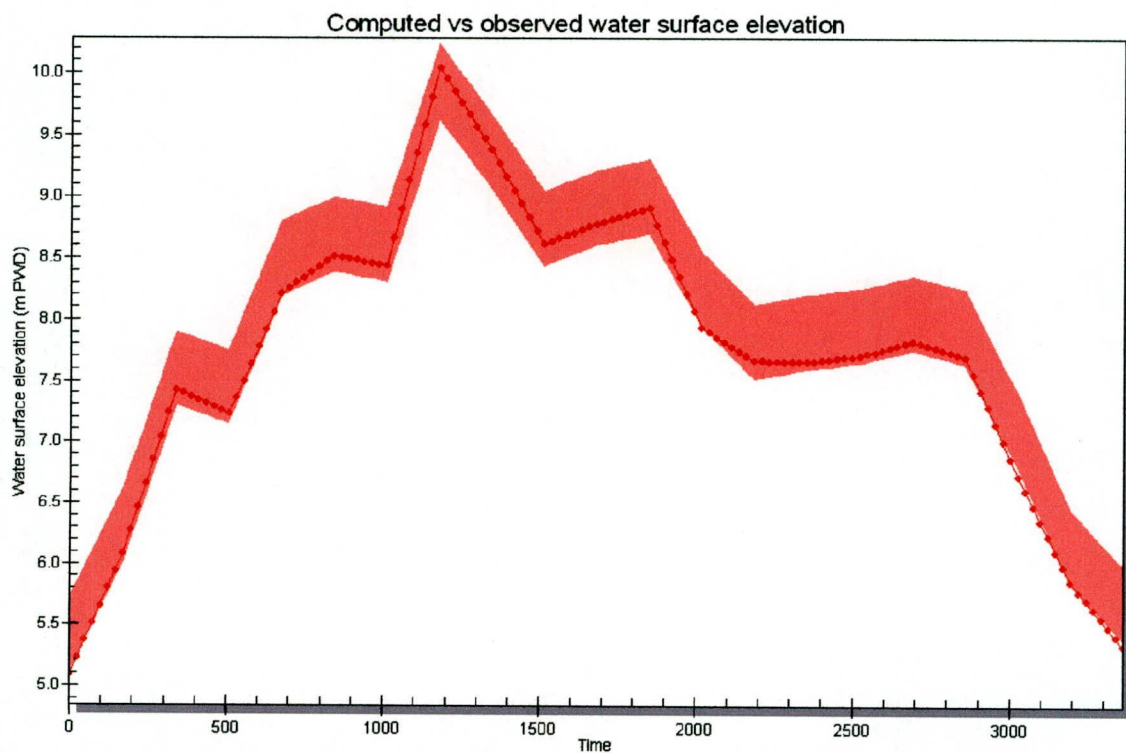


Fig. 4.9b Computed water surface elevations and 95% confidence band of observed values for 2002 at Aricha

Observed and simulated bed elevations

For sediment model simulated bathymetry of 23rd August 2001 is compared with the observed bathymetry of 23rd August 2001. Results are presented as the bed elevations above and below 2.0 m PWD in Fig. 4.10a. From the results it is found that simulated bed elevations adequately matched the observed bed elevations. The sediment model is also validated with simulated bathymetries of end of October 2002 and end of October 2003 with observed bathymetries of November 2002 and November 2003 respectively as shown in Fig. 4.10b.

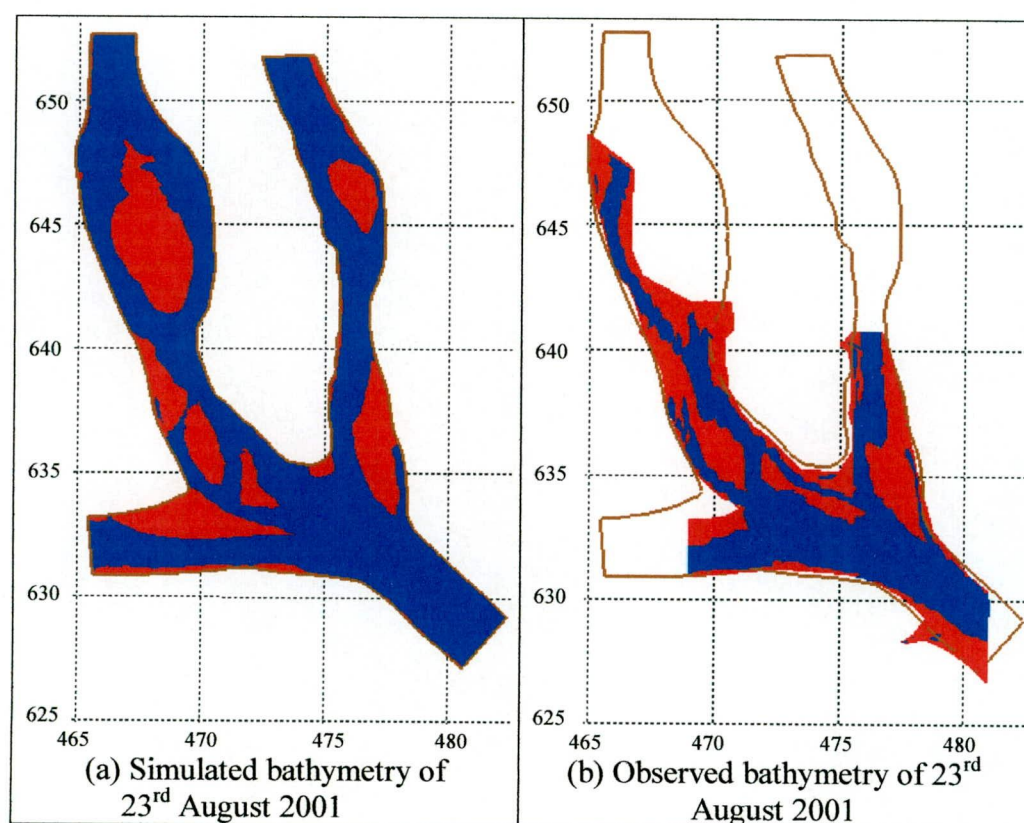


Fig. 4.10a Calibration of sediment model with observed bathymetry for bed elevations 2.0 m PWD below and above

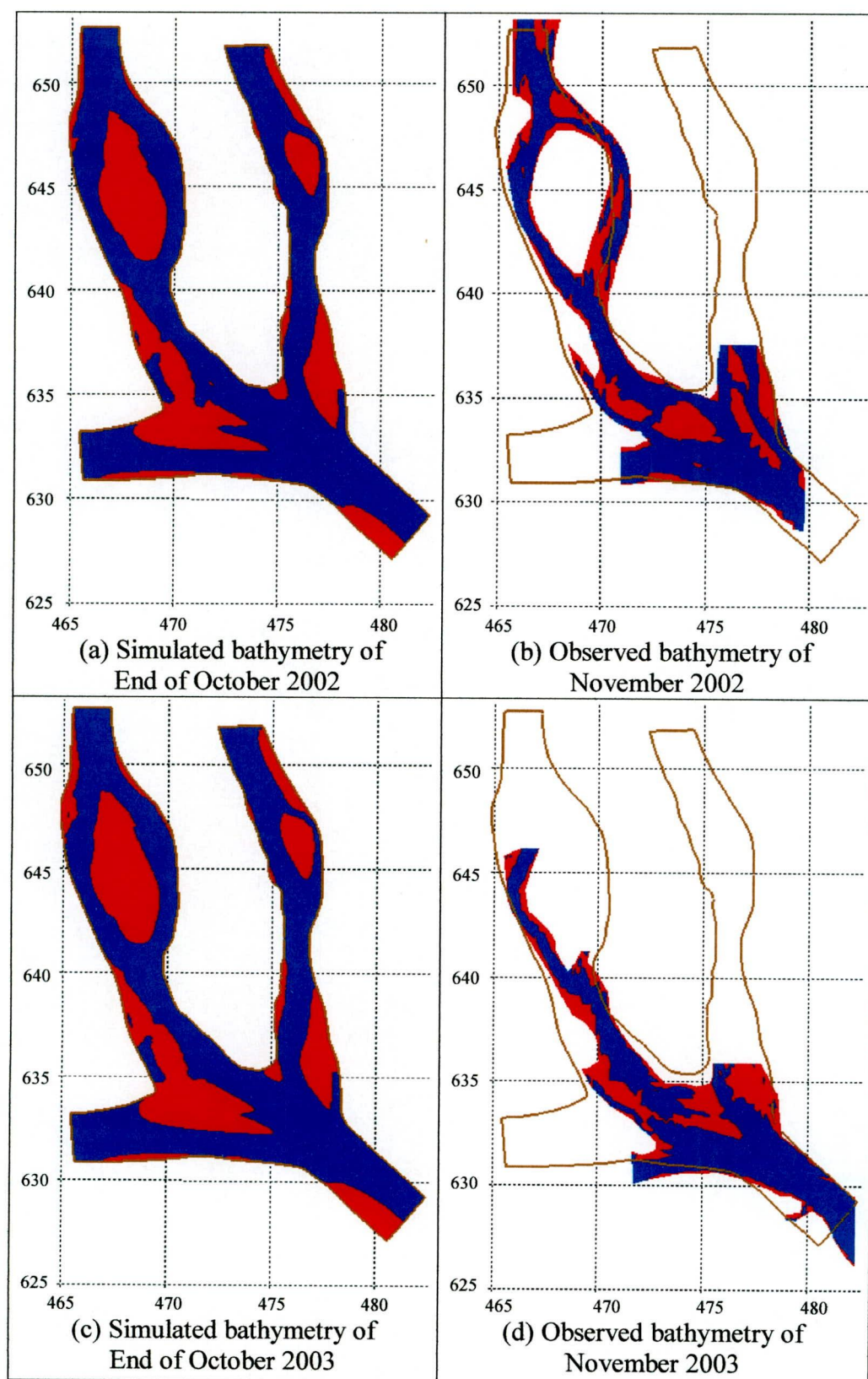


Fig. 4.10b Validation of sediment model with observed bathymetries for bed elevations 2.0 m PWD below and above

Observed and simulated sediment rating curve

A sediment rating-curve is generated from the simulation data and compared with the observed data at Baruria (FAP-24, 1996). Results have been closely matched with the observed data (Fig. 4. 11).

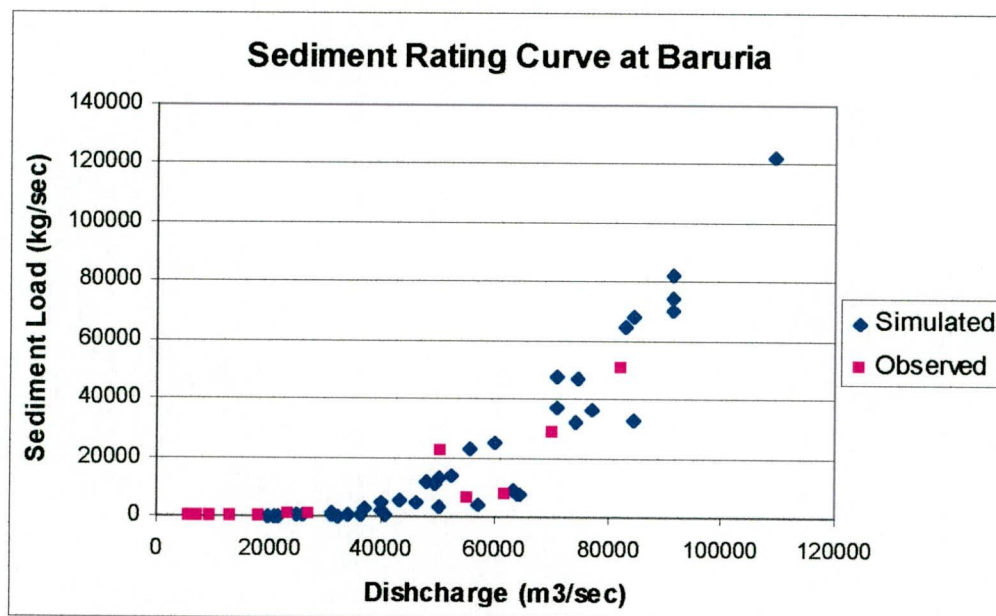


Fig. 4.11 Simulated sediment rates vs. observed rates (FAP-24) at Baruria

River bed is assumed consisting of effective sand grain diameter of 0.15 mm. This grain size is found satisfactory during calibration for the bathymetry. A less sensitive parameter that is diffusion coefficient for suspended sediment concentration is taken as $1.5 \text{ m}^2/\text{s}$.

4.7 Water levels and velocities at different location

Simulated time series water surface elevations and velocities for 2001 at Nagarbari, Kazirhat, Naradaha and near the confluence are presented in the next page in Figs. 4.12a and 4.12b.

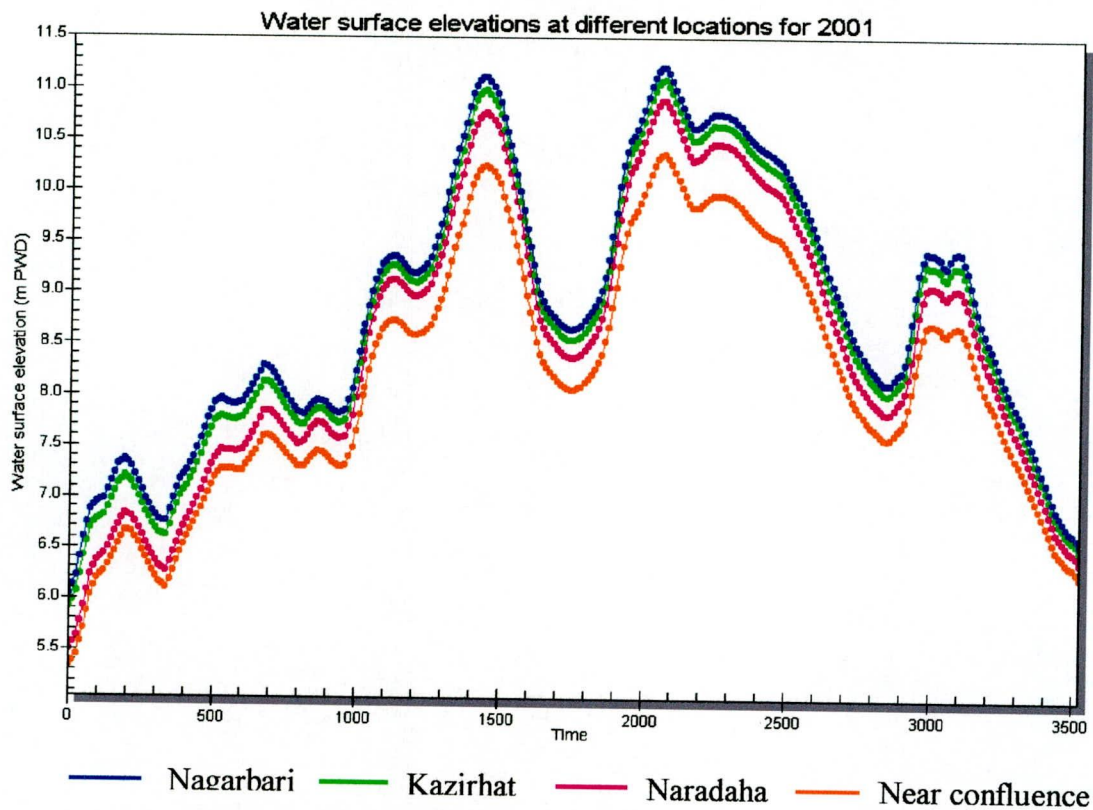


Fig. 4.12a Water surface elevations at different locations for 2001

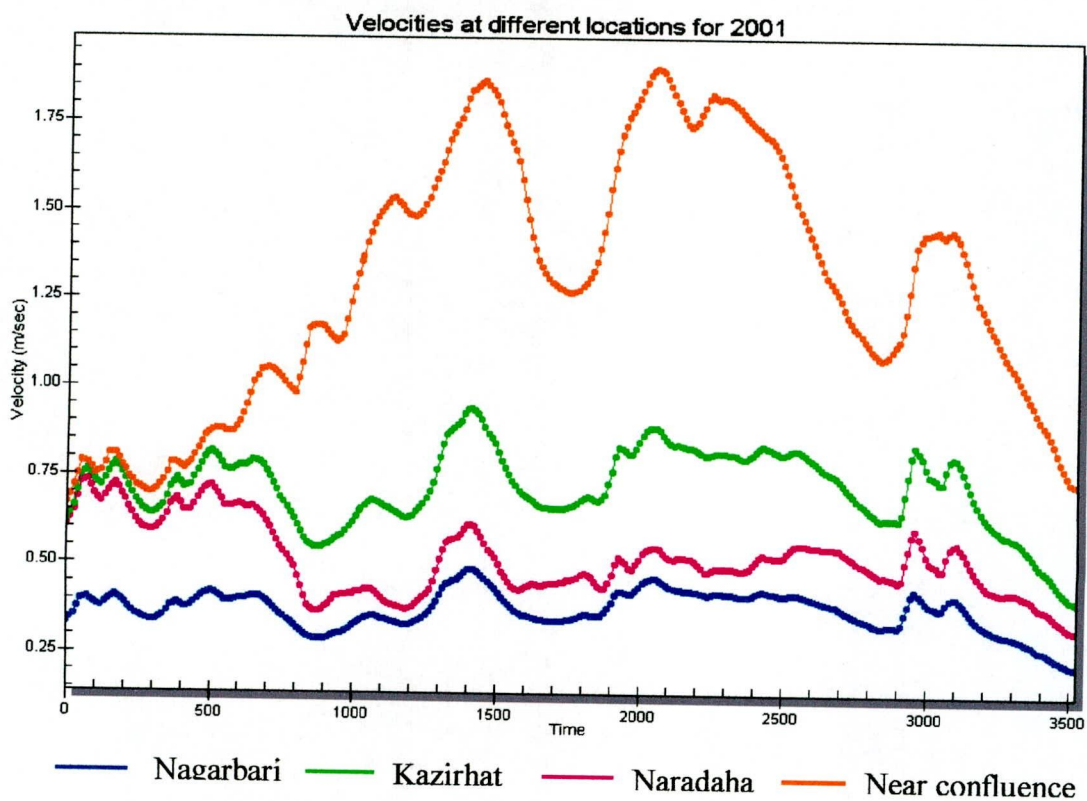


Fig. 4.12b Velocities at different locations for 2001

Chapter 5

Results and Discussion

5.1 General

RMA2 and SED2D under SMS environment are used for hydrodynamic and sediment transport modeling, respectively. April 2001 surveyed bathymetry data in the study region are used as an initial bathymetry. Initial bathymetry has been presented again in Fig. 5.1 for ready reference. The figure shows that the Jamuna has been divided into two anabranches in its upstream boundary. One is named as Eastern anabranch and other one as Western anabranch. The Western anabranch, near Nagarbari bifurcated into two branches; these branches are named as Branch1 and Branch2. Near Kazirhat these two branches meet again and after Natibpur there exist three channels. Main channel is the middle one (Middle channel) and others named as Left channel and Right channel as shown in Fig. 5.1.

Along the above tracks of branches and channels, morphological processes of Jamuna river have been investigated. Model gives erosion/deposition for the nodes to produce the bed level lowering or rising, however, it can not automatically shift the bank-line when a bank node gets erosion/deposition for itself. So any lowering of nodes at the bank, indicate the bank at that location is vulnerable, which is supposed to produce bank erosion and subsequent bank-line shifting. In this model vulnerable banks are identified by taking several cross-sections at different locations of the model, where the bank nodes have undergone lowering of its bed elevations. Some engineering interventions have been investigated through the calibrated and validated model, to maintain a minimum navigable depth in the channels in question.

5.2 Erosion and deposition processes

The series of figures as shown in Figs. 5.2 to 5.4 reveal that the three morphological years have much similar type of erosion and deposition patterns. Both erosion and deposition occur mainly in August and September of each year.

The results indicate that erosion mainly takes place in the Eastern anabranch and in the Left channel of Western anabranch. On the other hand severe deposition is taking place in the Middle and downstream of Middle channel of Western anabranch near Naradaha. This deposition is most likely due to backwater effect in the

confluence. Erosion also takes place in the lower boundary of the Padma. For a clear understanding of erosion deposition patterns of different years, several cross-sections are taken from the same location of the model. The locations of those cross-sections are named as Arc1 – Arc11 as shown in Fig. 5.5

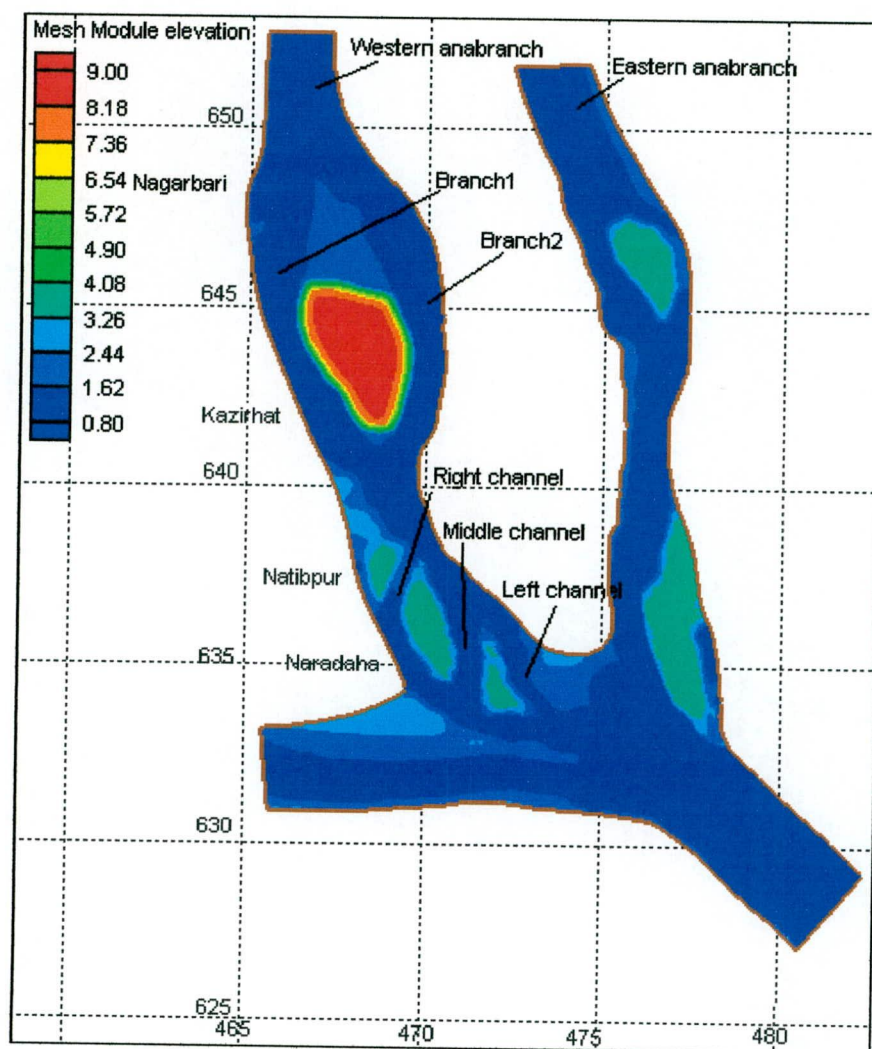


Fig. 5.1 Initial bathymetry in April 2001

In Eastern anabranch there is a small island in the upstream end of the model (Fig. 5.1). This island normally remains dry during low flows and flooded during monsoon seasons. In the beginning of the simulation, in June 2001, the main flow was passing through the left side of the island. In the subsequent years, it is clear from the Figs. 5.2 – 5.4 that the right channel of the island has undergone severe erosion. Cross-sections superimposed at Arc1 (Fig. 5.6a) for years 2001 – 2004 also indicate the same finding that the right side of the island has gone around 3 m erosion. The right bank has showed a lowering of its surface by 2.5 m, while the other left bank

showed 0.6 m erosion. So, both banks are vulnerable with erosion in this location but right bank is more affected than the left bank. Due to meandering behavior of alluvial channel, erosion is taking place at outer bank and deposition at inner bank, which has been revealed in the next two cross-sections as shown in Figs. 5.6b-5.6c. In Arc2, left bank erosion of 5.5 m and in Arc3, right bank deposition of 1.5 m has been revealed.

In Western anabranch eight cross-sections have been taken to observe the erosion/deposition pattern in that channel. Near Protabpur (Arc4, Fig. 5.6d) deposition has been found in both branches. Near Kazirhat (Arc5, Fig. 5.6e) slight deposition has been found in Branch1 and little erosion in Branch2. Near Natibpur (Arc6, Fig. 5.6f) severe erosion of around 3 m has been found in the main channel as well as in the left bank. However, deposition in the Right channel (Arc7, Fig.5.6g) has reduced the flow from its main channel towards its downward channels. Near Naradaha (Arc8, Fig. 5.6h) it has been observed that erosion takes place in the Left and Middle channels whereas Right channel remains unchanged. In its course of flow, both the Left and Middle channels together enforces the main flow of the river through its left side. Just downstream of this section (Arc9, Fig. 5.6i) shows that Middle channel and downstream of Middle channel are silted up, which also divert the flow towards Left channel.

A major change has been observed at downstream of Naradaha (Arc10 and Arc11, Fig. 5.6j and 5.6k). Huge deposition around 6-7 m has been observed in the Middle channel and in the down of the Middle channel. On the other hand, around 2 m erosion has taken place in the Left channel as well as in the left bank. This indicates that main navigation channel (Middle channel) and its downstream portion is being closed up due to heavy siltation, while the Left channel is getting open and setting opportunity for navigation towards Kazirhat.

The whole process can be rationalized as a deposition dominated progression near the confluence due to back water impact of the Ganges. Also it is striking to say that Jamuna has gone through major morphological changes immediately after 1998 flood, which is still causing all these sort of shifting until today due to instability inflicted far upstream. These findings are elaborated in Articles 5.2.1 and 5.2.2.

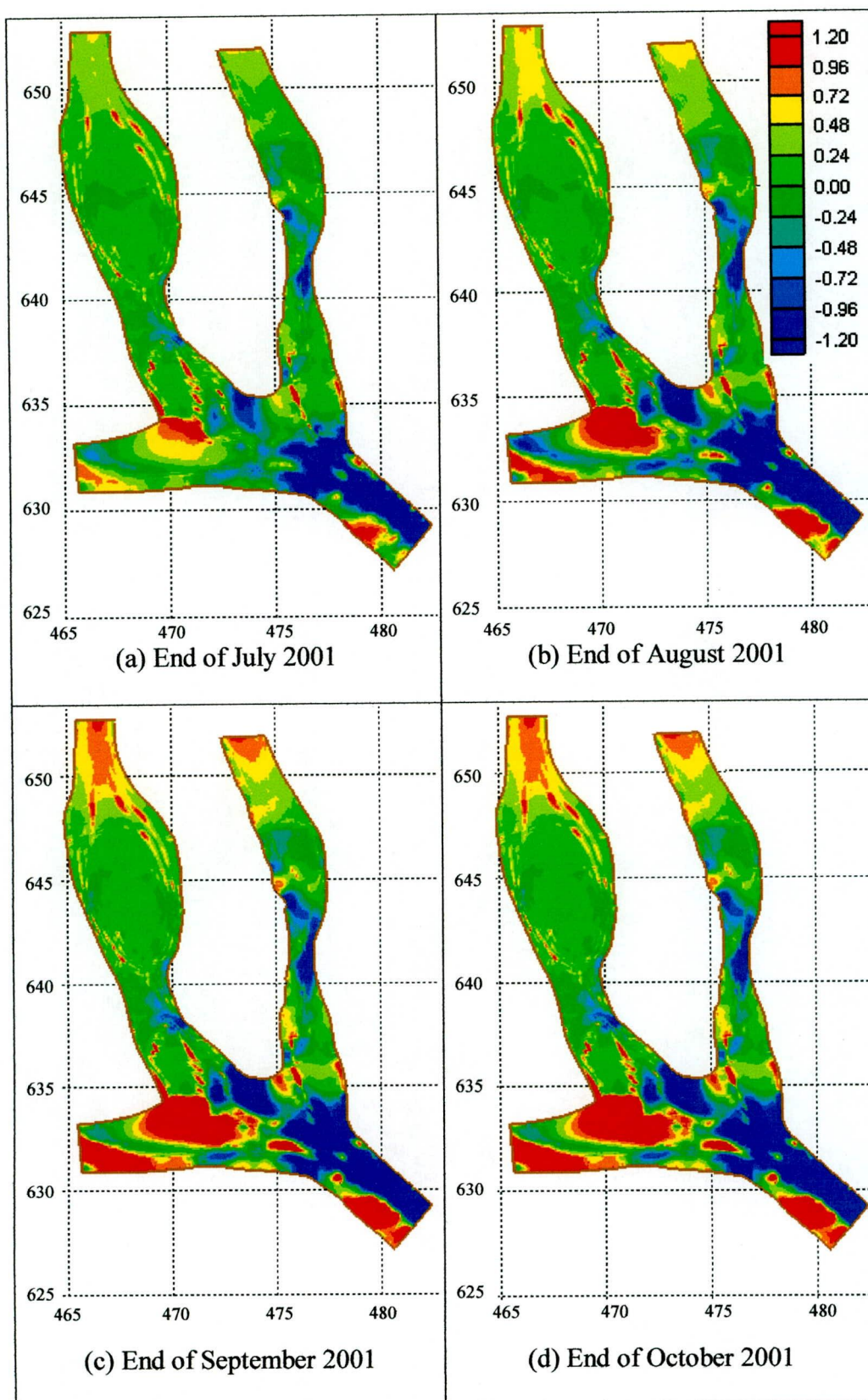


Fig. 5.2 Simulated erosion/deposition for July – October 2001

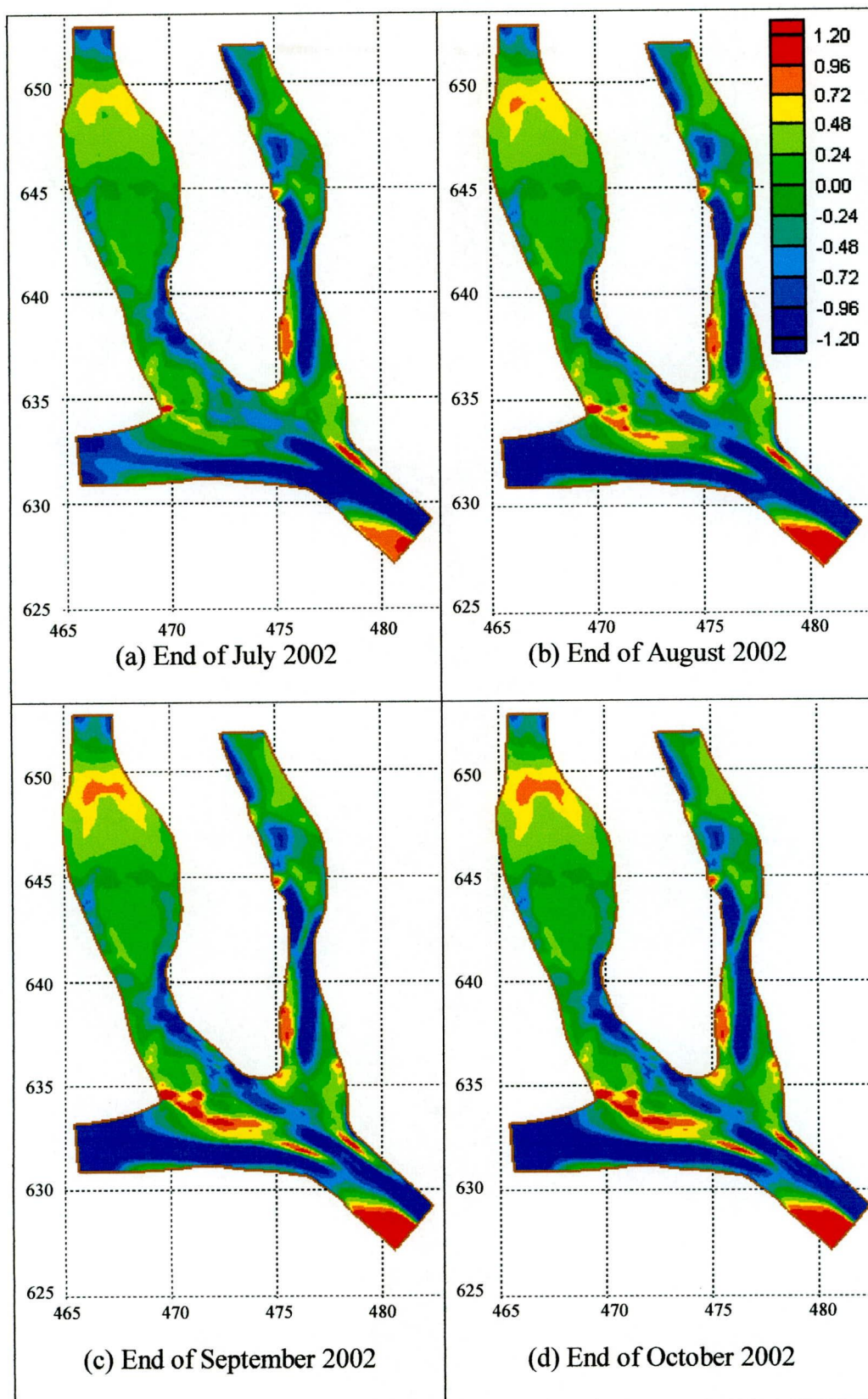


Fig. 5.3 Simulated erosion/deposition for July – October 2002

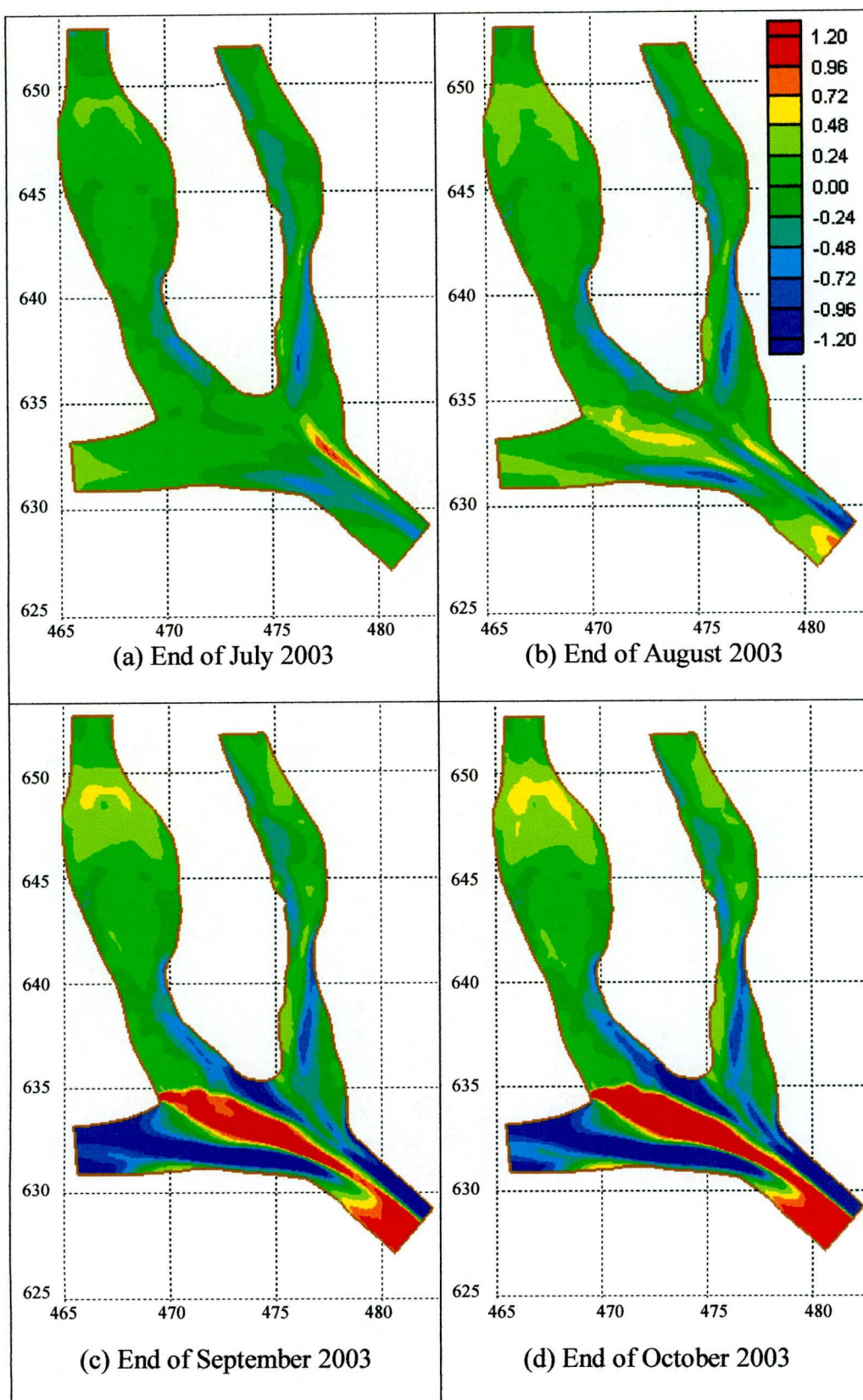


Fig. 5.4 Simulated erosion/deposition for July – October 2003

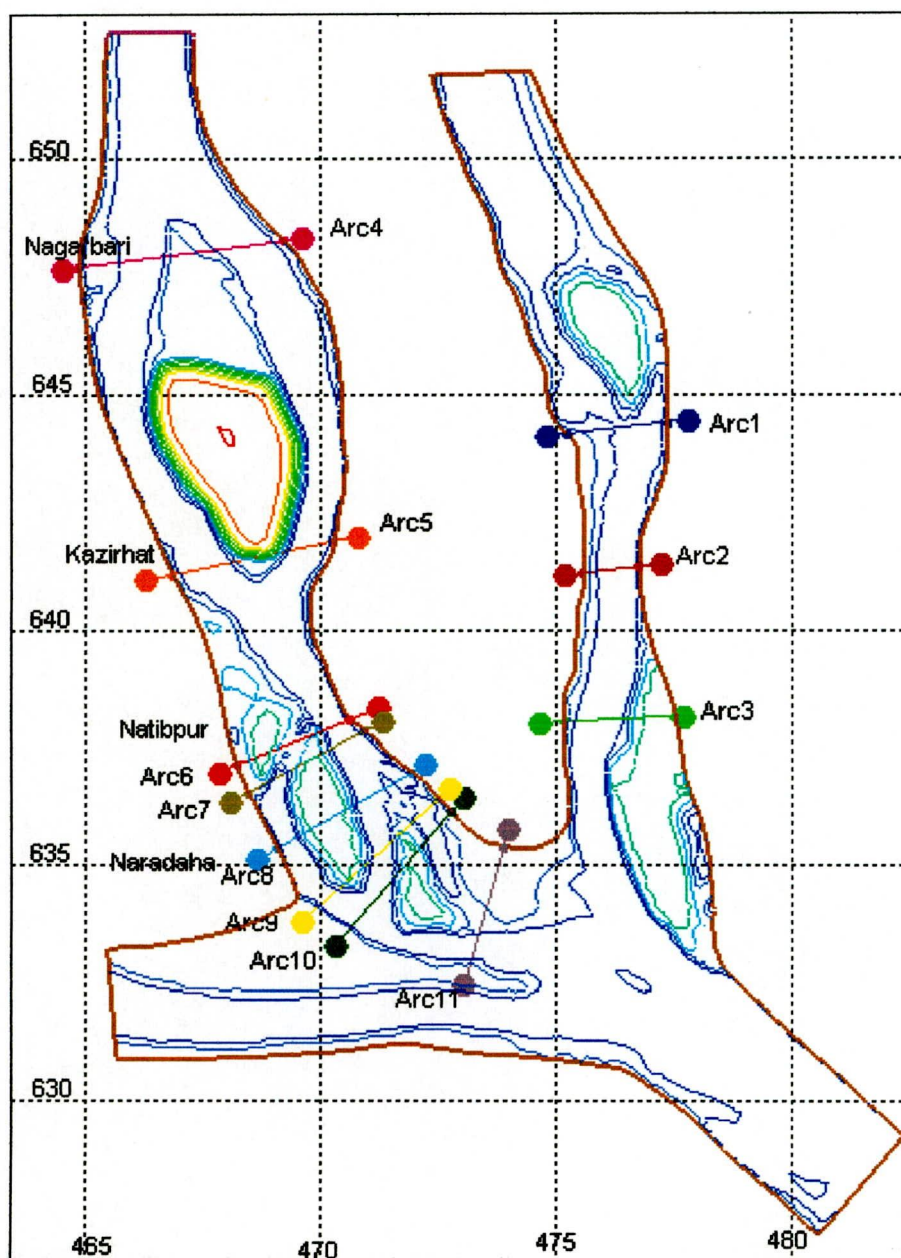
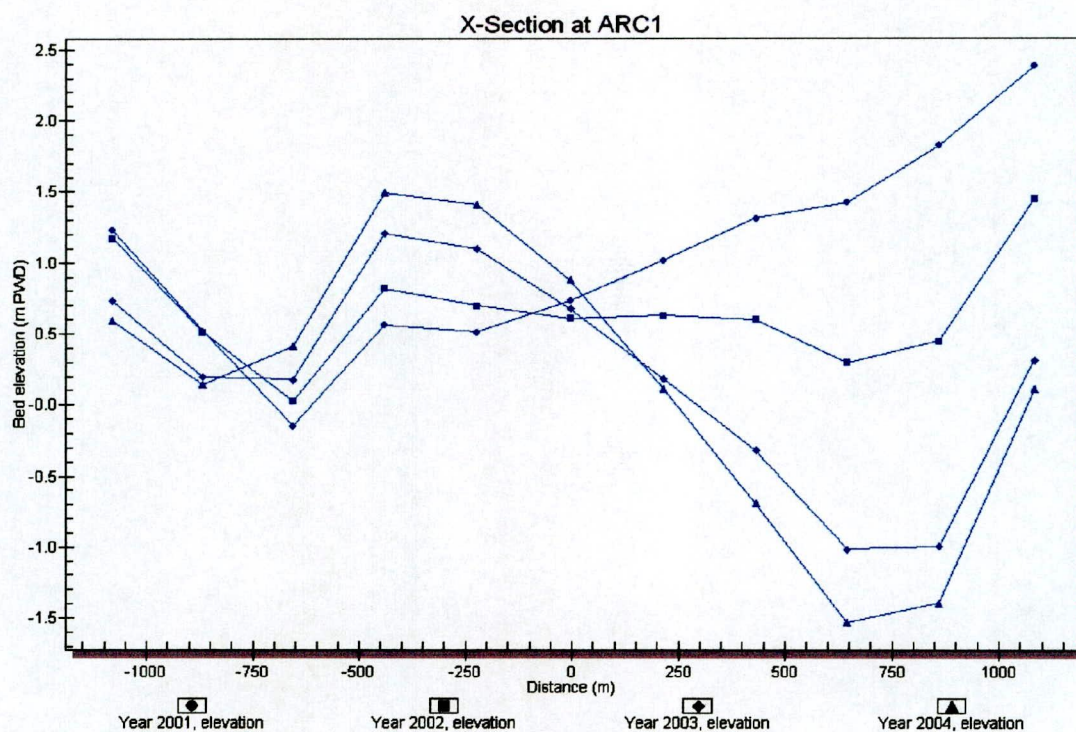
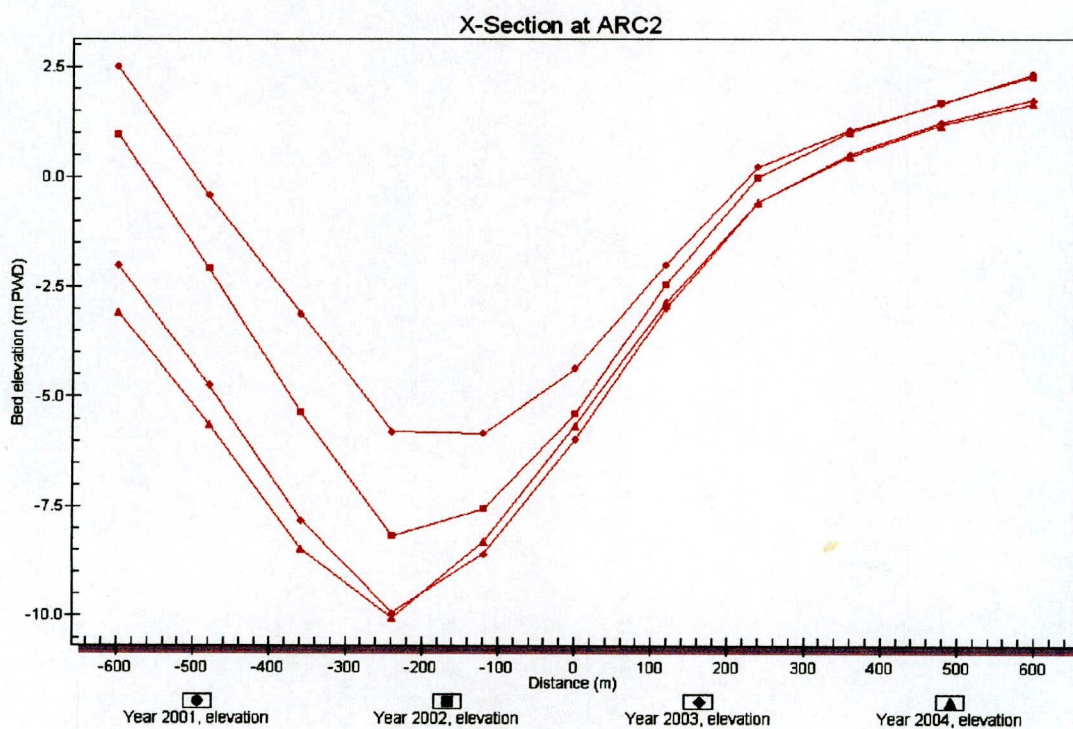


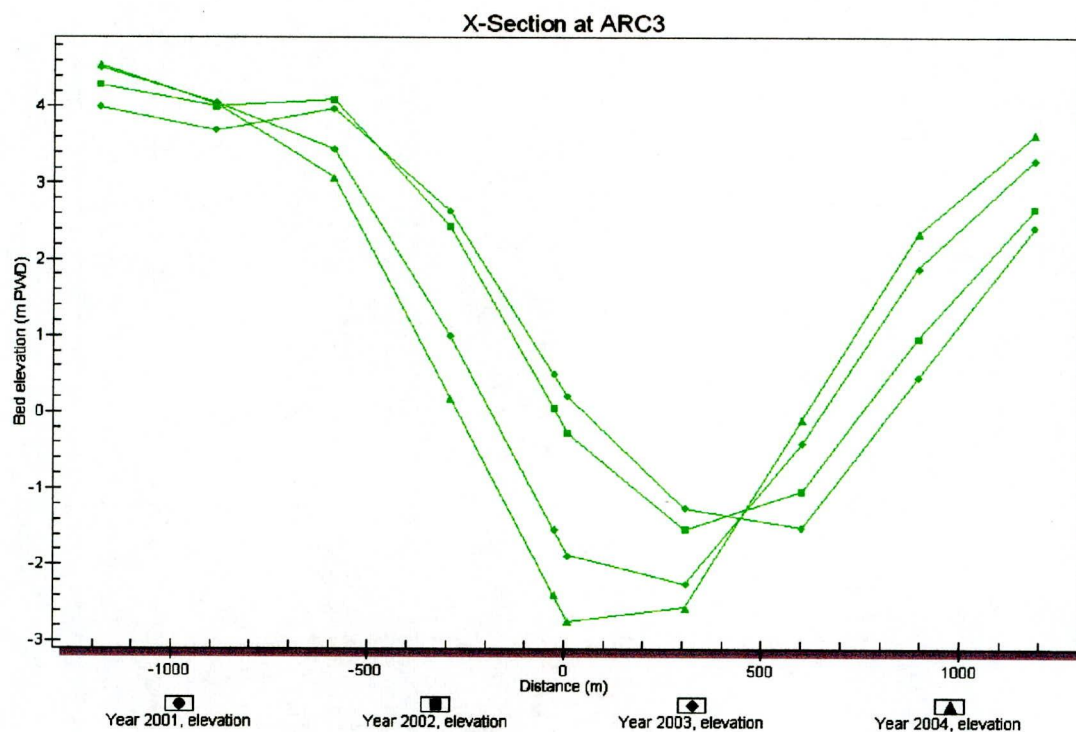
Fig. 5.5 Locations of different cross-section Arcs in the study area



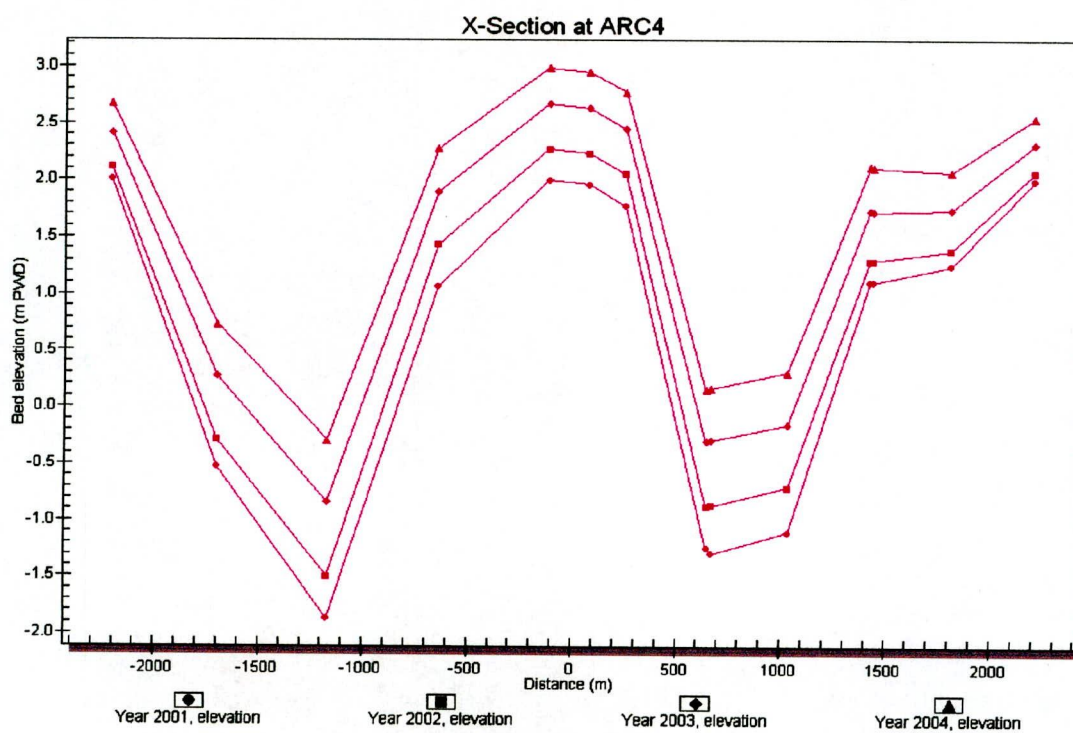
(a) Cross-section at Arc1



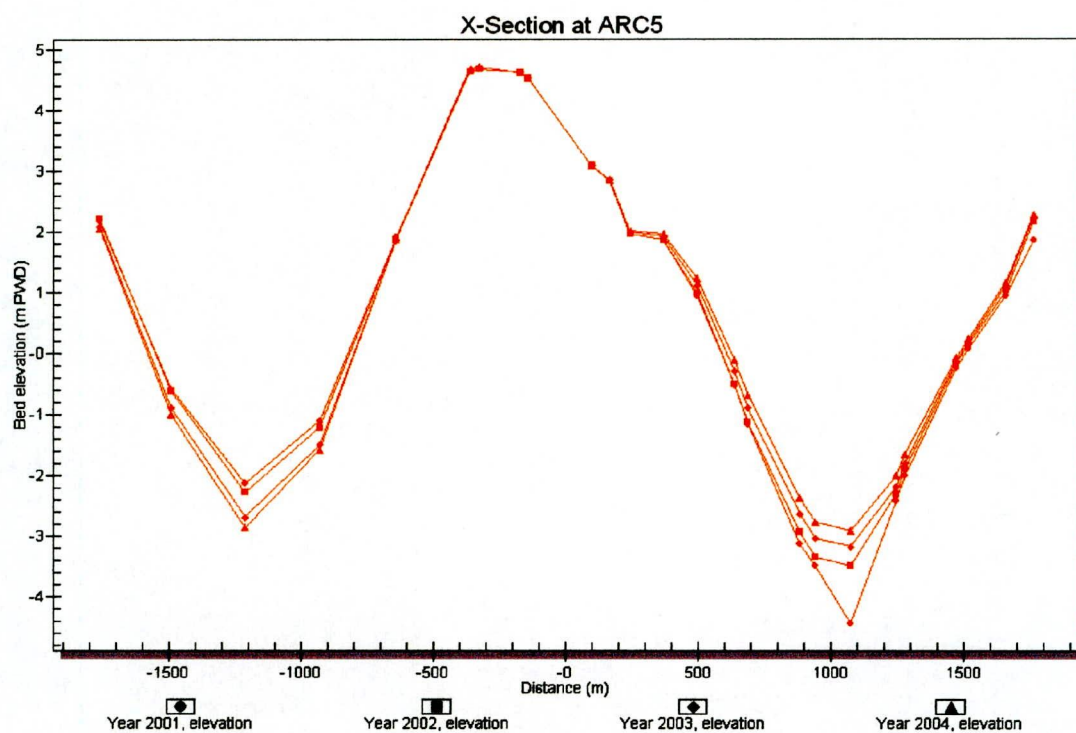
(b) Cross-section at Arc2



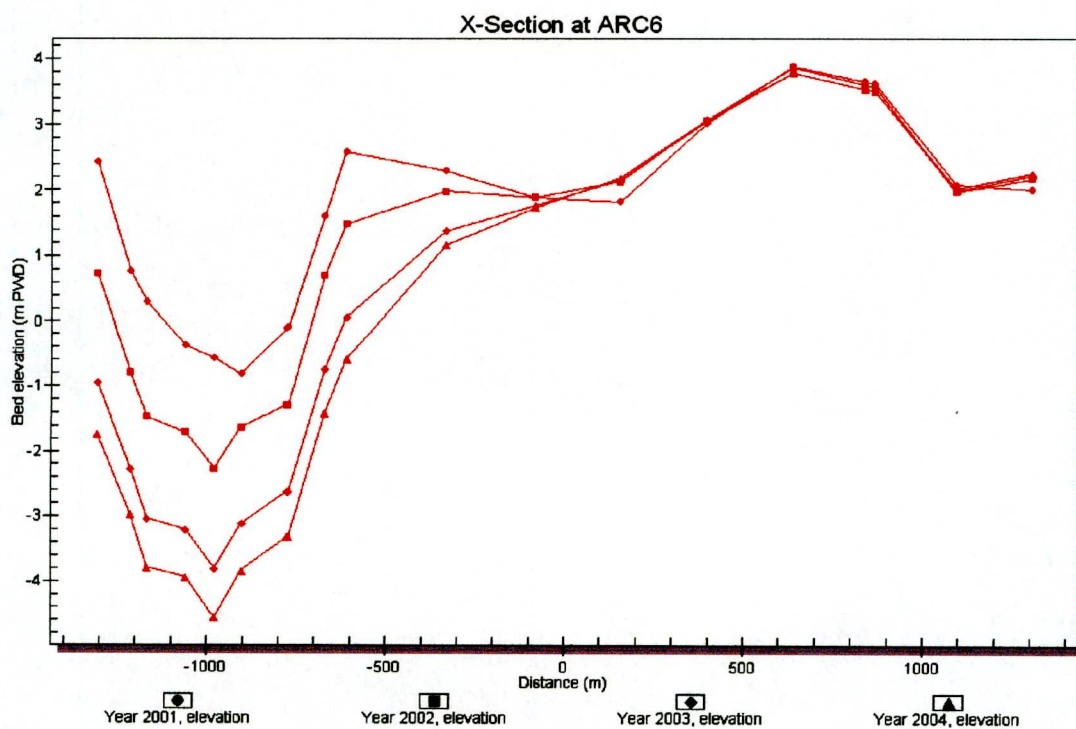
(c) Cross-section at Arc3



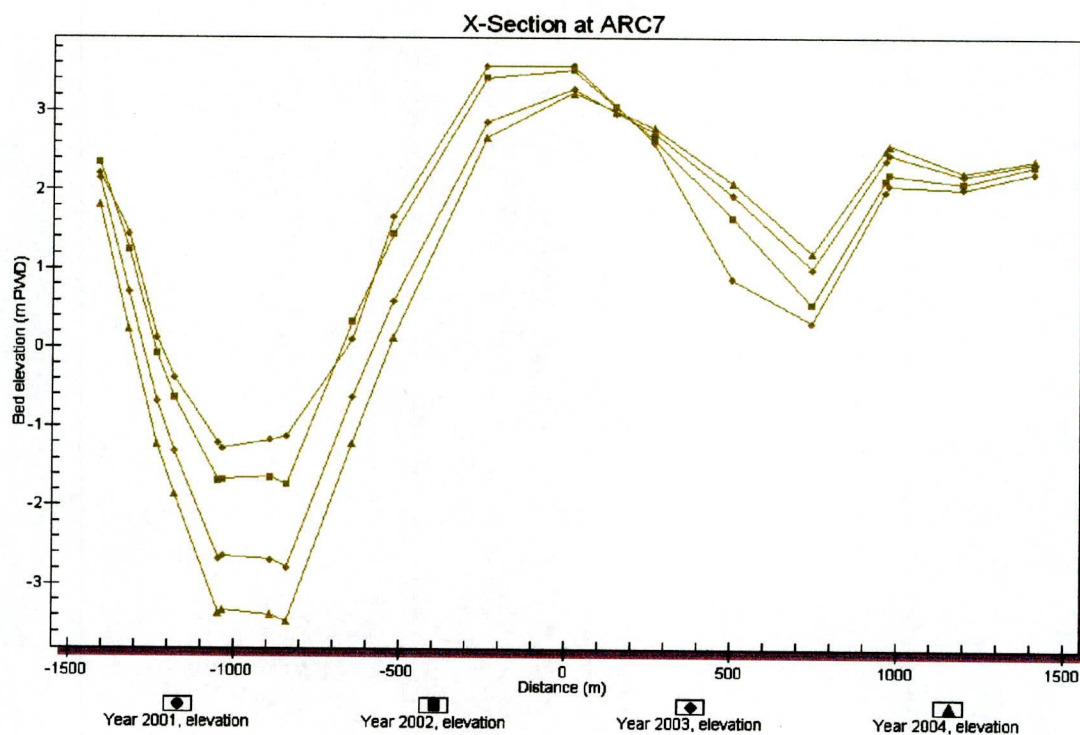
(d) Cross-section at Arc4



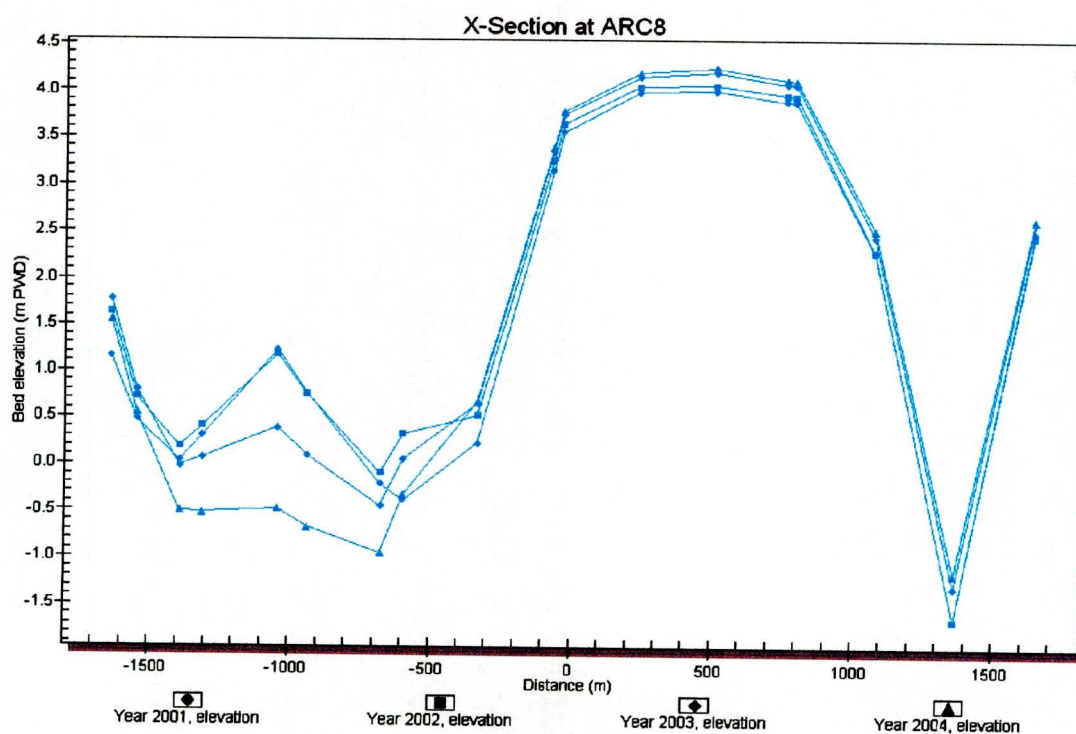
(e) Cross-section at Arc5



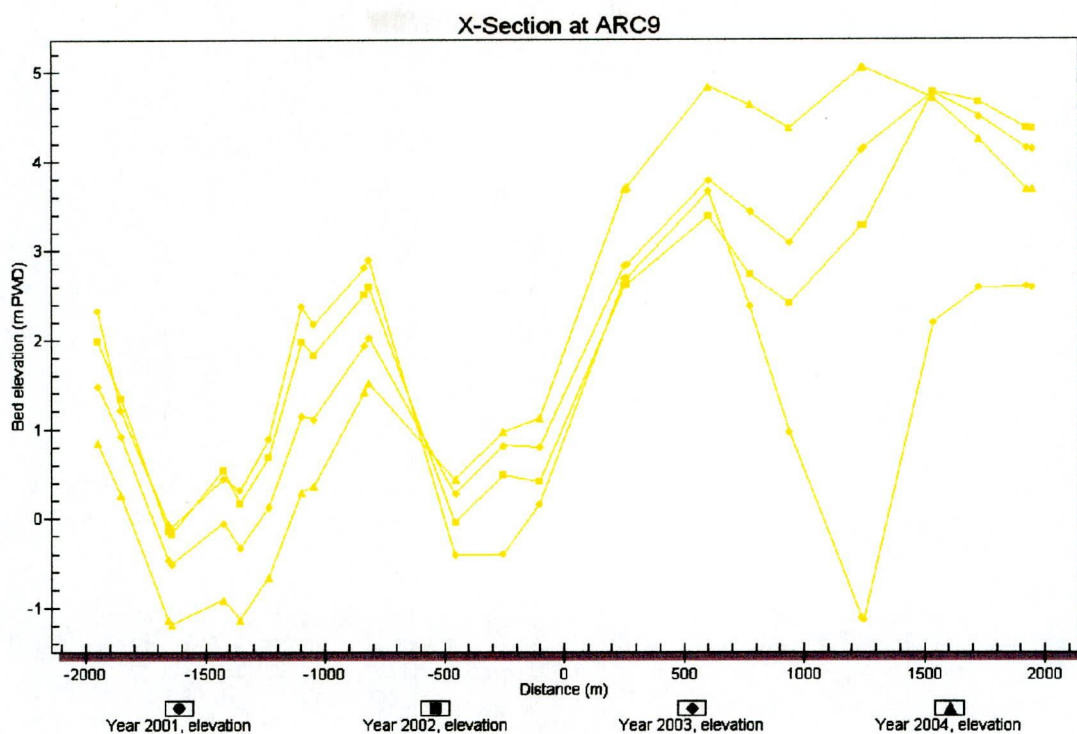
(f) Cross-section at Arc6



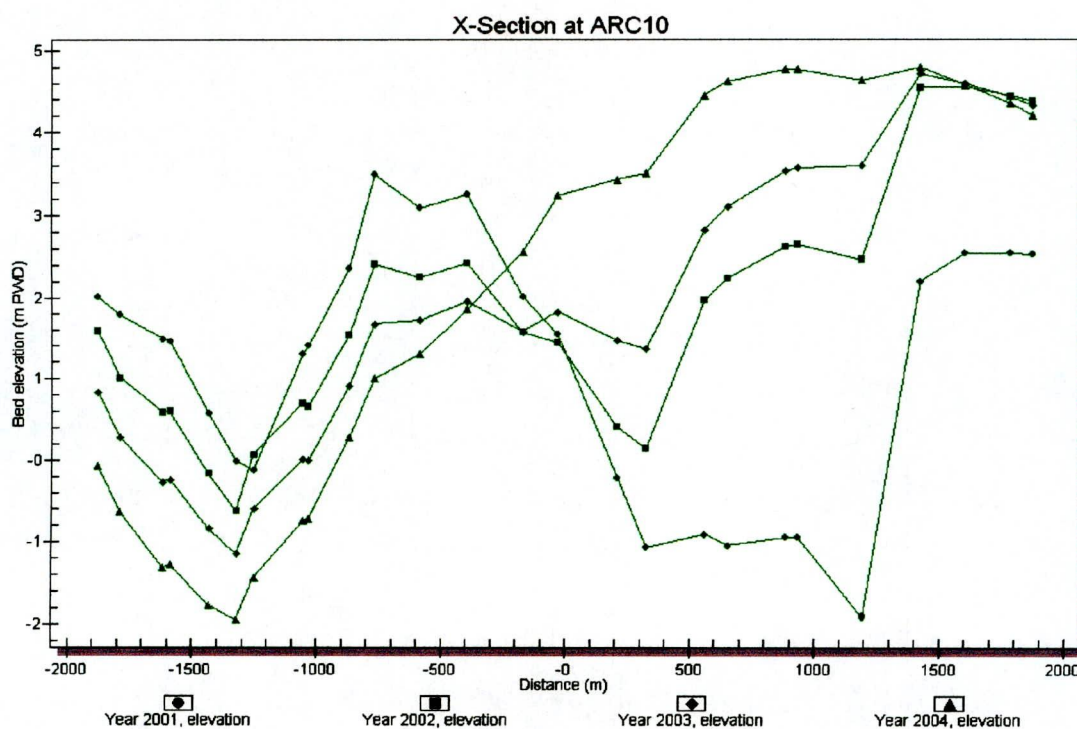
(g) Cross-section at Arc7



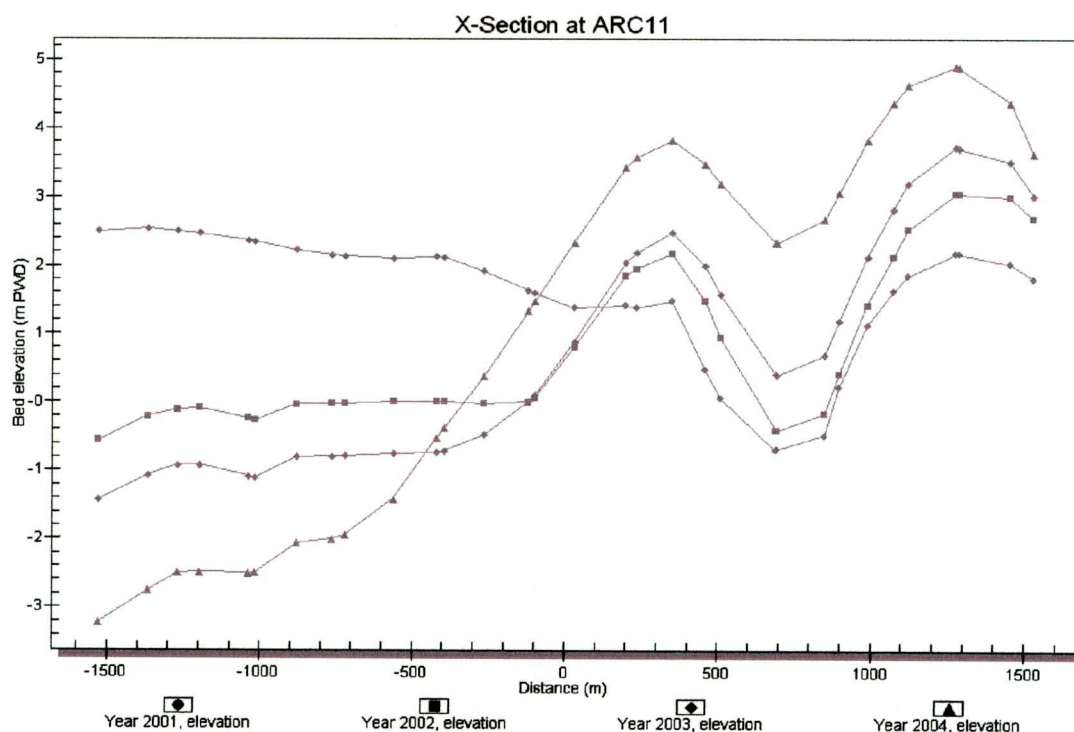
(h) Cross-section at Arc8



(i) Cross-section at Arc9



(j) Cross-section at Arc10



(k) Cross-section at Arc11

Fig. 5.6 Cross-sections at different locations for 2001 to 2004

5.2.1 Back water impact

Investigating the velocity vectors and its magnitudes, it is observed in the confluence that the velocity has been reduced drastically compared to their respective main channels. This velocity reduction in the confluence significantly diminishes their sediment transport capacity, and hence inducing deposition. It is revealed that a complex waterway prevails at confluence, which in a way is further complicated by the occurrences of their characteristic hydrographs, that differing in strengths with time, induces different dominating phenomena to work on sediments to settle at assorted positions.

When Jamuna river has the early peak and has a larger flow than the Ganges, it is found from the velocity vectors (Fig. 5.7a) that the flow of Jamuna river thrusts the flow of Ganges further down, and as a consequence Jamuna flow velocity reduces considerably in the lower part of the confluence and induces settlement in that region. Light and deep blue areas of Fig. 5.7a indicate the dominating deposition areas, while yellow and red colors indicate eroding high velocity areas.

When Ganges flows are of larger magnitudes than the flows of Jamuna, it is found from the velocity vectors of Fig. 5.7b that the Ganges flow drives on to the Jamuna flow, and as a consequence Ganges velocity has been significantly reduced in the same area that has been occurred during Jamuna at its peak. This time backwater effect of Jamuna has been shifted further upward. Now settlement of Ganges sediment takes place in the upper portion of the confluence. This deposition normally starts from the end of July when Jamuna at the falling stage and maximum in August and September, when Ganges at its peak. Paste color areas of Fig. 5.7b indicate the dominating deposition areas, while yellow and red colors indicate eroding high velocity areas.

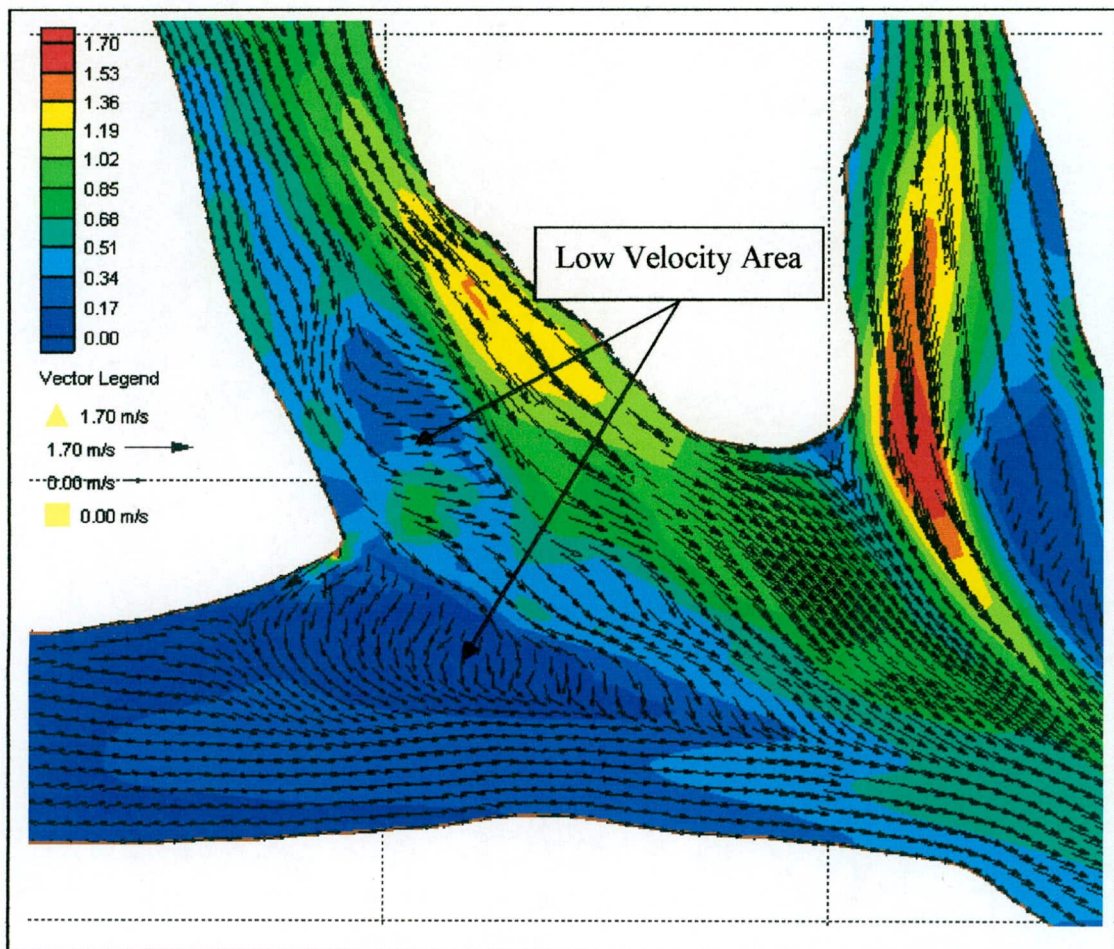


Fig.5.7a Velocity vectors in July 2003

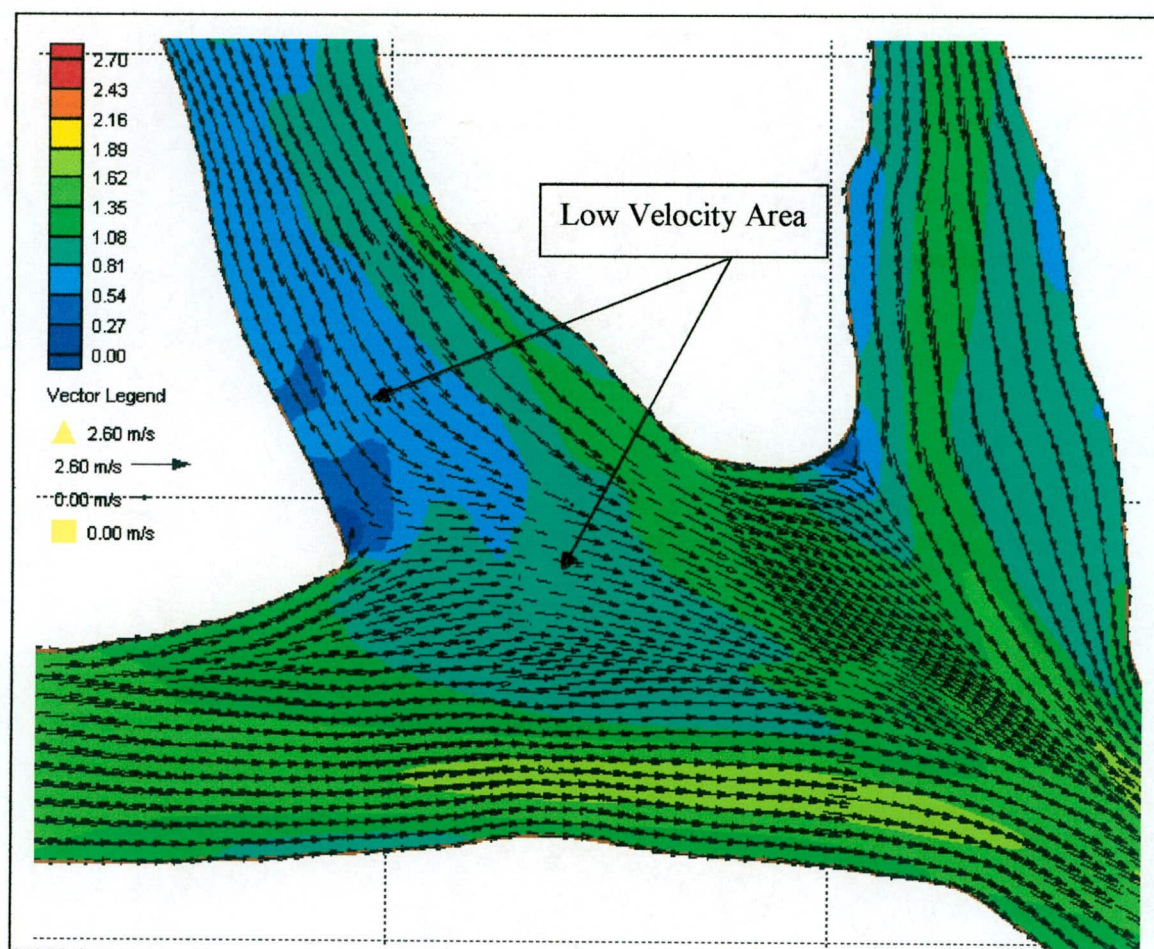


Fig. 5.7b Velocity vectors in September 2003

5.2.2 Plan-form changes

Continuous erosion and deposition are taking place in the Jamuna river. There are reasons for closing old channels and opening new channels. Main channels are also changing its course with time.

Examining the surveyed bathymetries from 1996 to 2003 of BIWTA (Fig. 5.8), it is clearly observed that upstream of Kazirhat before 1998, there was only one main channel in Western anabranch, and further downstream, near the confluence at Naradaha, the river was flowing all the way through right periphery of the bank. But after 1998, a big deposition has been occurred in the areas of Nagarbari to Kazirhat. This has created a large island in the main channel, bifurcated the channel into two branches (Branch1 and Branch2) near Nagarbari, and as a natural consequence, the downstream flow near Naradaha is touching through left flank of the bank.

From a series of steady runs, using initial (April 2001) and simulated bathymetries (for October 2001, October 2002, and October 2003), up to middle of

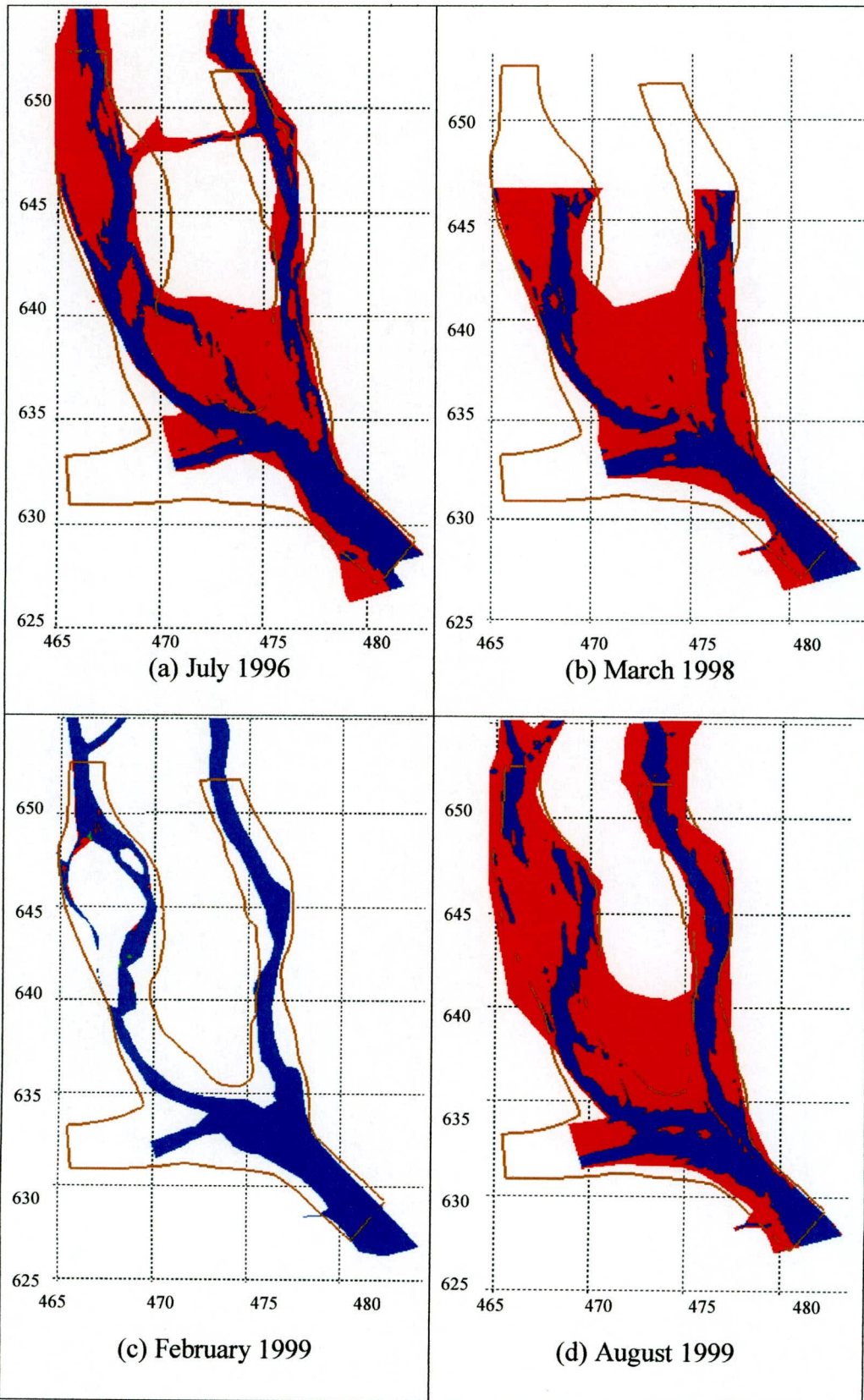
Nagarbari to Kazirhat (Fig. 5.9), it has been found (Table 5.1) that the percentages of flows in the Branch1 are higher than the Branch2 and these percentages are increasing with time due to the developments occurred in 1998 flood. This observation reveals that as Branch1 is dominating and due to meandering behavior in the downstream, near the confluence, Jamuna as stated above is trying to flow towards Left channel. Reduced velocities, in the inner bend that happens to be in the Middle and Right channels, are creating sedimentation in those channels.

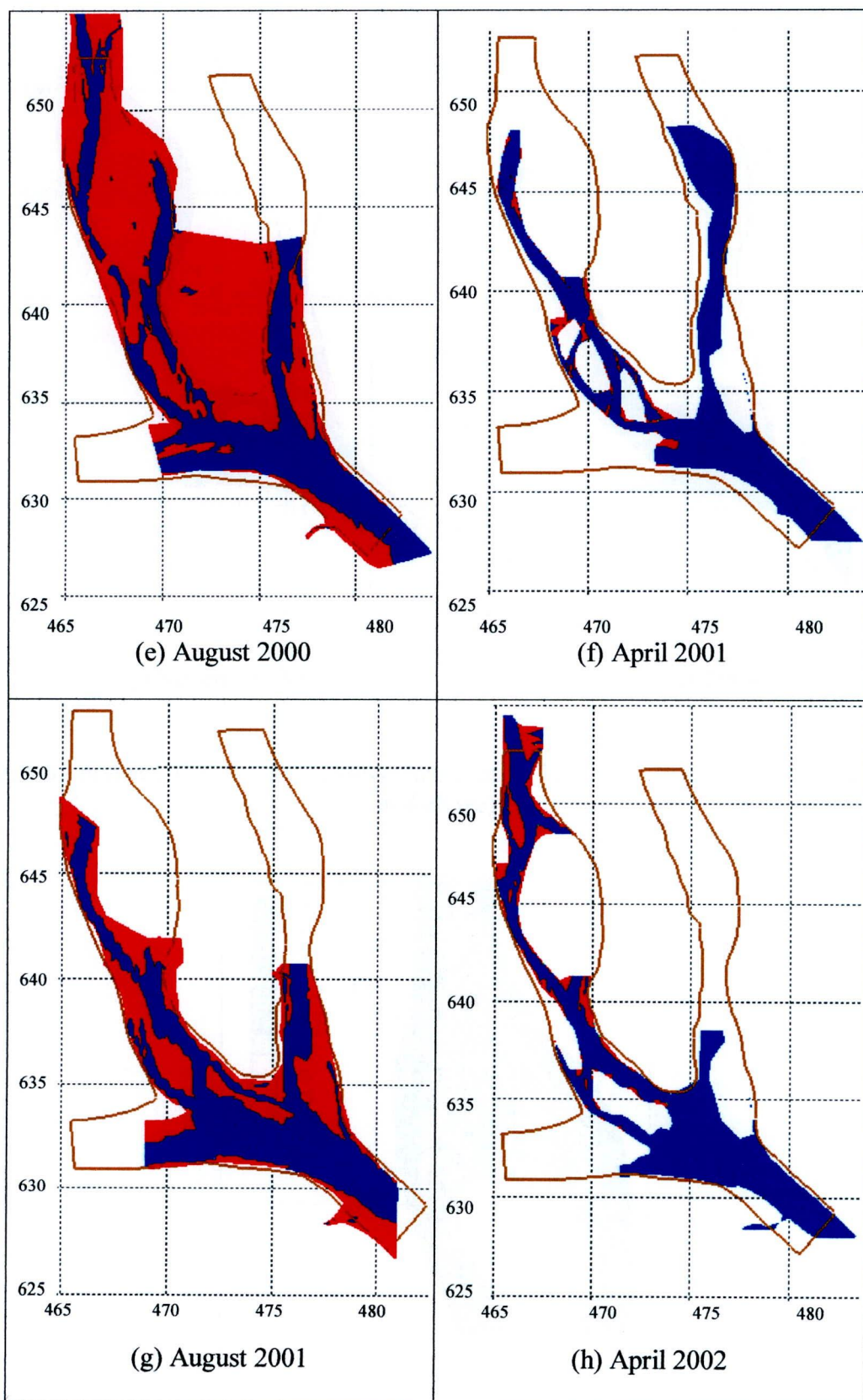
Table 5.1 Percentages of flows through different branches of Western anabranh

Reach / Period	April 2001	End of October 2001	End of October 2002	End of October 2003
Branch1	50.8%	51.1%	51.5%	51.7%
Branch2	49.2%	48.9%	48.5%	48.3%

The above findings have also been observed in the simulations by the models developed for the study. After three years of morphological runs, the simulated bathymetries indicate that the Middle channel, near Naradaha (Fig. 5.10), is being closed up due to heavy siltation and Left channel has been opened up due to erosion.

A similar kind of observation was being found by Hoque (1999) for 1988 flood using series of satellite images of 1973-1996. Before the devastating flood of 1988, the recent position of Western and Eastern anabranhcs was the location for a single channel of the Jamuna river. Hoque (1999) stated that any concurrence of Jamuna and Ganges peaks may change the plan-form radically, and this incidence has happened in both 1988 and 1998 floods.





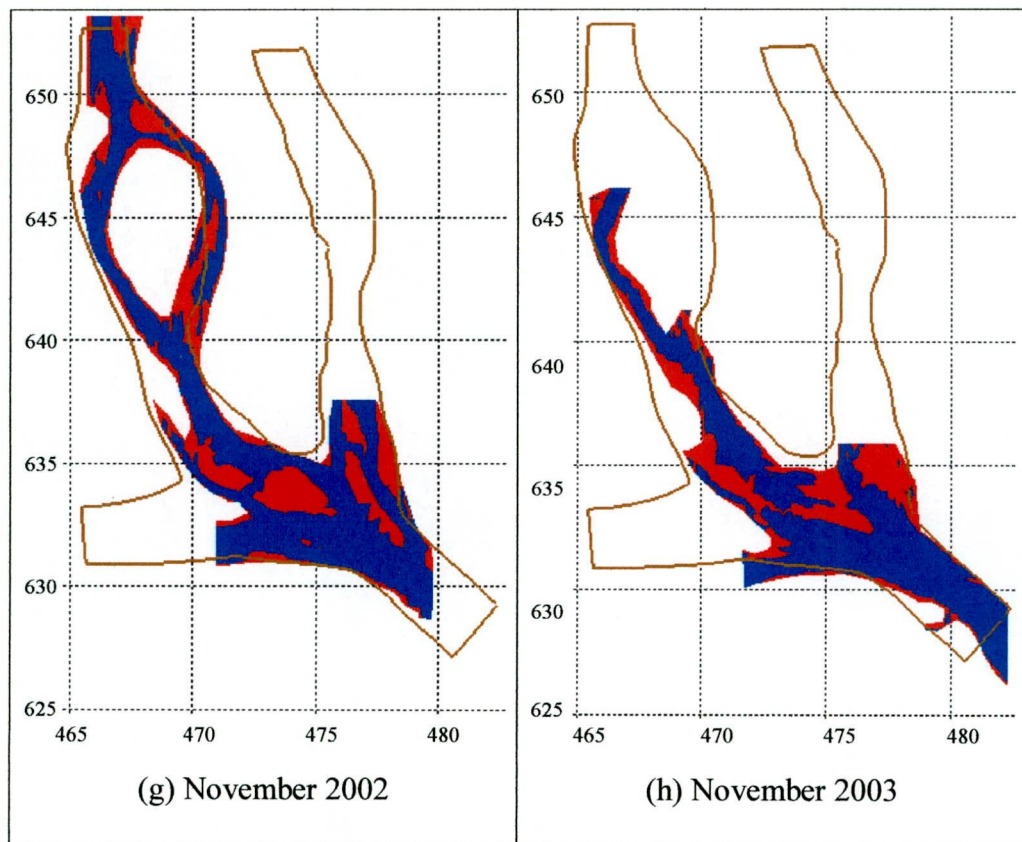


Fig. 5.8 Surveyed 1996 to 2003 bathymetries (using bed elevations 2.0 m PWD below and above)

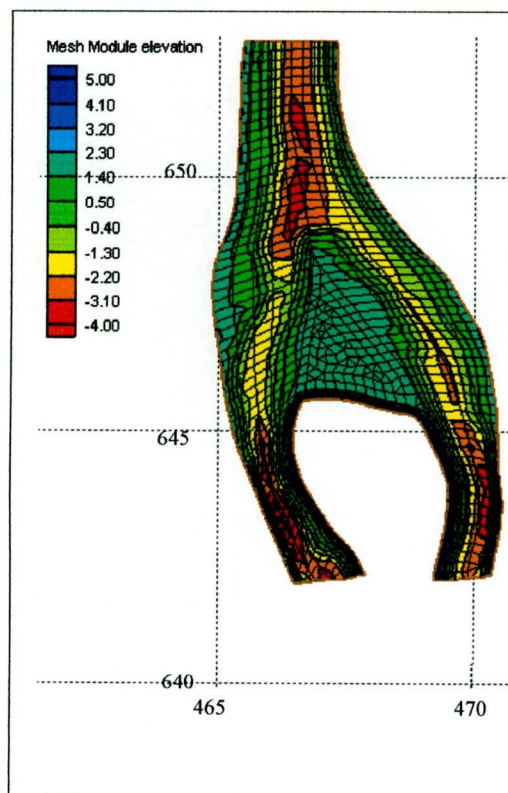


Fig. 5.9 Flow distribution in the bifurcation

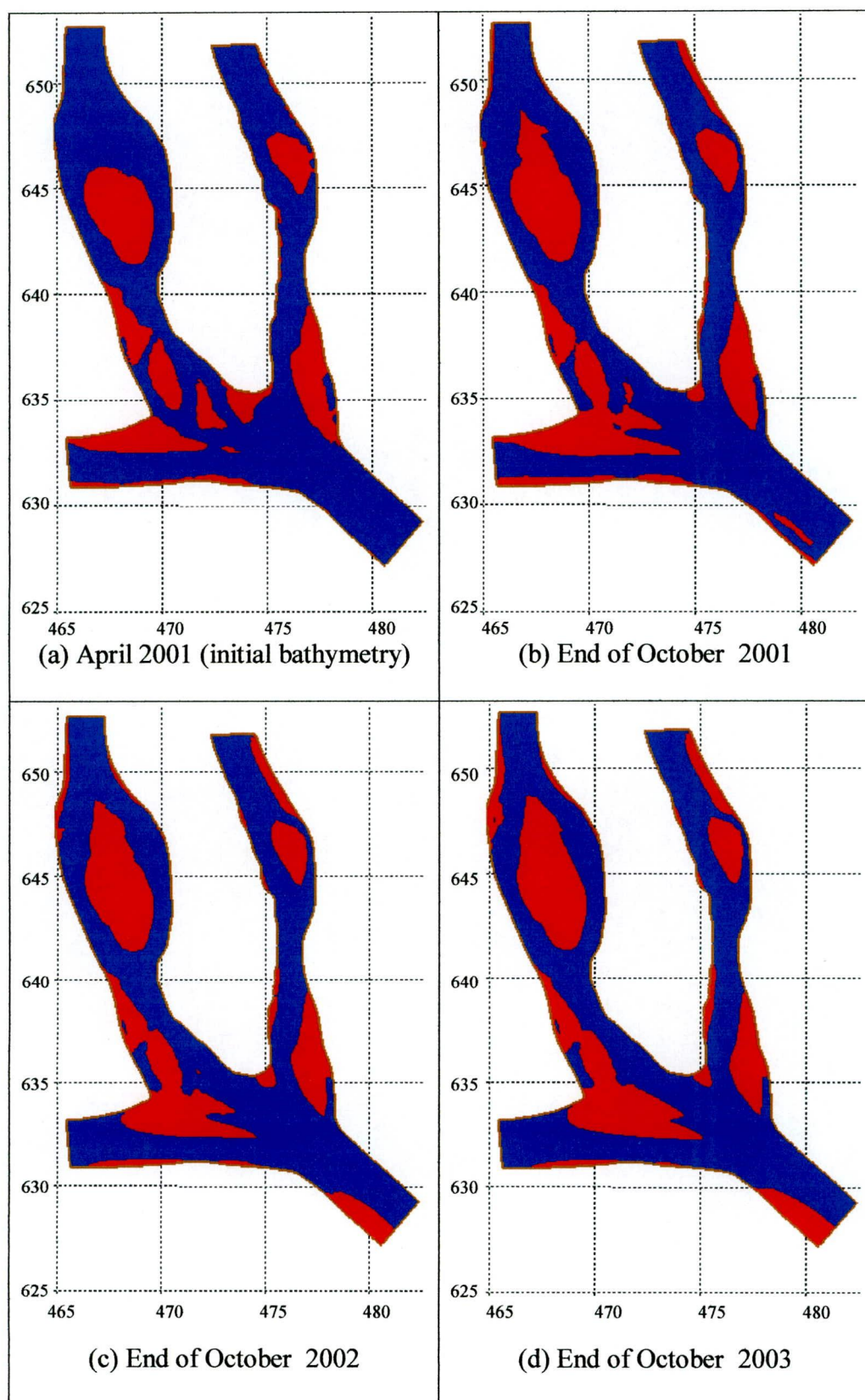


Fig. 5.10 Initial (April 2001) and simulated 2001 to 2003 bathymetries (using bed elevations 2.0 m PWD below and above)

5.3 Navigable depth

One of the main objectives of this study is to find a suitable route for navigational purpose. According to BIWTA the minimum depth required for a ferry is 2.3 m. Simulation runs have been given using monsoon period data (June-October) starting from 2001, up to 2003. To obtain the depths at lean periods, using lowest water levels and corresponding discharges, several steady runs have been generated for initial (April 2001) and simulated bathymetries (for October 2001, October 2002, and October 2003). Lowest water level of 2.6 m PWD at the downstream boundary has been applied for the above steady runs. The corresponding flows at Jamuna and Ganges are $4100 \text{ m}^3/\text{sec}$ and $2110 \text{ m}^3/\text{sec}$, respectively. Results indicate that old route (Middle channel) near Naradaha has been blocked due to deposition and new route (Left channel) has been opened up (Fig. 5.11).

It is observed from Fig. 5.11 that a deeper pocket channel exists, through out the study-period, near right bank at Naradaha. Nominal deposition has been observed as shown in Fig. 5.6h (Arc8) for three years. It seems the location is in the leeway besides the heavy siltation region. To use that natural deep pocket as a location for ferry ghat, three possible options, as shown in Table 5.2, have been explored to find a sustainable navigable route. The amounts of capital dredging required to implement those options, as calculated from the respective 2003 simulated bathymetry, are also shown in Table 5.2.

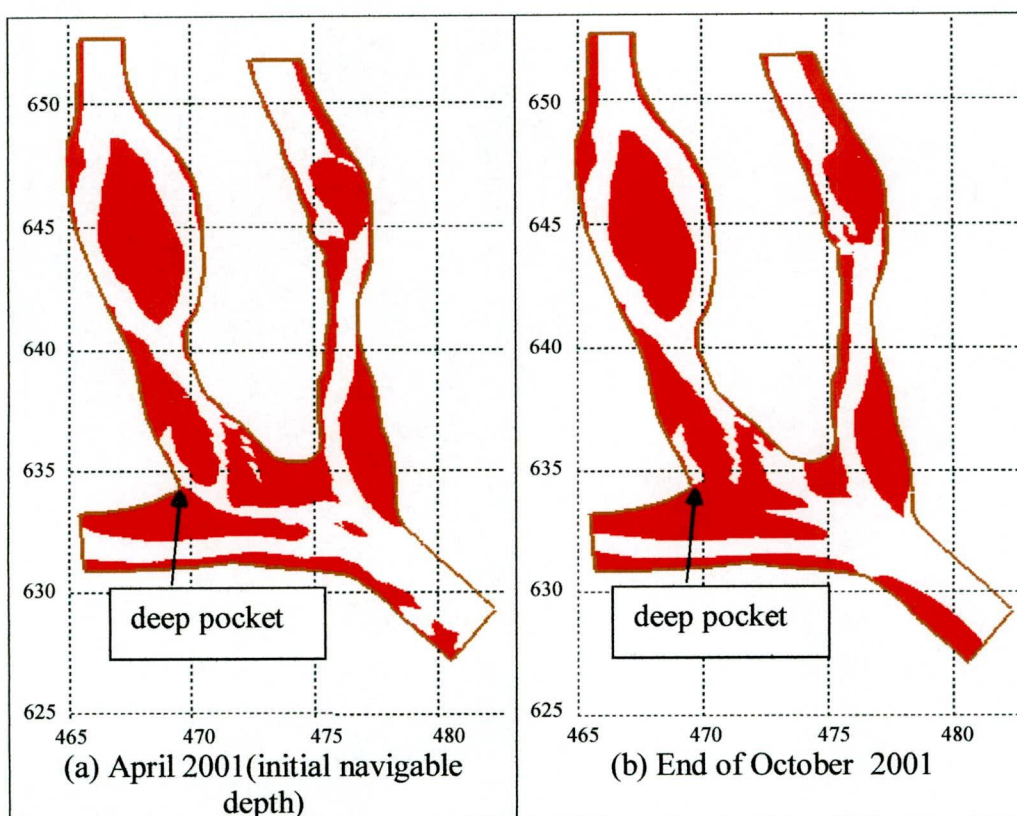
To connect with this deep pocket, one or two channels have been dredged to formulate the options. The motivation for those options is being generated by looking into the Fig. 5.12. From the shades of 0.33 m or above depths of water as seen in Fig. 5.12, for simulated bathymetry of October 2003, it is clear that two shallow channels near Natibpur are still connected to the deep pocket. So connecting the deep pocket by means of different dredged channels has given the possible options.

The first option (Fig. 5.13a) is taken as, dredging of a channel near Naradaha to connect the lower segment of deep pocket, and second option (Fig. 5.16a) is taken as, dredging of Right channel near Natibpur to connect the upper segment of deep pocket. Scrutinizing these two options in the model runs, it is found that Option1 has shown severe deposition, whereas Option2 has shown little deposition. In a bid for further improvement, Option 3 (Fig. 5.19a) has been designed, where both upper and lower segments of the deep pocket would be connected to proposed dredged channels,

along with a spur placed in the left bank near Natibpur. The options are described in next sub-articles.

Table: 5.2 Options with the amount of capital dredging and their locations

Options	Location	Intervention	Amount of dredging, Mm^3
Option 1	near Naradaha (635 Lat.)	dredging (2438 m)	3.57
Option 2	near Natibpur (637.5 Lat.)	Dredging (1474 m)	0.9
Option 3	dredging in both Natibpur and Naradaha, and spur at Natibpur	dredging and spur	4.47



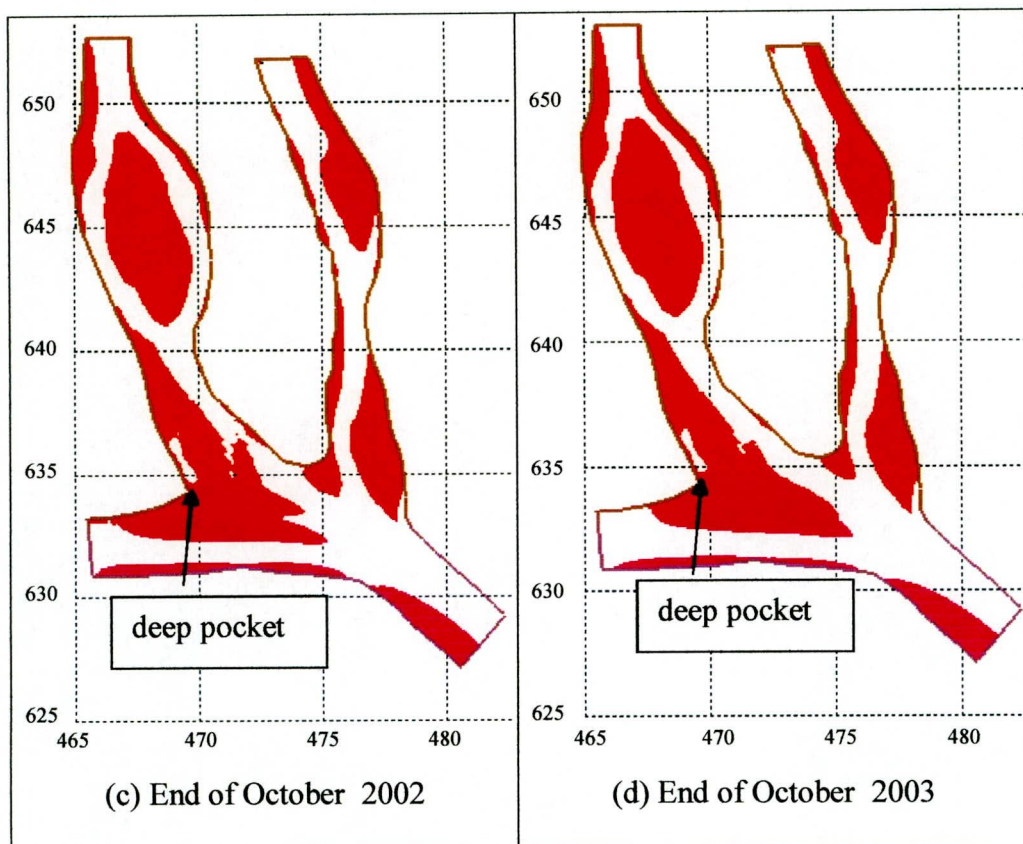


Fig. 5.11 Initial (April 2001) and simulated 2001 to 2003 navigable depths (using depths 2.3 m below and above)

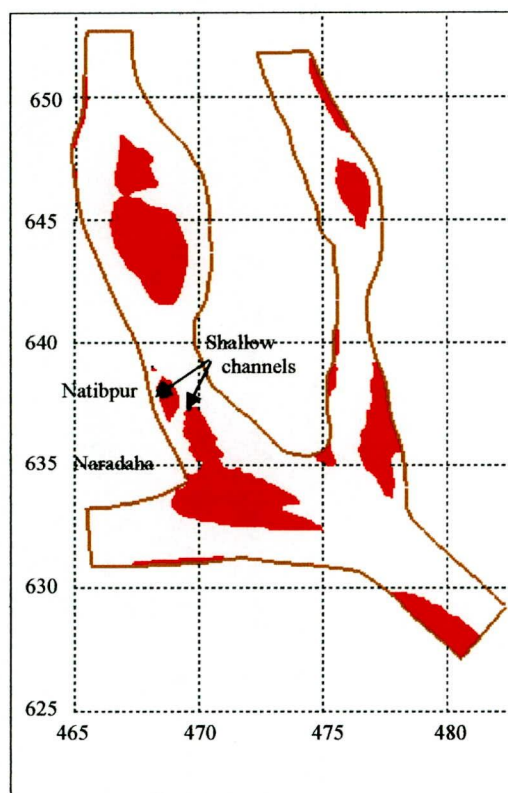
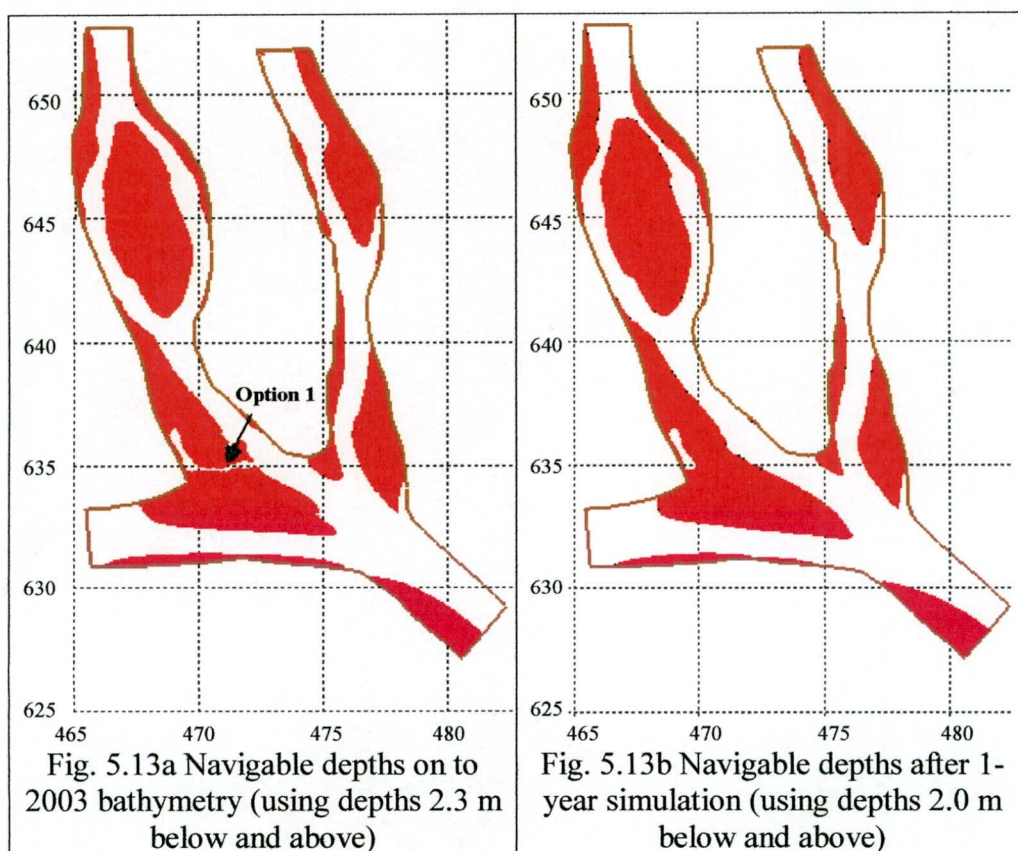


Fig. 5.12 Simulated 2003 navigable depths (using 0.33 m or above water depths)

5.3.1 Option 1: dredging downstream channel

This option is taken to connect the deeper pocket by dredging a channel in the downstream of deep pocket near Naradaha (Fig. 5.13a). Bed elevations of the nodes in question of the proposed dredged channel are lowered on to the 2003 bathymetry, to obtain the minimum navigable depth and thus the resultant bathymetry has been used to run the model for next one morphological year. After one year of simulation, navigable depths are presented in the Fig. 5.13b. To obtain the erosion/deposition patterns, six cross-sections (Arc1-Arc6) have been taken in the proposed dredged channel as shown in Fig. 5.14. It has been found that the dredged channel has been closed due to deposition. An average deposition of 3.0 m depth has been obtained in the channel under Arc1 to Arc4 (Fig. 5.15a to 5.15d). Deep pocket shows little deposition as shown in Arc5 and Arc6 (Fig. 5.15e and 5.15f). As described in Art 5.2, severe deposition that takes place near the confluence at Naradaha, results in closing of the proposed dredged channel.



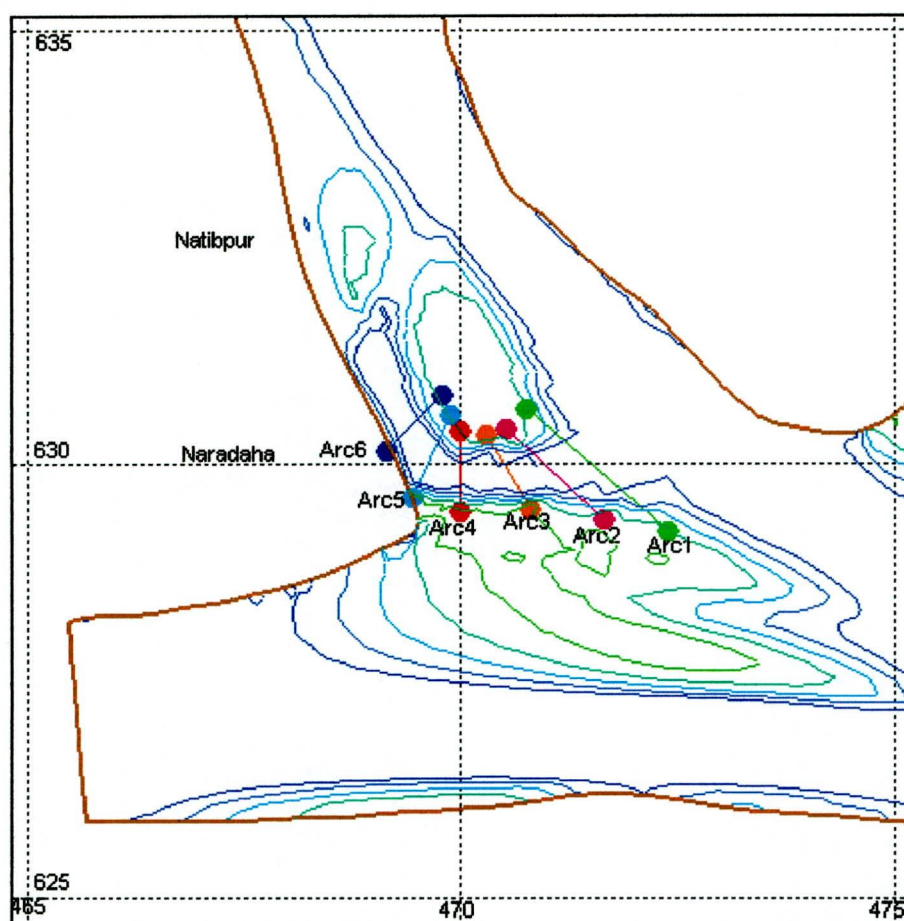
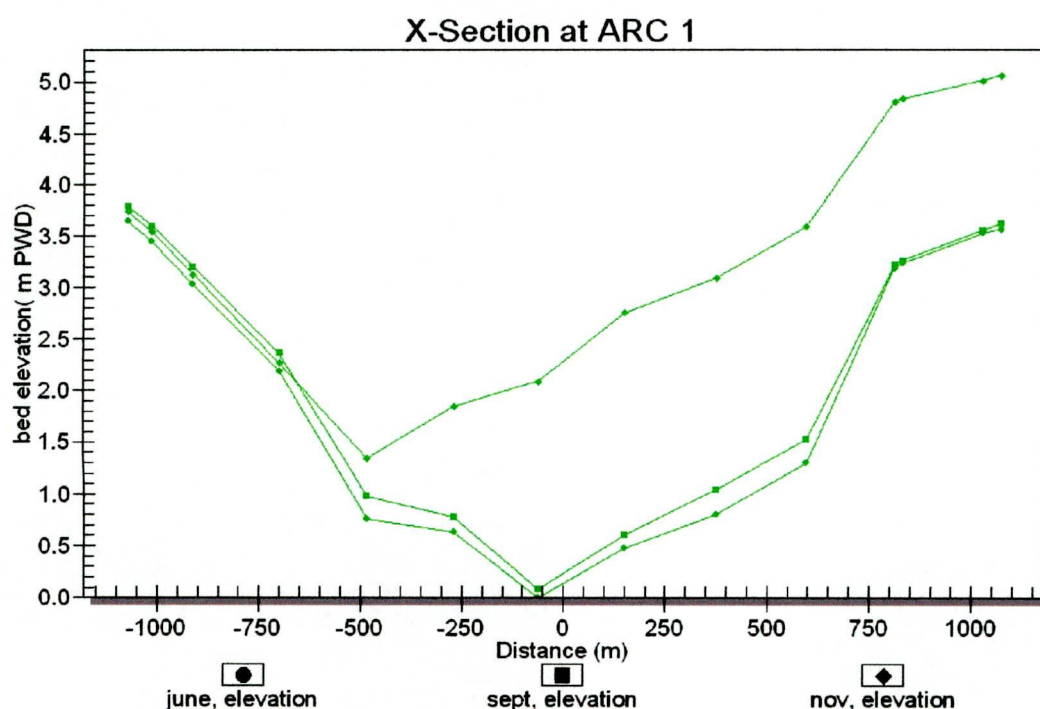
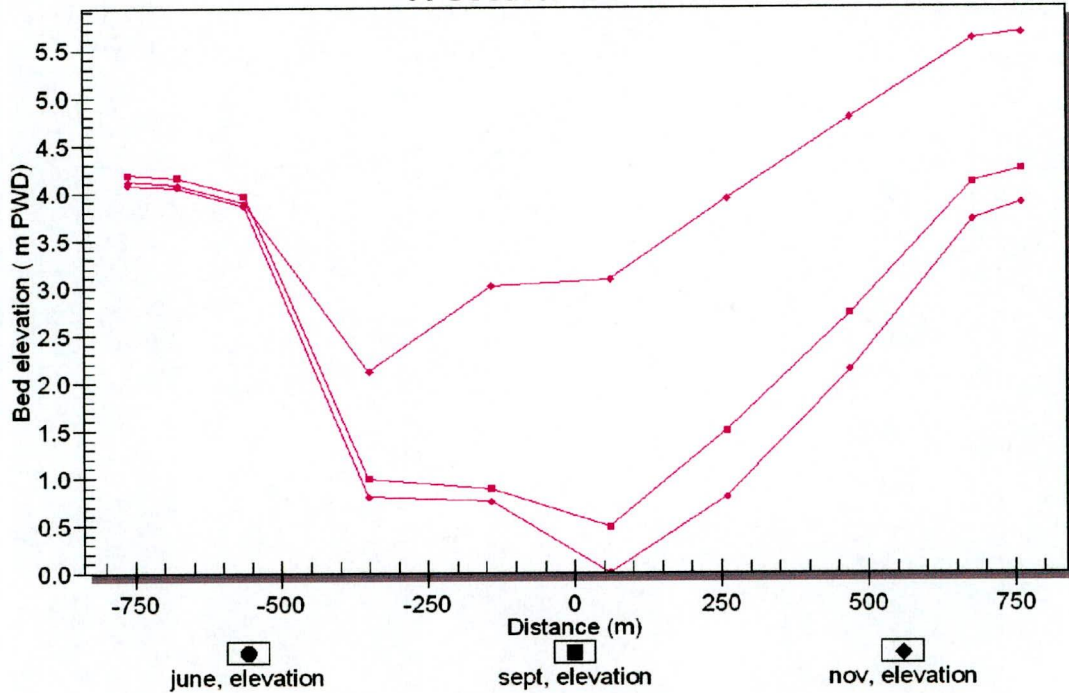


Fig. 5.14 Locations of different cross-section Arcs in Option1



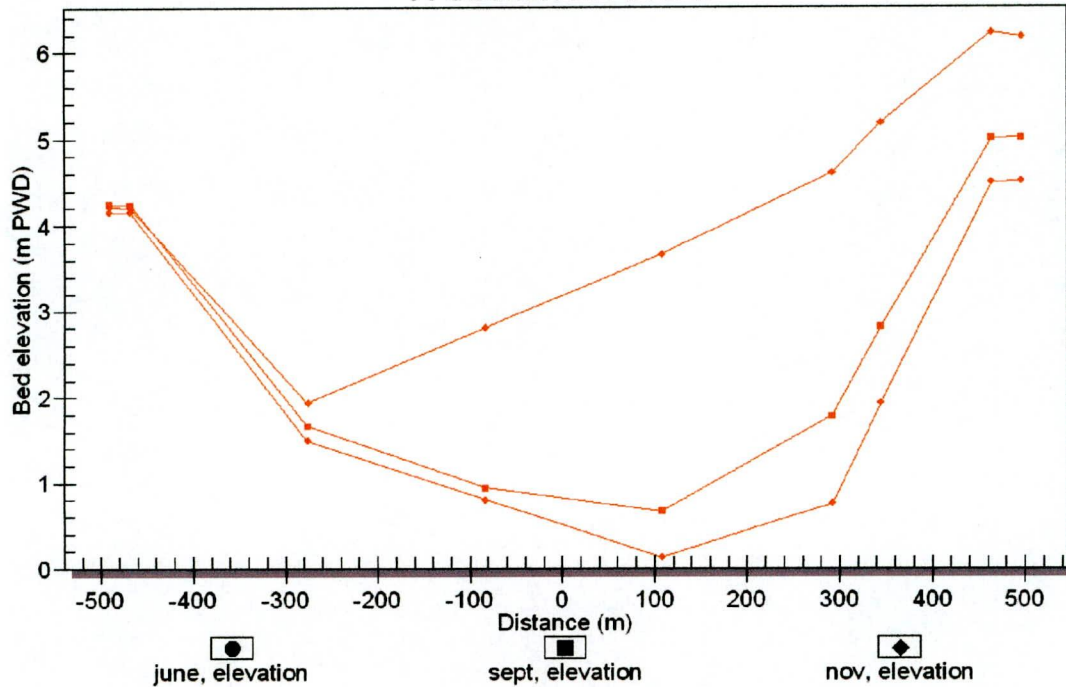
(a) Cross-section at Arc1

X-Section at ARC 2

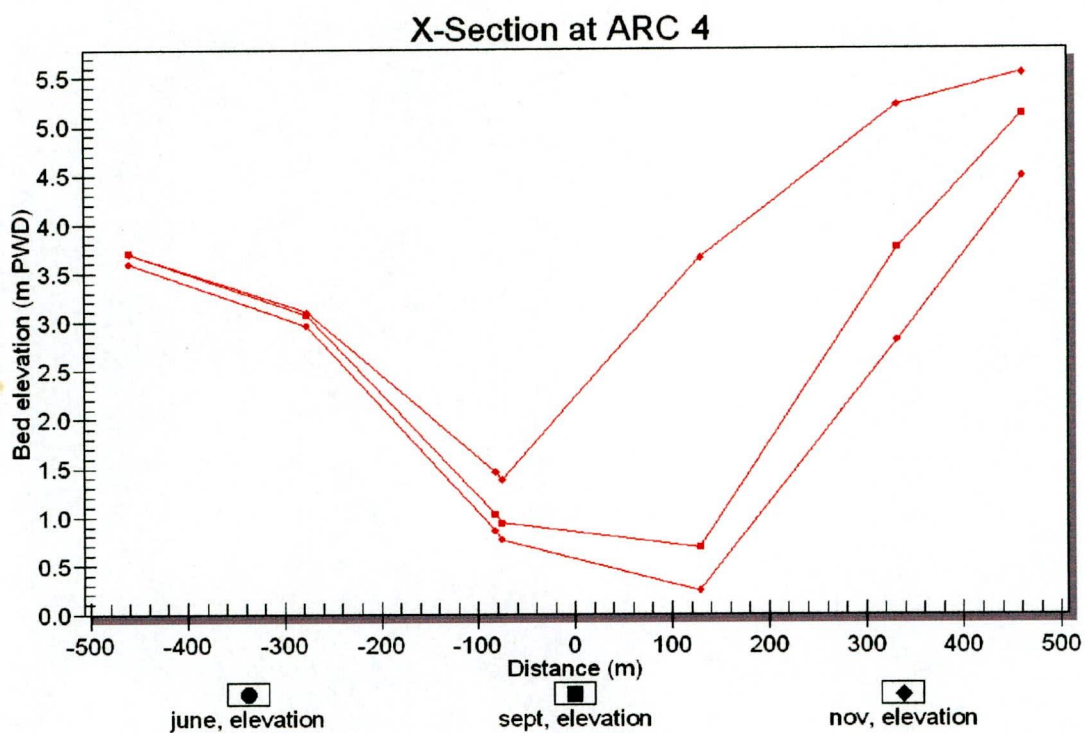


(b) Cross-section at Arc2

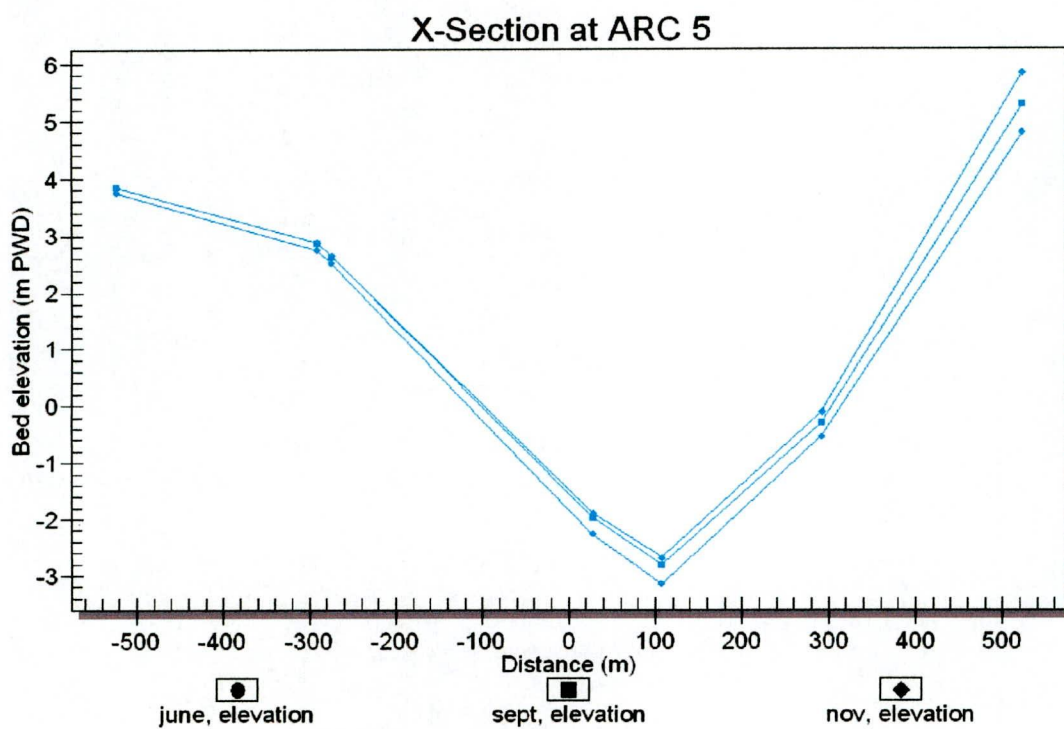
X-Section at ARC 3



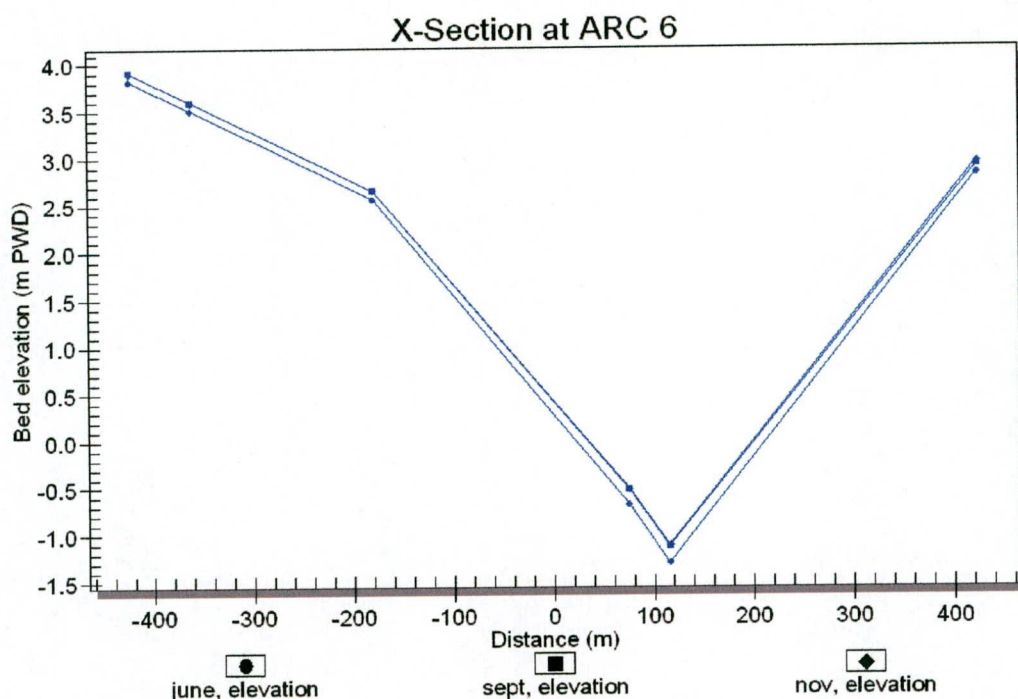
(c) Cross-section at Arc3



(d) Cross-section at Arc4



(e) Cross-section at Arc5



(f) Cross-section at Arc6

Fig: 5.15 Cross-sections at different locations after one-year simulation for Option1

5.3.2 Option 2: Dredging upstream Right channel

From three years simulations, it has been found (Arc6-Arc7, Fig. 5.6f-5.6g) that about 1.0 to 1.5 m deep shallow channel exists (or have a deposition of 0.6 to 0.8 m) in the Right channel of Western anabbranch near Natibpur. To be connected with the deeper pocket, dredging of this shallow channel has been taken as another option. Bed elevations of the nodes in question of the channel are lowered on to the simulated 2003 bathymetry, to have a minimum navigable depth (Fig. 5.16a) and thus the resultant bathymetry has been used to run the model for next one morphological year. After one year of simulation, navigable depths are presented in the Fig. 5.16b. To obtain the erosion/deposition patterns, six cross-sections (Arc1-Arc6) have been taken in the proposed dredged channel as shown in Fig. 5.17. It has been found that the dredged channel has shown little deposition. Examining the cross-sections at different locations (Arc1-Arc6, Fig. 5.18a to 5.18h) of the proposed channel, it has been found that an average deposition of 0.35 m occurred. So a total of 0.18 Mm^3 ($0.35 \text{ m} \times 350 \text{ m width} \times 1474 \text{ m length}$) volume of dredging in every year would be enough to maintain the channel as an entrance to the deep pocket. Dredging spoils should be dumped in a safe place, so that it can not trace its path towards deep pocket. Moreover, dredging be done before the lean season.

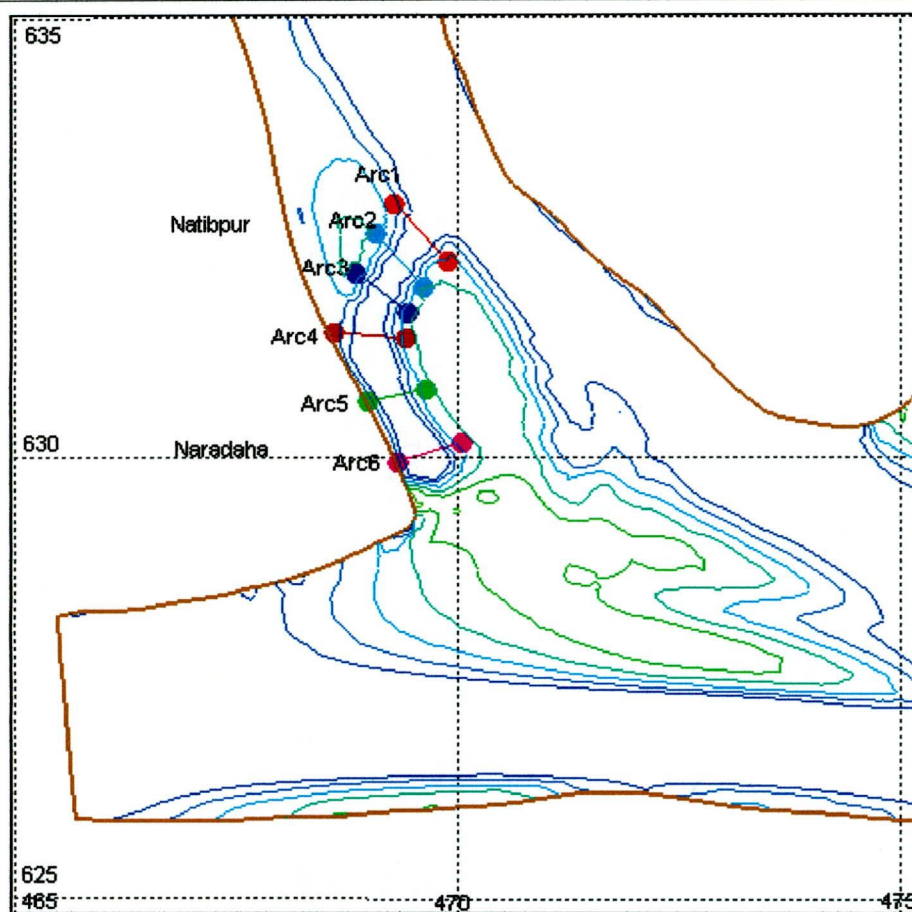
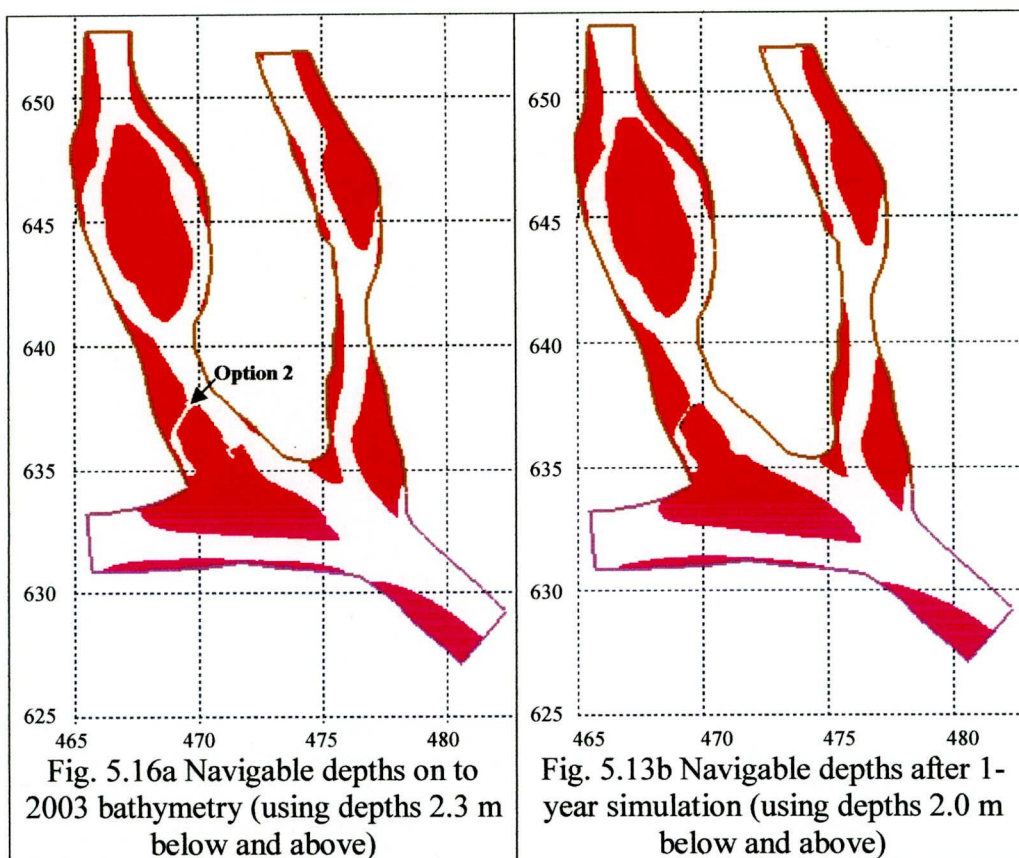
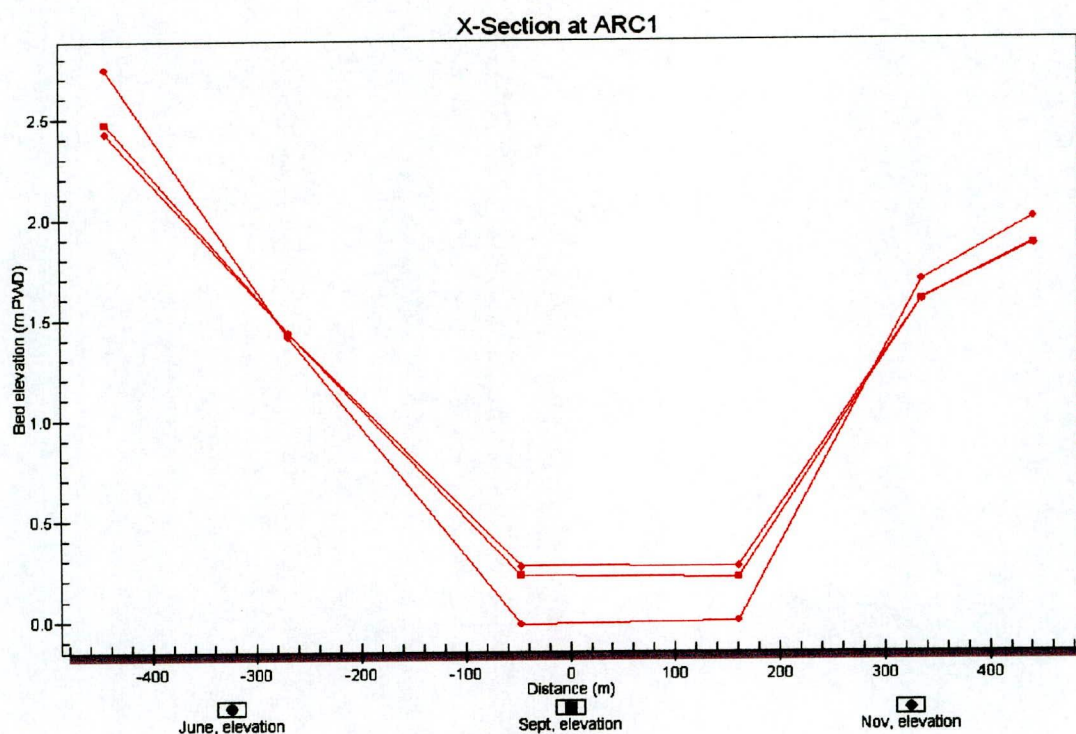
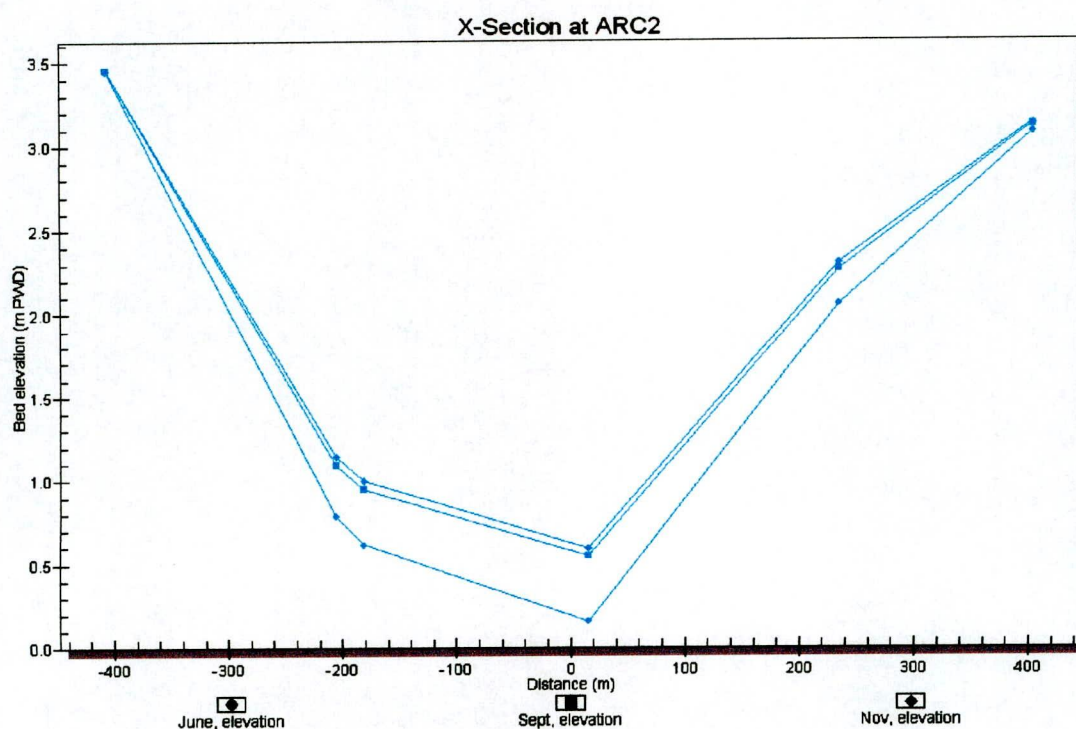


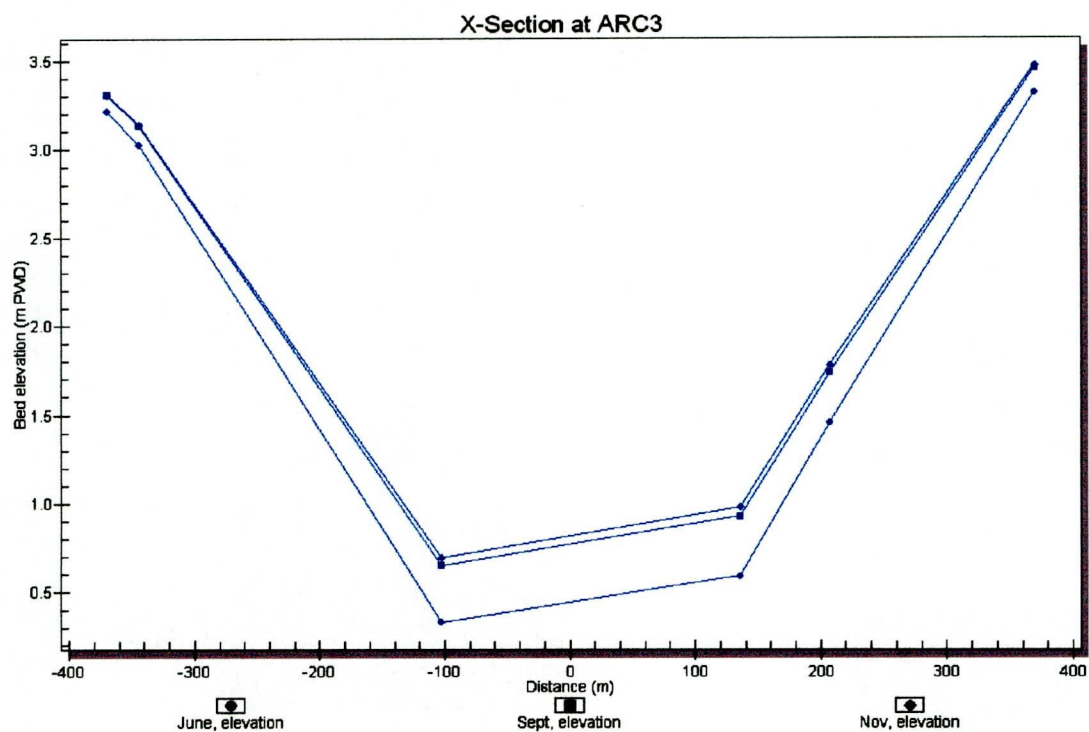
Fig. 5.17 Locations of different cross-section Arcs in the Option 2



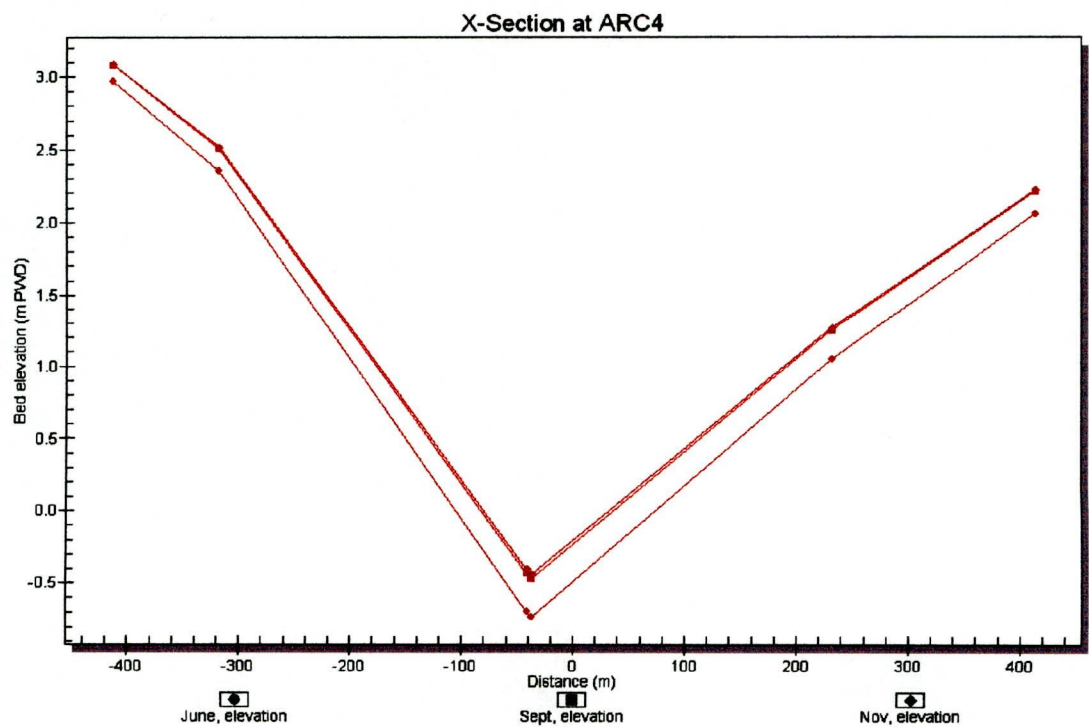
(a) Cross-section at Arc1



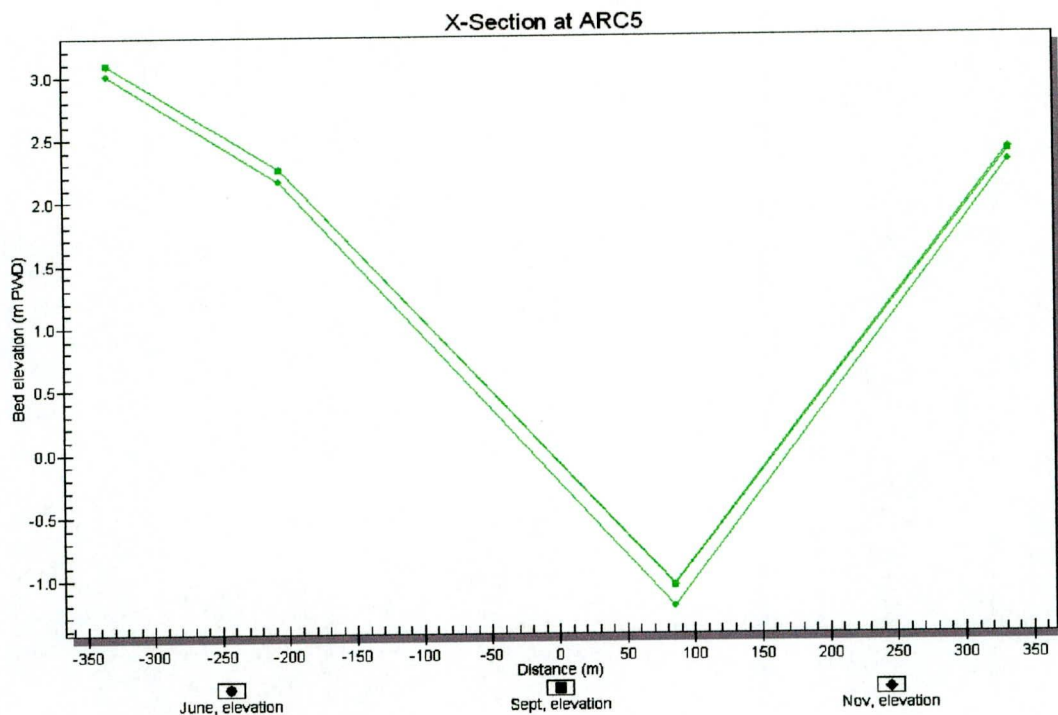
(b) Cross-section at Arc2



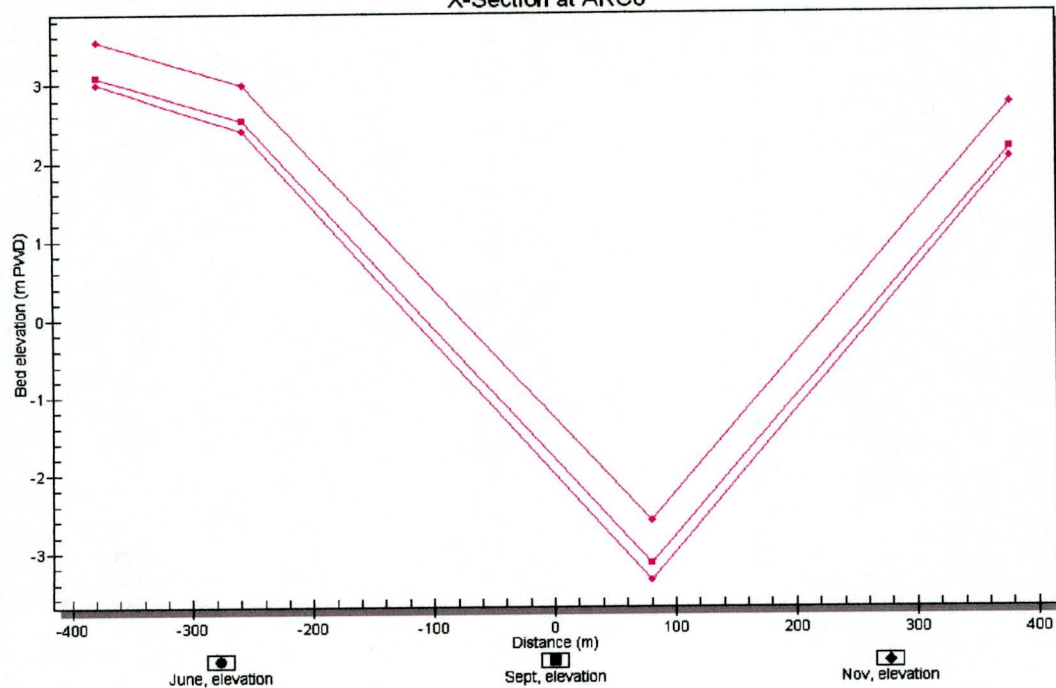
(c) Cross-section at Arc3



(d) Cross-section at Arc4



(e) Cross-section at Arc5
X-Section at ARC6



(f) Cross-section at Arc6

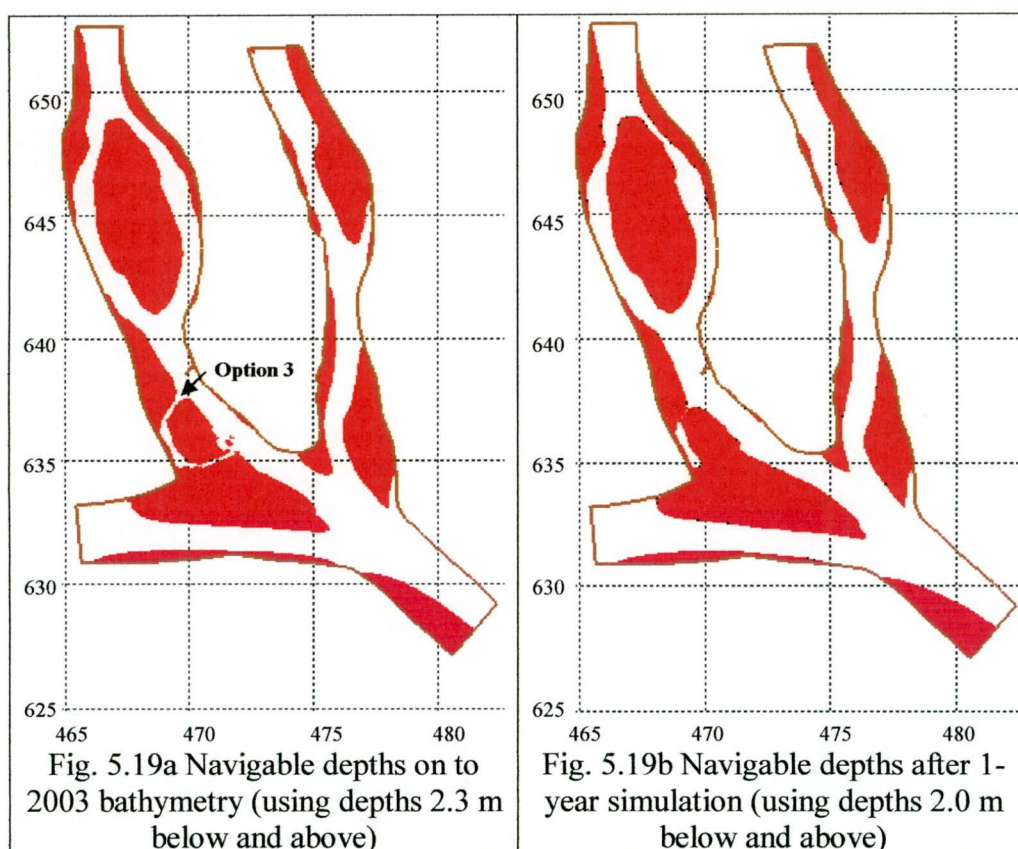
Fig: 5.18 Cross-sections at different locations after one year simulation for Option 2

5.3.3 Option 3: Dredging and spur

In this option, channels that are created in Option 1 and Option 2 are taken along with a spur in the left bank near Natibpur as shown in Fig. 5.19a. The spur has a width of 20 m and length of 480 m. Fig. 5.19a that shows the resultant bathymetry has

been used to run the model for next one morphological year. After one year of simulation, navigable depths are presented in the Fig. 5.19b. Presence of spur induces erosion in its downstream locations starting immediately from its nose as shown in Fig. 5.20. To obtain the erosion/deposition patterns, nine cross-sections (Arc1-Arc9) have been taken in the proposed dredged channels as shown in Fig. 5.21. Construction spur has attracted more erosion at the entrance of the proposed channel as can be seen in Arc1 of Fig. 5.22a. However, subsequent Arc2 and Arc3 (Figs. 5.22b-5.22c) show the opposite, around 0.45 m deposition has occurred, which is slightly more than the Option 2 deposition (average 0.35 m). The deep pocket (Arc4-Arc6, Figs. 5.22d-5.22f) has also shown slightly more deposition than Option 2. An average deposition of around 3.0 m (Arc7 to Arc9, Fig. 5.21g to 5.22i) has been found in the downstream proposed channel near the confluence.

Though erosion takes place at the entrance of the Right channel, part of those eroded materials have been deposited in the interior of the proposed channel, which in a way has induced higher deposition compare to Option2. Dredged downstream channel near Naradaha has disappeared, by as usual process of heavy siltation that developed due to backwater effect in the confluence. So presence of spur does not improve the situation anymore.



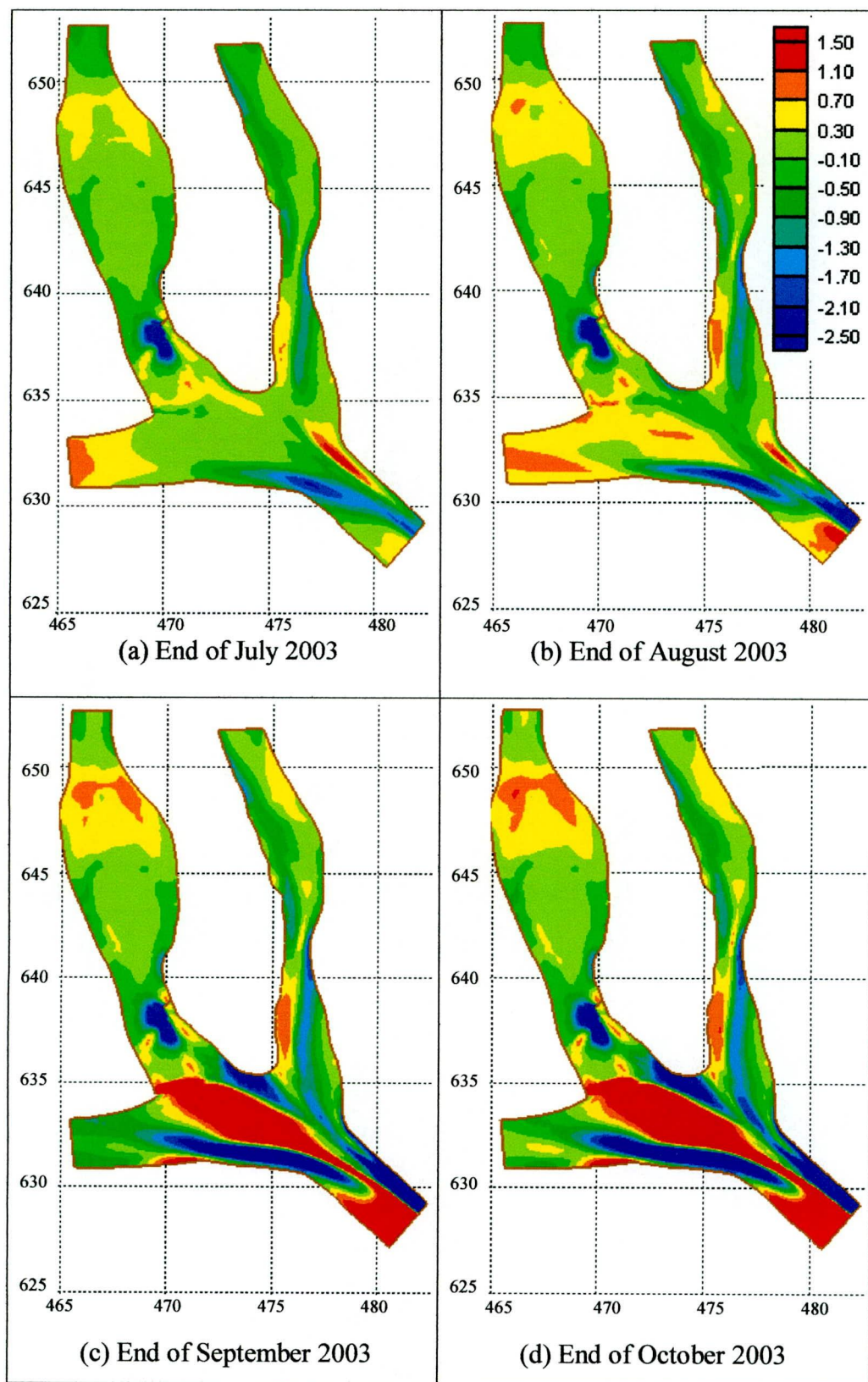


Fig. 5.20 Erosion/deposition in Option 3 particularly to show the spur induced erosion

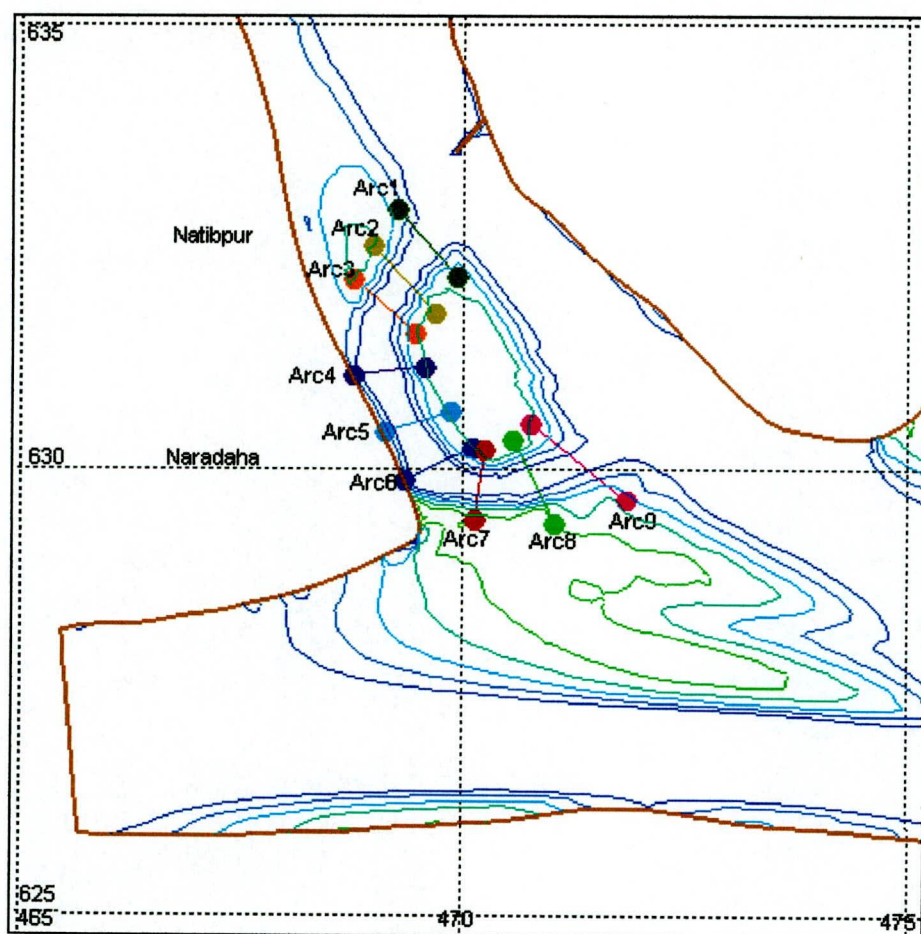
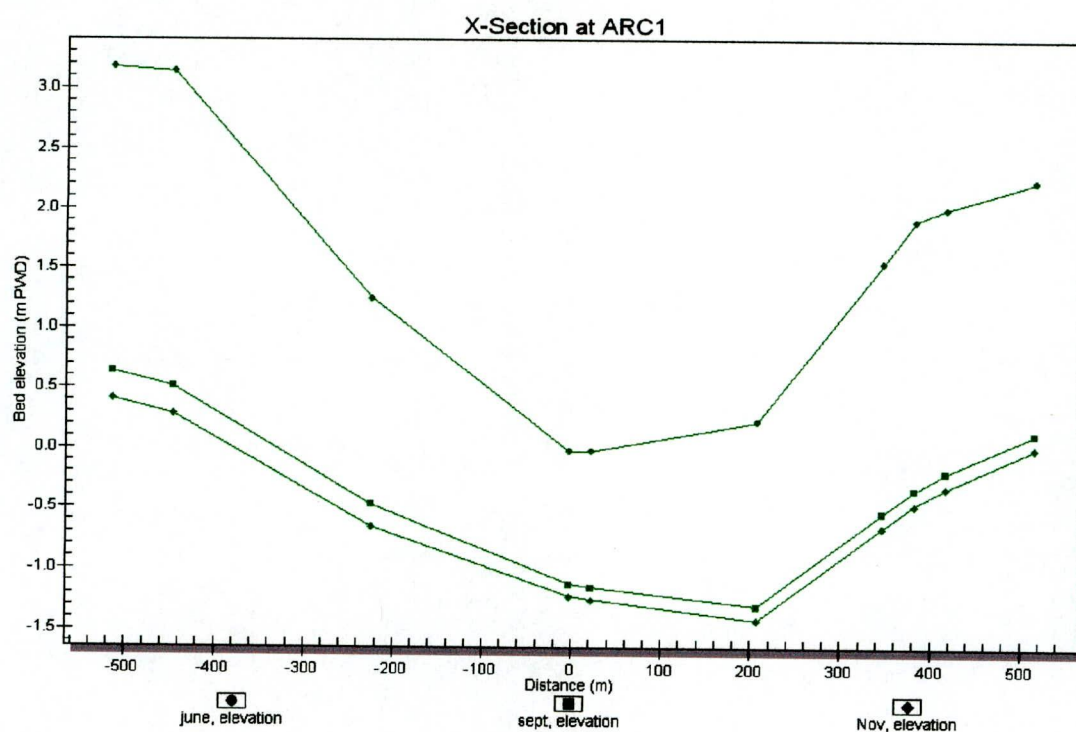
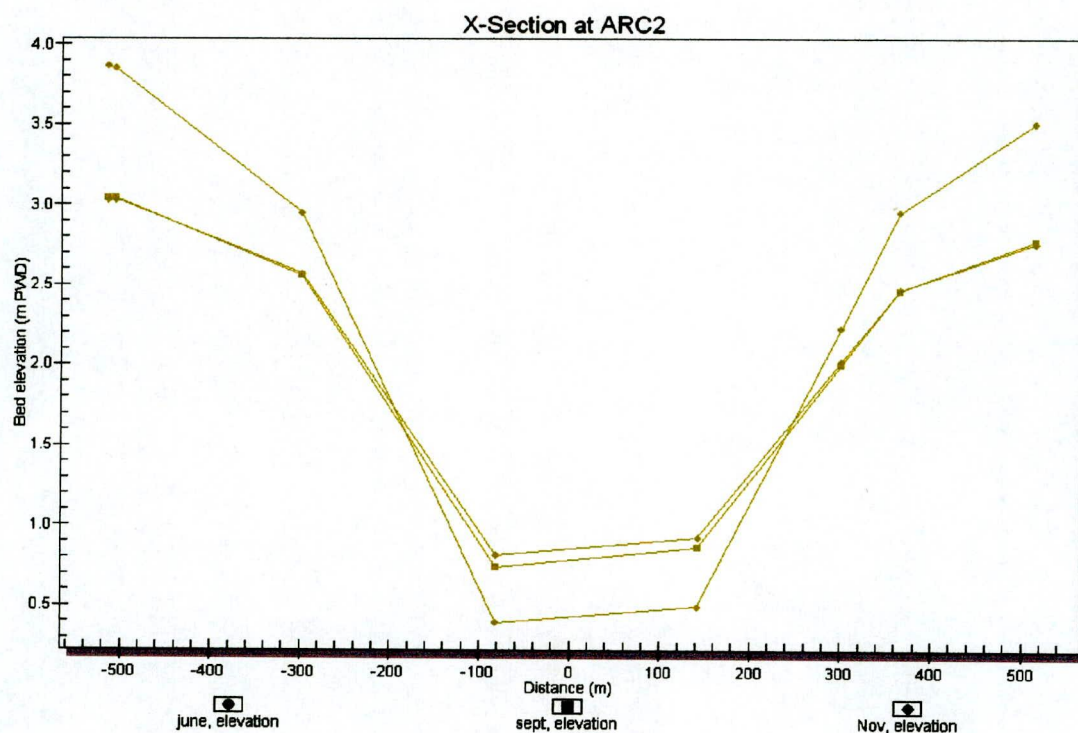


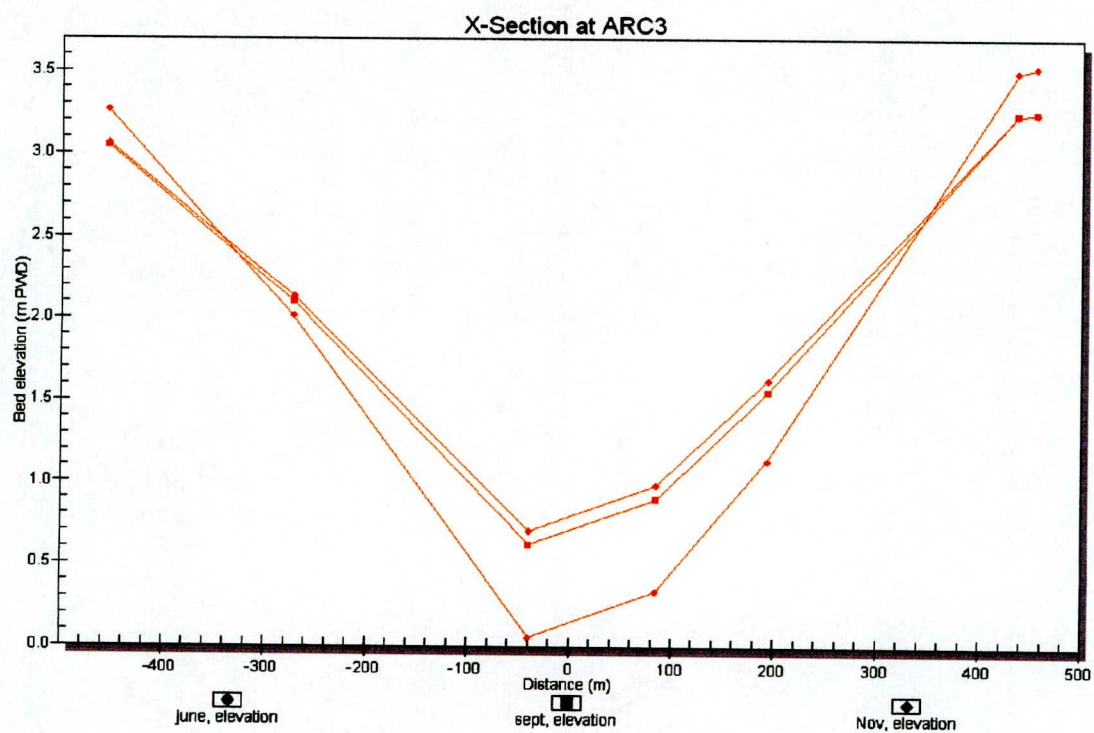
Fig. 5.21 Locations of different cross-section Arcs in the Option 3



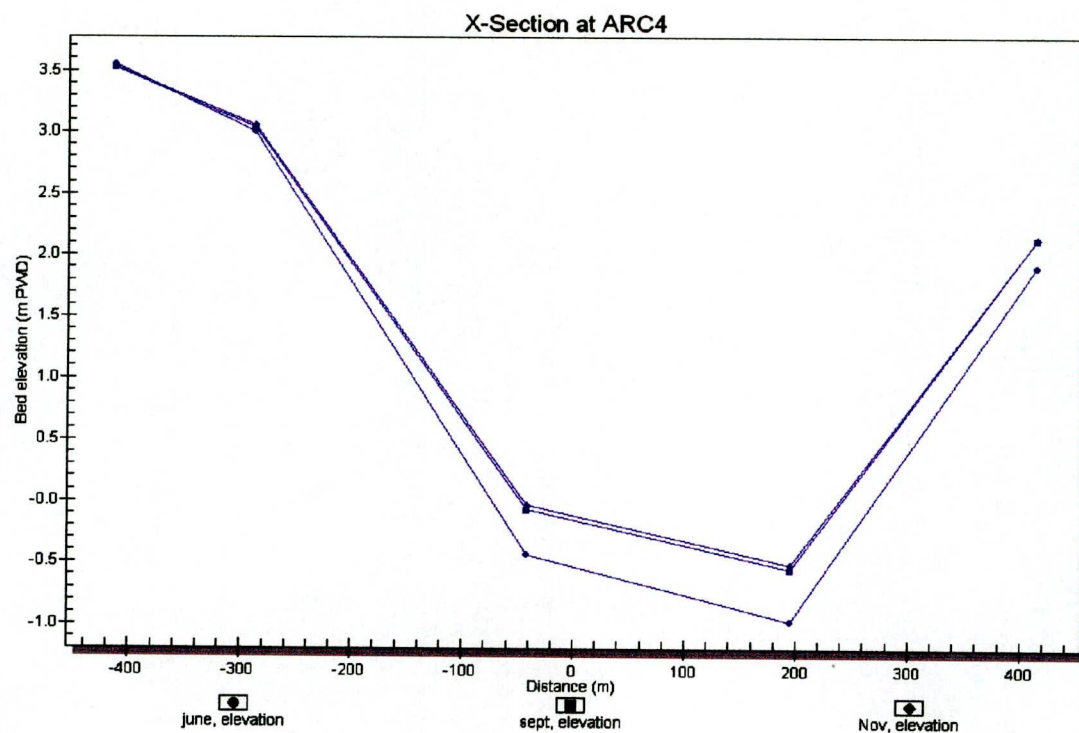
(a) Cross-section at Arc1



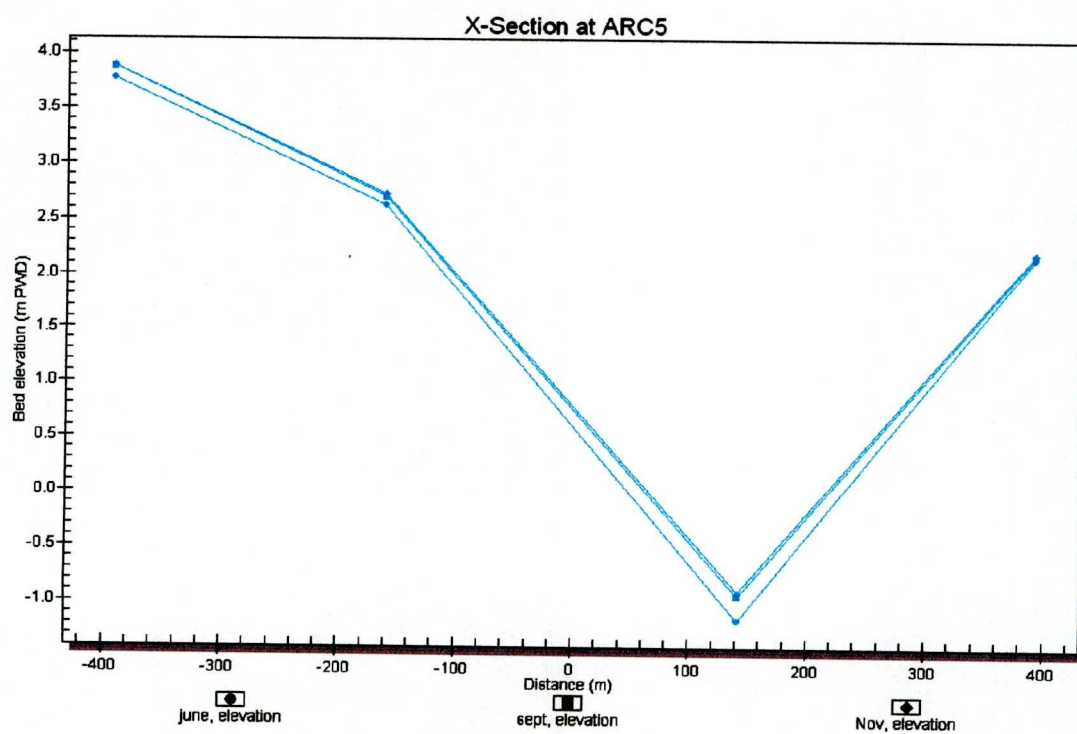
(b) Cross-section at Arc2



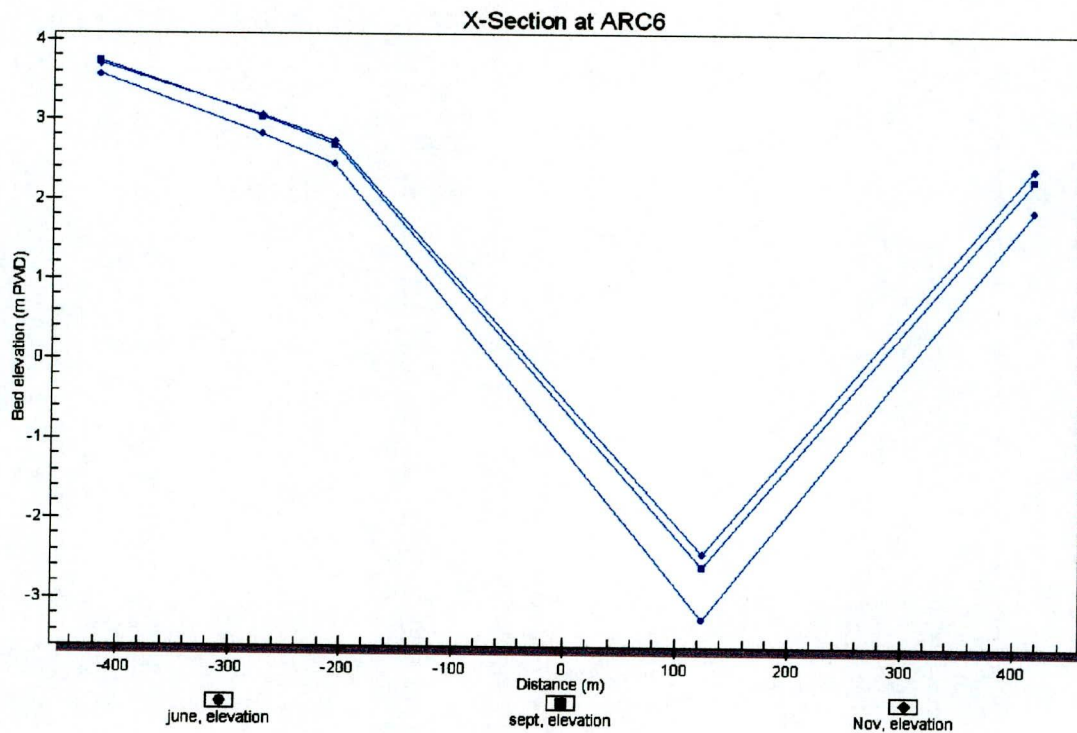
(c) Cross-section at Arc3



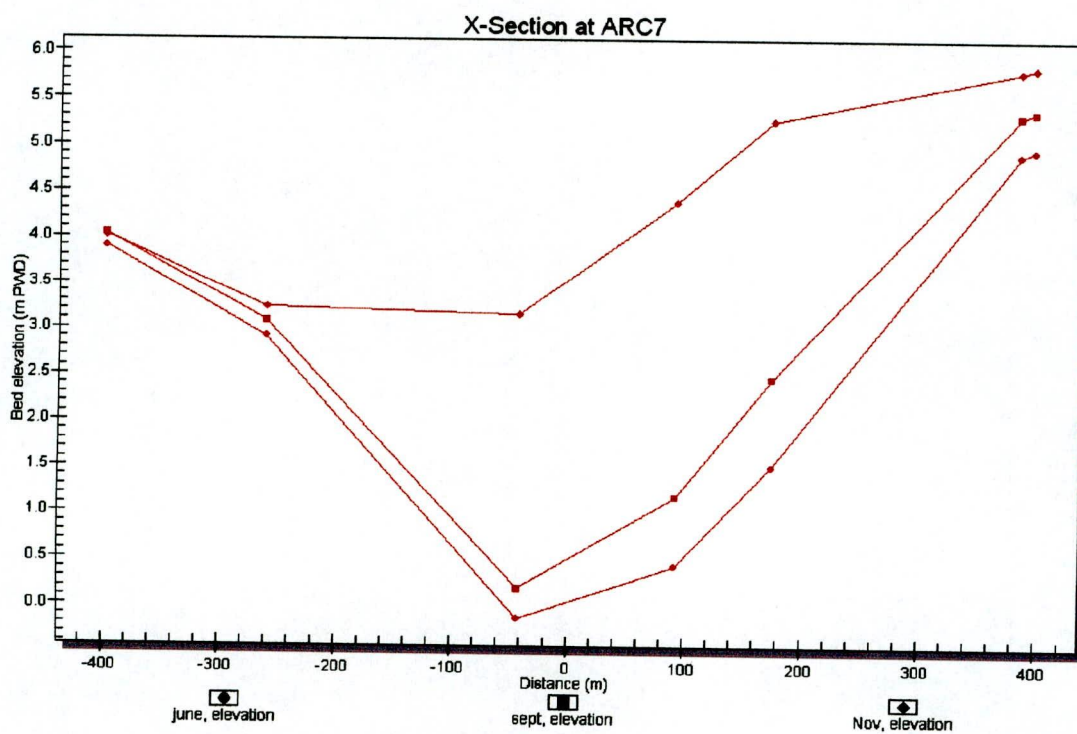
(d) Cross-section at Arc4



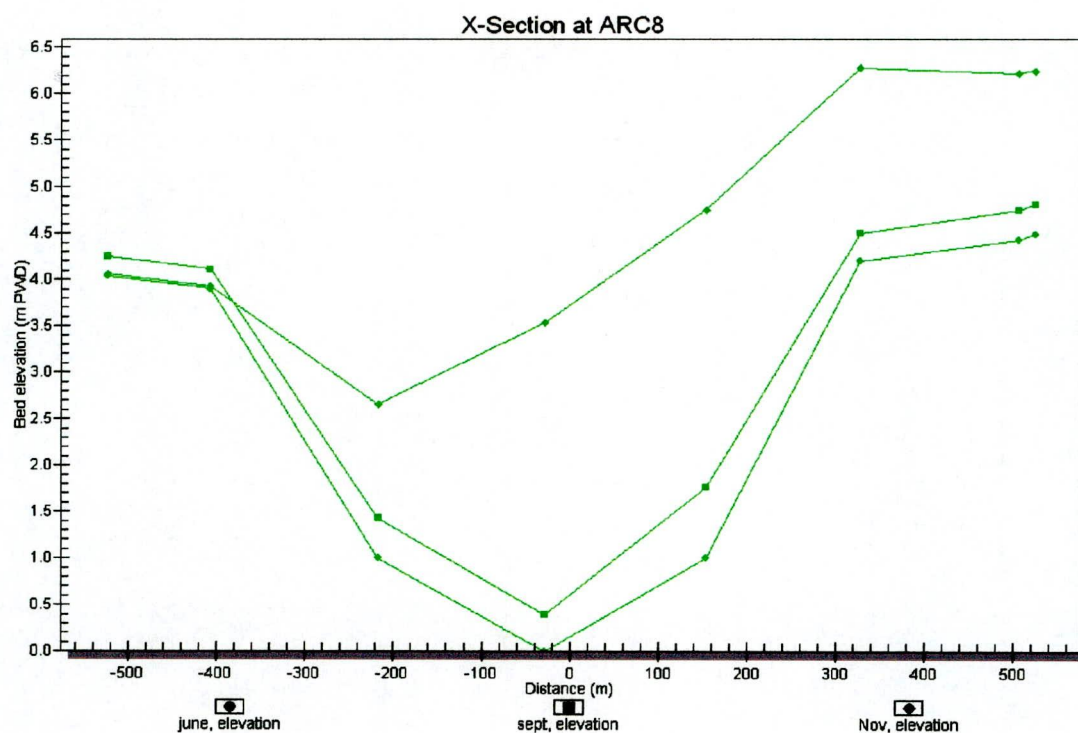
(e) Cross-section at Arc5



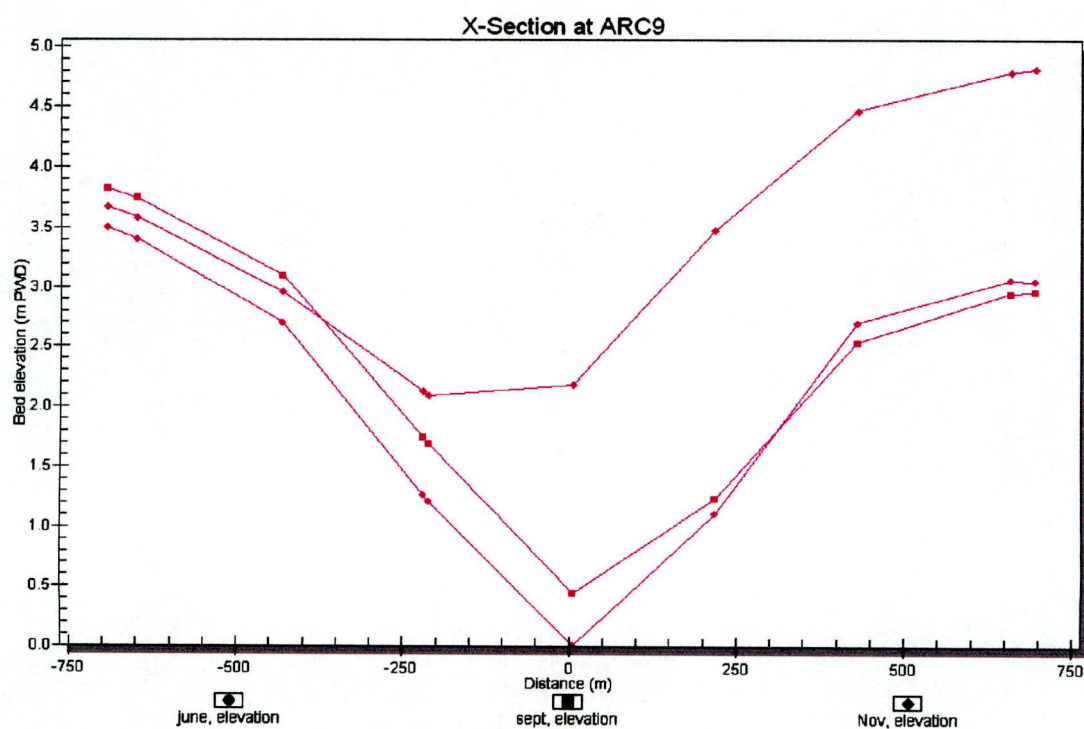
(f) Cross-section at Arc6



(g) Cross-section at Arc7



(h) Cross-section at Arc8



(i) Cross-section at Arc9

Fig. 5.22 Cross-sections at different locations after one-year simulation for Option 3

5.4 Location of ferry ghat

Protabpur and Kazirhat are two temporary locations for existing ferry ghats. In the past, BIWTA maintained a ferry route from Aricha to Nagorbari. This route has long been abandoned due to large-scale siltation and shifting of the western anabranch. Morphological changes have also been observed in the simulated bathymetries. A mathematical model study carried by BUET and IWM (BIWTA, 2003), suggested construction of a ferry ghat in Kazirhat. As alternatives three more locations (Khanpura, Khayerchar, and Natibpur) have been identified for possible ghat construction, however, priorities of these locations were less compared to Kazirhat. It is worthy to mention here that Khayerchar is a site, which has been favored and provisionally selected by Inter-ministerial Committee, formed in December 2002. It is about 1.0 km upstream of Naradaha, where bank elevation is around 8.0 m PWD and during monsoon the site goes under water. However, the committee in its report pointed that the crossing distances, travel time and fuel cost can be kept at minimum and greater turnouts of ferry operations may be achieved.

It was mentioned in BIWTA (2003) that Khayerchar/Naradaha site has a possibility for further siltation to discontinue the existing navigable channel in near future. A huge dredging, which is like Option 1, has been anticipated for keeping the route alive. During the time of study of BIWTA (2003), the existence of the deep pocket, as mentioned earlier, was overlooked to be connected from upstream. So this deep pocket motivates this present study to take into account the proposed dredged channel at upstream end, and explore its future sustainability. In a way, Option 2, the upstream dredged channel, has turned to be a productive option. It shows a requirement for maintenance dredging, of the order of 0.18 Mm^3 , and a capital dredging of 0.9 Mm^3 has been determined to initiate the proposed option. So the new route to deep pocket is found to be 3.3 km less (Fig. 5.23) than the route followed in Kazirhat by BIWTA (2003). This site poses a new alternative compared to Kazirhat.

Satellite images show that the Khayerchar area, once under Ganges-Jamuna, still bears the marks of numerous shallow channels and creeks connecting the two mightiest rivers. It appears that the process of shifting and reclamation just upstream of the confluence is very unstable, and in near future new shoal development would force the confluence to attain further indeterminate positions. Therefore the new highway embankment that has been proposed by R&HD, which is of 6.0 m above existing ground level, and runs parallel to bank line, necessitates the need for further

study by including these new developments of the char area under the model mesh. This prospective study may suggest means, by which to achieve the goals, for sustainability of the Khayerchar area for ghat construction.

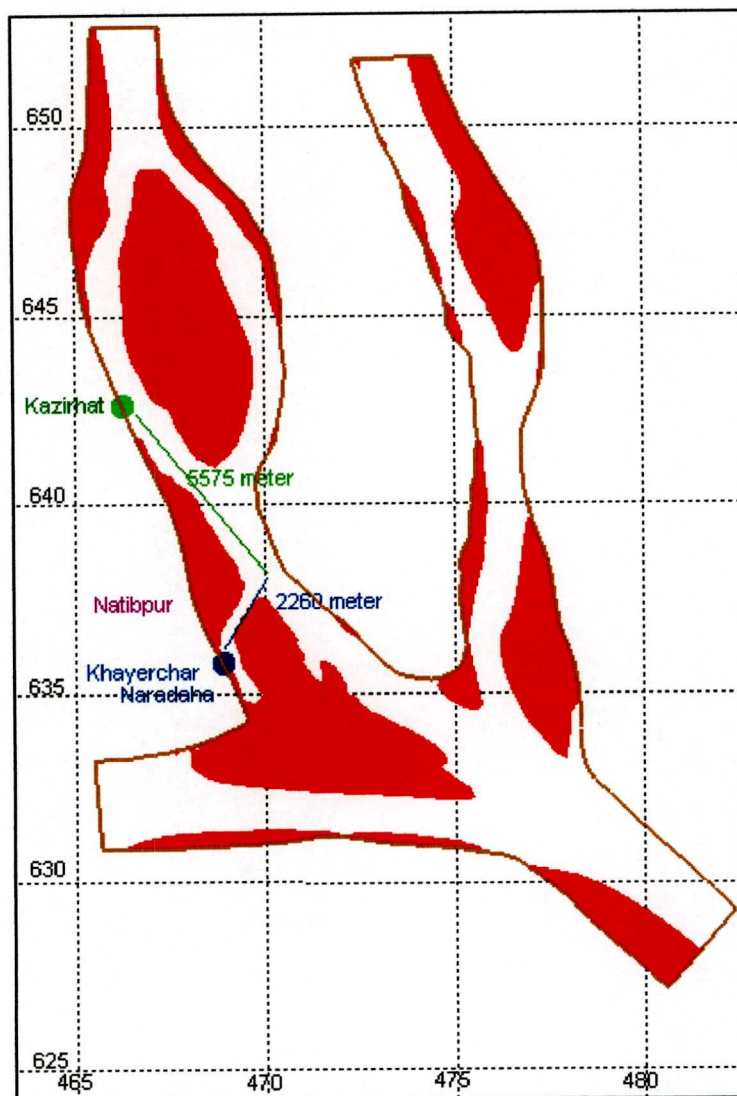


Fig. 5.23 Location of ferry ghats (contour using depths 2.3 m below and above)

Chapter 6

Conclusions and Recommendations

6.1 General

Morphology of braided river is a very complex phenomenon. To study the morphological behavior of Jamuna river, two-dimensional simulations are formulated using finite element models RMA2 and SED2D under SMS environment.

The finite element mesh has been generated using LANDSAT image of 17th November 2000, and initial bed elevations for the nodes of the mesh have been composed from the scattered survey data of April 2001 by BIWTA. Once the mesh and bathymetry have been obtained, the models are ready thereby to incorporate boundary conditions, initial conditions and material properties. To simulate the morphology of the river, models have been run for monsoon, June-October of each year. It is assumed that negligible changes occur during lean seasons, and therefore these time periods have been kept out of purview of modeling. Simulations have been done for 2001-2003 for their given boundary conditions of June to October.

The models developed in this study have been calibrated against the observed water surface elevations at Aricha for 2001. Sediment model has also been calibrated using measured bathymetry by BIWTA with the simulated bathymetry of 23rd August 2001. Also sediment rates at Baruria have been generated from the SED2D model and compared with the FAP24 data (1996). All these calibrations have shown adequate agreement with the observed values. Besides, validation for next one more season (2002), for water surface elevations and bed elevations, has shown satisfactory matches between observed and estimated values.

6.2 Conclusions

The summary of the findings of the present study are as follows:

1. All three years simulations have shown much similar type of erosion/deposition processes. Both erosion and deposition occur mainly in August and September of each year.
2. Erosion takes place in the outer bend of the meandering Eastern anabranch and in Western anabranch, severe deposition has been observed near the confluence due to backwater effect of Jamuna-Ganges flow. Velocity

reduction in the confluence significantly diminishes their sediment transport capacity, and hence inducing deposition.

3. It is evident that the complex waterway at the confluence is further complicated by the occurrences of characteristic hydrographs from Ganges and Jamuna, that differing in strengths with time, induces different dominating phenomena to work on sediments to settle at assorted positions.
4. It has been found from the observed bathymetries of 1996-2003 that Jamuna has gone through a major transformation after 1998 flood. Its course has shifted more towards left bank particularly near confluence. This is one of the reasons for enhanced deposition in the downstream of Middle channel near Naradaha. These observations from measured data are further substantiated by the results obtained from the present simulation models.
5. Calibrated and validated model has been used to find a sustainable navigable channel. Three options have been examined using a deep pocket found near west bank of Naradaha. Option 1 is the dredging of a downstream channel connecting the lower segment of the deep pocket near Naradaha. This channel fills up with serious deposition within a season. Option 2 is the dredging of Right channel connecting the upper segment of the deep pocket near Natibpur. This channel shows little deposition and can be maintained with yearly dredging of the order of 0.18 Mm^3 . To improve further, Option 3 has been designed with a blend of Option 1 and Option 2 along with a spur in the left bank of the permanent char near Natibpur. However, the option failed to improve the situation. Lower channel again silted up within a season, and the erosion that has been initiated by the spur at the entrance of the Right channel, transport part of these sediments in the interior of the Right channel for enhanced deposition. Therefore, Option 2 has been considered for using as a navigable channel towards Khayerchar/Naradaha instead of Kazirhat proposed by BIWTA (2003).
6. The new route to deep pocket is found to be 3.3 km less (Fig. 5.23) than the route followed in Kazirhat. This site represents a new alternative compared to Kazirhat.

6.3 Recommendations

The following studies have been outlined for further undertakings as a continuation of the present work.

1. Different years satellite images near Naradaha/Khayerchar show that the process of shifting and reclamation just upstream of the confluence is very unstable, and in near future new shoal development would force the confluence to attain further indeterminate positions. Therefore any new developments particularly construction of roads, necessitate the need for further study by including the new infrastructure and latest positions of channels and shoals under the model mesh. This prospective study may suggest means, for sustainability of the Khayerchar area for ghat construction.
2. Others engineering options such as spurs at different locations or using series of spurs in a stretch of river reach can be examined to find a sustainable navigable channel.
3. A major limitation of SED2D model is that it is not coupled with hydrodynamic model. SED2D model needs velocity flow field from another model, like RMA2. There is another finite element model named FESWMS in SMS environment, which is a coupled model. The documentation of this model is not rich enough to undertake present type of work without external help. However, this model may be taken for future work, which may require some longer time before coming to the point of its proper understanding and application for field problems.
4. A study on bank line shifting due to erosion can be undertaken, using manual procedure of shifting the bank line, by lowering the ground elevations in the prospective bank line nodes of the model. This would be a trial exercise to check its effectiveness before reporting the procedure to the developers of the software.

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