CS(AR)-29/96-97

MODELLING OF AN INDIAN ESTUARY USING TWO DIMENSIONAL FINITE ELEMENT MODEL

NATIONAL INSTITUTE OF HYDROLOGY
JALVIGYAN BHAWAN
ROORKEE - 247 667
1996-97

ABSTRACT

The basic equations for modeling of any surface water problems are the three dimensional hydrodynamic equations arising from consideration of mass and momentum conservation. In vertically well mixed shallow water bodies, the horizontal components of flow quantities are normally much more significant than vertical components. In such cases, vertically integrated form of the hydrodynamic equation or shallow water equations can be employed efficiently. These are two dimensional dynamic equation of motion and the unsteady continuity equation. Shallow rivers, flood plains, estuaries, harbours, etc. are examples where shallow water equation can be employed.

The study of circulation pattern in estuaries and coastal deltas, where tidal and wind action are predominant is essential for understanding the various processes taking place within the system. A two-dimensional finite element mode, FESWMS-2DH, developed by USGS, is used in this study to simulate the hydrodynamics of Cochin estuary, which lies along Kerala coast.

Calibration have been done using pre-monsoon tide data and the current velocity measured at 11 observation points within the estuary. Model parameters like roughness coefficient and eddy viscosity have been adjusted to simulate the practical scenario. Calibrated model is used to simulate the hydrodynamics of the estuary for pre-monsoon and post-monsoon tides and the results indicates that the model is capable of simulating the hydrodynamics of the estuary.

CONTENTS

LIST OF FIGURES

1.0 INTRODUCTION

Estuaries are coastal bodies of water, which are connected to the sea at one end and fed by sources of fresh water at its landward boundaries. They are complex and highly dynamic aquatic environment as they are influenced by river flow, tide, wind, and density factors, and are further modified due to earth's rotation, bottom friction and the geometrical properties of the estuarine system.

Estuaries are integral part of coastal environment. They represent outfall regions of river and mark transition between fluvial and marine environment, where tidal actions cause intermingling of fresh water and salt water regime. They are extremely important ecosystems in the natural environment. They play a dynamic role in the mixing and circulation; sediment; and water dynamics in the transitional zone between land and sea.

Being at the confluence of the river with the sea, this environment naturally has the interaction of the sea, river and the land, characterised by variable gradients in physico-chemical factors. These in turn influence and determine the nature of living organisms of this area. Among the physico-chemical factors, the nature of the substratum, the extent of tidal influence, the size and frequency of the waves, the strength of currents, the nature of distribution of salinity, the type of sediments, the oxygen content of the water, pH, temperature, amount of organic matter and its oxidation, presence of hydrogen sulphide, concentration of irons, nature and extent of pollution, among others are important.

The study of circulation pattern in estuaries and coastal deltas, where tidal and wind actions are predominant, is one of the important factors in coastal designs, coastal and river engineering techniques for combatting pollution, determining friendly habitat for aquaculture, etc. Mathematical modeling is the most efficient method, among several approaches, for evolving an idea about the circulation patterns occurring in an estuarine system. The basic equations for the modelling of any surface water problems are the three dimensional hydrodynamic equations arising from consideration of mass and momentum conservation. In vertically well mixed, shallow bays, the horizontal tidal circulation is normally more significant than vertical motion. Therefore, the vertically integrated form of the hydrodynamic equations or shallow water equations can be employed.

Mathematical modeling essentially consists of representation of actual processes by mathematical equations, which are subsequently solved by analytical or numerical techniques. The numerical models have traditionally employed the finite difference method, to solve these governing differential equations. This method satisfies the governing equations by replacing derivatives of difference approximation. For a problem in two spatial dimensions, this implies a descritization with a constant sized, square grid mesh. Although grids of other shapes are possible, they are too inefficient to use. In recent years, a more powerful method, the finite element technique, has emerged. It is a numerical procedure for solving differential equation. This method divides study area, or domain, into subdomains or elements which are defined by a finite number of nodes located along the element boundary or interior. Values of a dependent variable are approximated within each element using values defined at the elements' nodes and a set of piecewise continuous interpolation function.

This method seems well suited for solving estuarine types of problems (governed by depth averaged two dimensional dynamic equations), and it has replaced the finite difference method. It affords very efficient descritization of the flow domain, since it allows a great versatility and simplicity in the construction of network grid and in the choice of the shape and size of elements. This not only gives better adaption to the different gradients of the physical magnitudes and consequently greater accuracy, but also more ease to guarantee overall continuity in the domain.

A number of finite element techniques have been developed, and the most commonly used techniques employ Galerkin method of weighted residuals (Lee and Froehlich, 1988). Following this method, a general functional behaviour of the dependent variables which approximately simplifies the boundary condition is assumed. In general, the governing equations are not exactly satisfied when these assumed values are substituted, which results in an error or residual. To ensure that the error is minimised, the residual is required to vanish, in an average sense, when multiplied by a weighting function and summed at every point in the solution domain. In Galerkin method, the weighting functions are chosen to be the same as the interpolation function. A set of simultaneous equations result when the weighting functions are specified. All the element (local) equations are assembled to obtain a complete (global) set of equations. These equations are then solved to obtain the parameters of the functional representation of dependable variable.

Finite Element Surface Water Modeling System: Two Dimensional Flow in a Horizontal Plane (FESWMS-2DH), (Froelich,1989), is developed to simulate surface water flow, where the flow is essentially two dimensional in a horizontal plane. It calculates depth averaged velocities, water depths and the time derivatives of these quantities if a time dependent flow is modeled. The equations that govern depth averaged surface water flow account for the effects of bed friction, wind induced stress, fluid stress caused by turbulence and the effect of Earth's rotation.

Covering an area of nearly 7000 sq. kms., estuaries are distributed all along the east and west coast of India. The mouth of great rivers such as Brahmaputra, Ganga, Mahanadi, Godavari, Krishna and Cauvery on the east coast; and the extensive system of backwaters of Kerala along the west coast are examples of typical estuarine systems. Some of the estuaries are not open all through year being partially or fully cut off from the sea, especially during the summer, when the river flow is reduced by the formation of sand bars. In others, owing to the man made changes such as the construction of dams, barrages, etc., the inflow is reduced except during the monsoon period.

Study of ecology of estuaries is thus beset with difficulties since no two estuaries are alike. The interaction of so many variables, and differences in the physico-chemical, biological and meteorological conditions that exist in different regions of our country considerably add up to the problem. This aspect makes generalisation somewhat difficult necessitating detailed studies on each estuary.

The estuarine system along the coastal area are characterised by convective movements and mixing and dispersive actions of tides, currents and winds. The interchange of sea water with bay water and the interchange of water among various components of an estuarine system have a significant influence on the circulation and transport patterns within these systems. An adequate understanding of mixing and physical exchange is fundamental to the assessment of many physical, chemical and biological processes taking place in those areas.

The present studies were carried out with a view of analysing the dynamics of the Cochin estuary in relation to its hydrographic variations caused by tidally and seasonally varying functions of sea water intrusion and fresh water discharges. Knowledge of the dynamics of the estuarine system will be helpful in planning future development programmes of the estuarine region in general and Cochin harbour in particular.

2.0 DESCRIPTION OF THE MODELLING SYSTEM

The FESWMS-2DH was developed by U.S. Geological Survey and may be run on a main frame computer or a microcomputer. It is a modular set of computer programs that simulate surface water flows which are essentially two-dimensional in the horizontal plane.

The modeling system is capable of simulating flow through single or multiple bridge openings as normal flow, pressure flow, weir flow, or culvert flow. The finite element network can be designed to represent complex geometry as may be found at bridge crossings, training structures, islands, multiple channels, levees, river bends, or irregular shaped flood plains. The network can accommodate variable roughness as may be found in flood plains where dense vegetation is mixed with open areas. Wetting or drying of parts of the network is resolved by a feature which automatically adjusts boundary conditions enabling elements which are no longer submerged to be removed from the computations.

The numerical technique used to solve the governing equation is based on the Galerkin finite element method. Application of the finite element method causes the water body being modelled to be divided into smaller regions called elements. An element can be either triangular or quadrangular in shape; shapes that can easily be arranged to fit complex boundaries. The elements are defined by a series of node points located at the element vertices, mid-side points, and, in the case of nine-node quadrangular elements, at their centres. Values of dependent variables are approximated within each element using the values and a set of interpolation functions.

2.1 GOVERNING EQUATIONS

The three-dimensional equations of motion which describe the movement of water in a river consider the conservation of mass, as expressed by the continuity equation; and the conservation of momentum, as expressed by Newton's second law of motion.

The three dimensional flow structure is not required for most shallow water applications. Neglecting vertical velocities and vertical accelerations, the depth-averaged velocity may obtained by integrating the horizontal velocity components from the bed elevation to the water surface.

The depth averaged velocity along X axis is given by,

$U = 1/H \int_z^{z+H} u \, dz$

and the depth averaged velocity along Y axis is given by,

$V = 1/H \int_z^{z+H} v \, dz$

The two-dimensional depth averaged (vertically integrated) equations of motion used in FESWMS-2DH are; momentum equation in the X - direction is,

$$\partial (HU)/\delta t + \partial(\beta_{uu}HUU)/\partial x + \partial(\beta_{uv}HUV)/\partial y + gH \partial z_b/\partial x + 0.50g \partial H^2/\partial x - \Omega HV + 1/\rho[\tau_x^b - \tau_x^s - \partial(H\tau_{xx})/\partial x - \partial(H\tau_{xy})/\partial y] = 0$$

in the Y - direction is,

$$\partial (HV)/\partial t + \partial(\beta_{vu}HVU)/\partial x + \partial(\beta_{vv}HVV)/\partial y + gH \partial z_b/\partial y + 0.50g \partial H^2/\partial y + \Omega HU + 1/\rho[\tau_y^b - \tau_y^s - \partial(H\tau_{yx})/\partial x - \partial(H\tau_{yy})/\partial y] = 0$$

and the continuity equation is,

$$\delta H/\delta t + \delta(HU)/\delta x + \delta(HV)/\delta y = 0$$

where,

β_{uu} β_{uv} β_{vv} β_{vu}, are momentum correction coefficients is the Coriolis parameter

Ω is the density of water

τ_x^b, τ_y^b are bottom shear stresses

τ_x^s, τ_y^s are surface shear stresses

τ_{xx}, τ_{xy}, τ_{yx}, τ_{yy} are shear stresses by turbulence

U, V are depth averaged X and Y velocities

In the conservation of momentum equation, the first three terms describe the inertial force. The fourth and fifth terms describe the pressure gradient resulting from a sloping water surface. The sixth term represents the Coriolis force which acts perpendicular to the velocity. The seventh and eighth terms represent bottom stresses and surface stresses respectively. The ninth and tenth terms represent the effects of the Reynolds' stresses. Boussinesque eddy viscosity concept is used where the momentum transfer is proportional to the mean velocity gradients. The two-dimensional surface water flow equations account for energy losses through two mechanisms; bottom friction and turbulent stresses.

2.2 DATA REQUIREMENT

Data requirement can be classified as topographic, network and hydraulic. Topographic Data includes a contour map of the area and types of soil, vegetation and topography, at different regions of the study area which can be used to estimate the values of roughness coefficient. Once the study area is broken into a finite element network which consists of nodes and elements, it is required to know X and Y coordinates w.r.t to an origin and ground surface elevation at each node points. Node connectivity list has to be prepared for each element, by which an element can be defined by listing nodes in counter clockwise direction. Hydraulic data include model parameter values such as Manning coefficient and eddy viscosity; upstream and downstream boundary conditions such as discharge and water surface elevation; initial condition at each node and wind velocity and direction.

Input data to FESWMS-2DH can be classified broadly as 1.program control data, 2. network data, and 3. initial and boundary condition data.

Program control data govern the overall operation of a program. These data include codes that define functions to be performed, and constant values that are used as coefficients in equations and apply to the entire finite element network.

Network data describes the finite element network (grid). These data include element connectivity list, element property type codes, node point coordinates, and node point ground surface elevations. Also included as network data are sets of empirical coefficients that apply to a particular element property type.

Initial condition data are starting values of the dependent variables and their time derivatives at each node points in the finite element network. Boundary condition data are values of dependant variables that are presented at particular node points along the boundary of a network.

Output from the modelling system consists of processed network data, computed flow data (depth-averaged velocities and water depth at each node point, and the derivatives of these quantities with respect to time for unsteady flow simulation), and plots of both network data and flow data.

Boundary conditions consist of the specification of flow components or water surface elevations at open boundaries and zero flow components or zero normal flow (tangential flow) at all other boundaries called lateral boundaries. For a time dependant problem, initial conditions must also be specified. The above equations along with properly specified initial and boundary conditions constitute a well-posed initial-boundary-value problem.

2.3 MODEL DESCRIPTION

Galerkin's method of weighted residuals, a Newton-Raphson iteration scheme, numerical integration using seven-point Gaussian quadrature, and a frontal solution algorithm using out-of-core storage are used to solve for the nodal values of the velocity components and depth. The time derivatives are handled by implicit finite difference scheme.

To obtain a solution, both water depth and depth averaged X and Y velocity components need to be specified as initial conditions throughout the solution region. When initial conditions are unknown, a **cold start** procedure is used. During this procedure, the same water surface elevation is assigned to every node point in a network, and velocities are set to zero everywhere. When results from a run are available, they can be used as initial conditions for a subsequent run. The use of results from a previous run as initial condition is referred to as **hot start.**

FESWMS-2DH consists of three distinct but related programs:

DINMOD the data input module (preprocessing program), which checks the input data for errors, generates plots of the finite element network and ground surface contours, and puts the network data in an appropriate form for subsequent analysis. The program may be used to automatically generate a new network or refine an existing network. A feature of DINMOD is an element resequencing capability which ensures efficient equation solution, thus reducing the computation time.

Location of each element is fixed by inputting X and Y coordinates for corner nodes, centre node (for 9 noded elements) and midside node (for curved element sides) and by providing node connectivity list for each elements. Flow properties, such as Manning coefficient and eddy viscosity, were separately given in FLOMOD data file.

The solution of the 2-D depth averaged flow equations are performed by **FLOMOD**, the depth averaged flow analysis module. The flow depth and the x and y components of the velocity are evaluated using the complete St. Venant equations. The Galerkin finite element method is used to solve the above system of differential equations. The fluid density is considered to be uniform and the pressure distribution hydrostatic. The effects of bottom friction and turbulent stresses may be evaluated using the Chezy or Manning's equation and the Boussinseq eddy viscosity concept, respectively. Effects of wind stress and the Coriolis force may be included in the simulation.

ANOMOD, the output analysis module (postprocessing program), generates plots and printed reports from the network data and the flow data. The solution for the flow depth and velocity at each node generates a large amount of spatially related data. Since the two-dimensional model allows the water surface to vary along or across the network and allows the flow to follow any horizontal orientation, the water surface and flow field can be very complex. The interpretation of the results of the simulation is greatly facilitated by the plotting capabilities of FESWMS-2DH. A plotted map of the water surface contours is used to describe the three dimensional water surface since discrete water surface elevations or a water surface profile cannot represent these results completely. The velocity or unit discharge at each node may be represented by a plot of the flow field where the direction and magnitude of flow is represented by scaled symbols such as arrows.

3.0 STUDY AREA

Kerala has 336000 hect. of inland water area of which the backwater system consisting of estuaries of the rivers, their lower reaches within the tidal influx, the brackish water lakes and backwaters along with their estuaries, contributes 242600 ha. comprising about 68% of the inland water resources. Thus the backwater system is significant as the largest and the most important inland water resources of the State.

The backwater system is a unique ecosystem which shares the characteristics of both fresh water and marine habitats. The estuaries of Kerala are peculiar in the sense that a number of rivers open into a single estuary through backwaters.

The backwaters of Kerala, an important water resources, sprawling the entire coastal length, can play a crucial role in the socio-economic development of aquaculture, navigation, commercial fisheries, aquatic recreation, tourism, etc.

Vembanad lake system (9° 28' N to 10° 10' N and 76° 13' E to 76° 30' E) is a major estuarine system of the Kerala coast separated from the Arabian sea on the west by low belts of sand pits. The Cochin backwaters form the northward extension of the Vembanad lake, extending to the north and south of Cochin. Several rivers (Pamba, Meenachil, Periyar, and Muvattupuzha) and canals discharge large quantities of fresh water during the monsoon months into this backwaters.

Cochin backwaters which form the northward extension of the Vembanad lake have characteristics of a typical tropical estuary. The Cochin harbour entrance (9° 58' N and 76° 15' E) and another inlet near Azhikode connect the backwater with the Arabian sea. A third opening near Thuravur is seasonal which remains closed except during monsoon. The Muvattupuzha & Periyar rivers discharge into the estuary. The Cochin harbour has a dredged channel for the entry of ships. The approach channel, which is about 8 km. long, branches into two to form Ernakulam channel and Mattancherry channel, on either side of Willington island. The shipping channel, tanker berths, and the small islands present in the estuarine region have significant influence on the circulation in this estuary. Location of the study area is given in Fig.1.

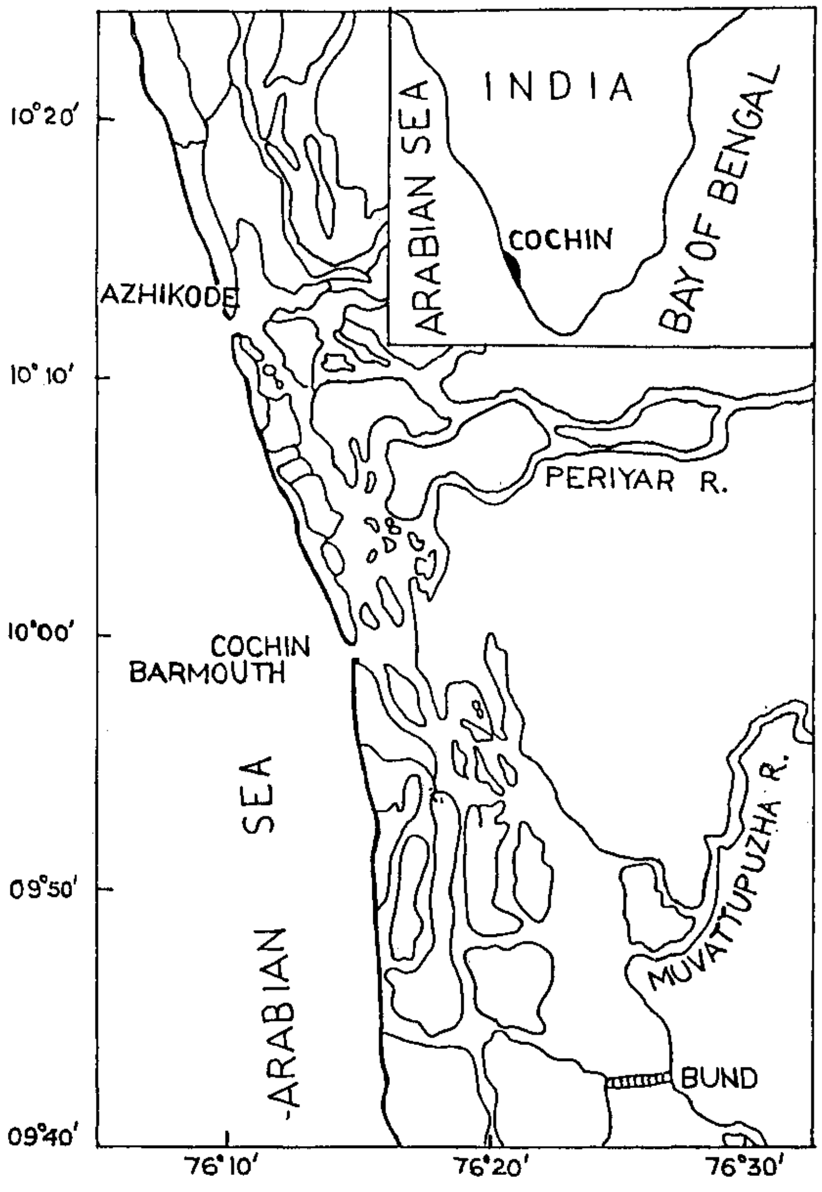


FIG. 1. LOCATION OF STUDY AREA

Out of the six major rivers, discharging fresh water into the Cochin backwaters, the Periyar joins on the northern part. The Muvattupuzha river joins the southern part of the backwaters. Discharge from other rivers influences the hydrology of backwaters only during monsoon when gates of Thannirmukkam bund (which is located on the Southern side of the study area) are kept open.

The variation in salinity are mainly controlled by runoff and tidal currents. Ecological conditions prevailing in the estuary is greatly influenced by the tides. Also, the tidal effects in the estuary affects the passage of oil tankers and other large vessels and this necessitates the prediction of tides all round the year. In this estuary, the tides are of mixed, semi-diurnal nature, with a maximum range of 1m. The average ranges of the tide for the monsoon, post monsoon and pre monsoon have been reported as 47.3, 43.1, and 46.08 cm respectively. As far as estuarine hydrography is concerned, three seasons viz. pre monsoon (January to May), south-west monsoon (June to September) and post monsoon (October to December) can be identified.

During the premonsoon period, the flow pattern depends mainly on the tidal conditions. During the monsoon season, the flow pattern is resultant of the tidal influx and the fresh water efflux, which are opposite in direction.

Present study has been performed for Cochin harbour entrance and its surrounding area, which covers an area of about 10.5km^2., as shown in Fig.2. Data from eleven current velocity measurement stations, located at the entrance of the Cochin harbour, were used for the calibration and validation of the model.

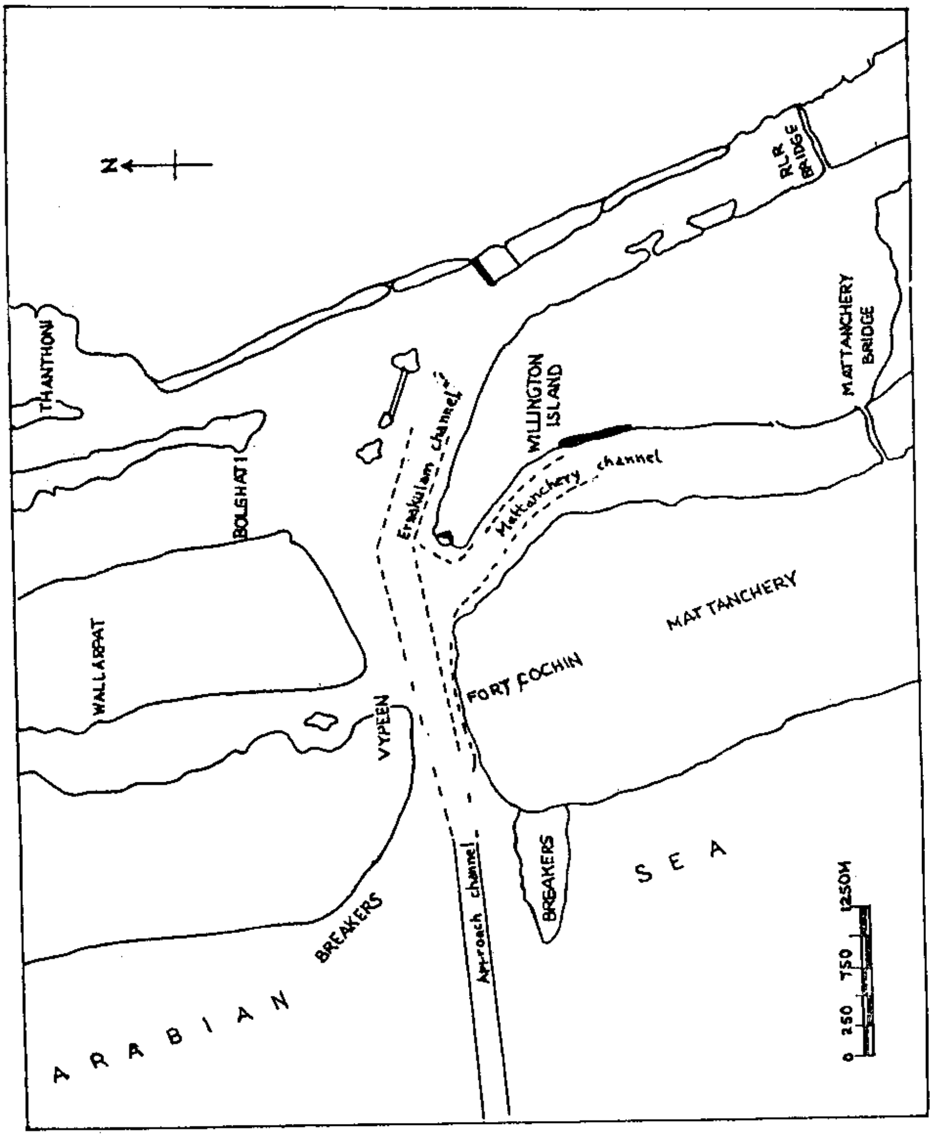


FIG. 2. COCHIN HARBOUR ENTRANCE

4.0 MODEL APPLICATION

For the creation of finite element network, 6 noded triangular and 8 noded Quadrilateral elements were used. Along the lateral boundaries, where the geometric complexity is considerable, curved sided elements were used.

Various steps followed during the calibration and application of FESWMS-2DH is described below.

4.1 DINMOD MODULE

Input for this module were X, Y coordinates and ground surface elevations for all corner nodes and mid side nodes (for curved sided elements). For convenience, the finite element network have been prepared on a transparent graph sheet and the X, Y coordinates have been directly taken from that. Ground surface elevations were calculated from the depth of water at different regions of the estuary and the assumed still water level (20.00 m). Node connectivity list for each element have also been prepared. Four property types were specified, as given below, for elements from different part of the study area, since the model parameters (suc'. as roughness coefficient and eddy viscosity) for the whole area will not be the same.

Property Type	Location of the Element
1	area near harbour entrance
2	deep area along the ship channel
3	shallow regions
4	near boundary

The model parameters for these four types of elements have been specified in FLOMOD data file.

Output from this module is a plot of finite element network and a formatted **GRID** data file which is transferred as an input to FLOMOD module. The finite element network for this study consisted of 398 elements and 1350 nodes, which is shown in Fig.3.

4.2 FLOMOD MODULE

This module calculates depth averaged velocity and depth of water at each node point using the GRID data from previous module and other flow parameters.

Five inflow boundaries and one outflow boundary were located as per the layout of the study area. These boundaries are as shown in Fig.4.

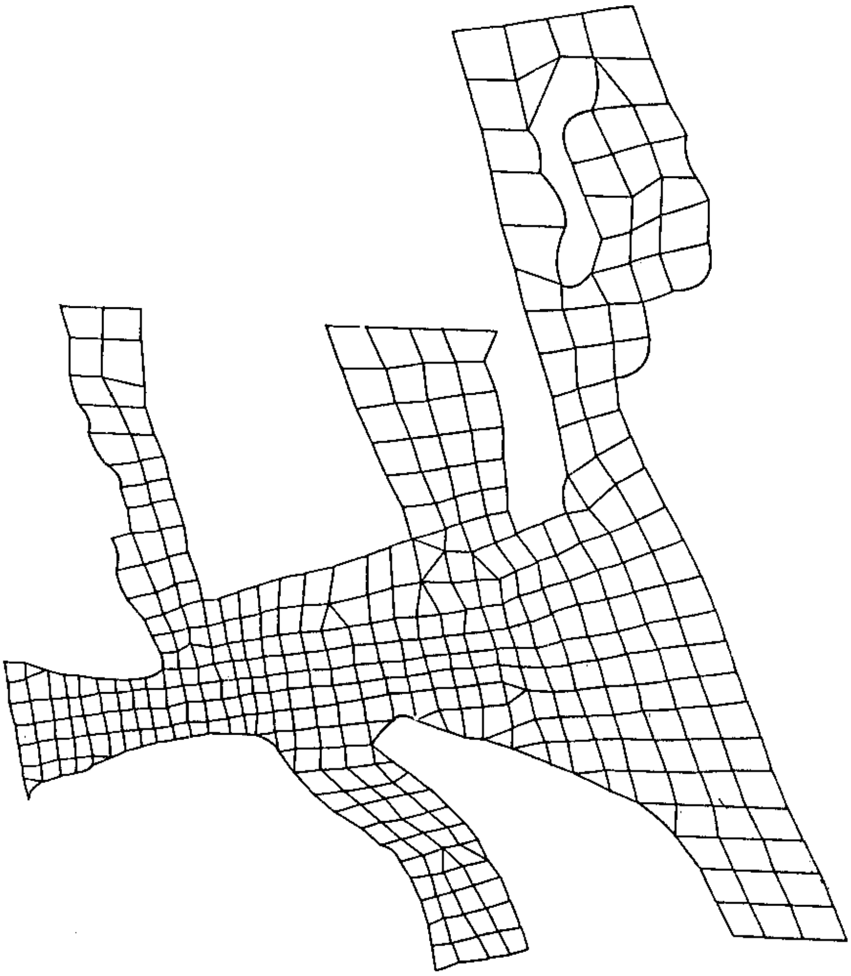


FIG. 3. FINITE ELEMENT NETWORK

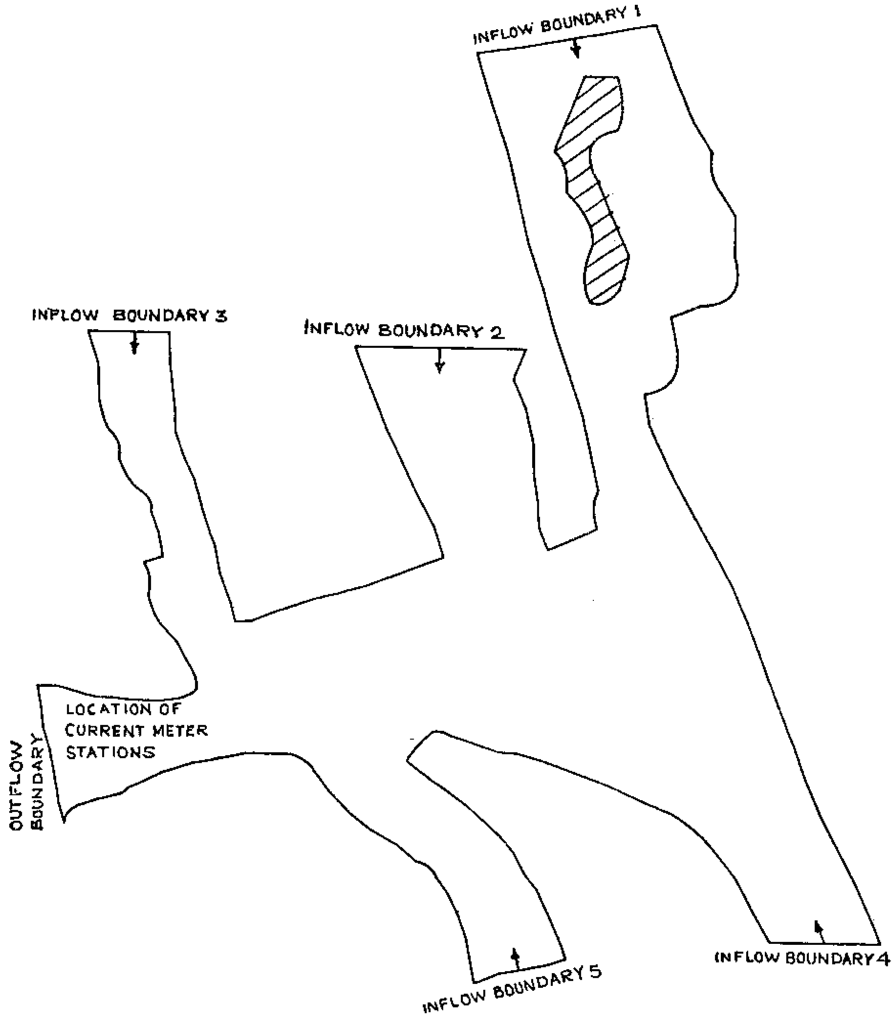


FIG. 4. LOCATIONS OF SPECIFIED BOUNDARY CONDITIONS

Boundary	Node Numbers
Inflow Boundary	
Section 1	292 291 290 293 508 667 682 1266 509
Section 2	791 790 789 788 787 786 802 785 784
Section 3	501 428 419 306 228
Section 4	510 184 771 758 1076 1149 1136
Section 5	1179 1327 1202 1025 1019 544 1262 1185 1071
Out Flow Boundary	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

Initial water surface level for the entire region has been assumed as constant at 20.00 m and velocities were taken as zero.

River inflows are mainly from Muvattupuzha river, which joins the study area on its Southern part. These flows will be increased during monsoon season, especially when the Thannirmukkam bund opens. Discharge from Periyar river (which is located on the Northern part of the study area) gets diverted along several channels and backwaters, before joining the study area, and hence only a small portion is reaching the study area. Average discharge from the above rivers are as given below.

Section	Discharge In Cumecs		
	Pre-Monsoon	Monsoon	With Bund Flow
1	4	40-50	-
2	7	80-100	-
3	5	50-60	-
4	35	150-200	400
5	25	100-150	320

Average wind velocity during non-monsoon season is 4-6 m/s, which blows in N-W direction and 7-10 m/s, which is in S-E direction, during monsoon periods.

4.2.1 Calibration:

Pre-monsoon tide and discharge were used for calibration of the model. A water surface elevation of 20.00 m is given as outflow boundary condition for a steady state run. Kinematic eddy viscosity has been assumed as 500 m^2/sec., for the initial run (cold start). Output from this run is stored as a **FLOW** file, which contains velocity and depth at each node points. Using this as the initial condition, and by reducing eddy viscosity value, next run was performed, which is a hot run. This procedure (of using the FLOW file of a run as an initial condition for the subsequent run) has been continued until a reasonable value of eddy viscosity has been achieved. Value of this parameter for different parts of the study area was found to be varying between 5 to 25 m^2/sec., from literature.

By using the output from the above steady state run, and using the tide data as boundary condition at the outflow boundary, unsteady conditions were created. Model parameters were adjusted along with boundary conditions to get results comparable with the observed data. Calibrated model parameters were;

kinematic eddy viscosity: 5-10 m^2/sec.

Manning roughness coefficient for different property type:

1 0.01
2 0.02
3 0.08
4 0.05

4.2.2 Validation & Application:

Calibrated model has been used to simulate another pre-monsoon scenario. Only slight adjustments were needed for the discharge values (within the limit), to get comparable results.

The model was then applied to simulate one pre-monsoon, monsoon, and monsoon with Thannirmukkam bund flow scenario. Tides used for these runs were shown in Fig. 5 to 7.

4.3 ANOMOD MODULE

GRID and FLOW files from the above modules have been transferred to this module for getting plots for different scenarios, showing the value of dependant variables and time history reports for particular node numbers. Velocity vectors and water surface elevation contours have been plotted for all these cases and time history reports were prepared for the nodes corresponding to the 11 current meter stations.

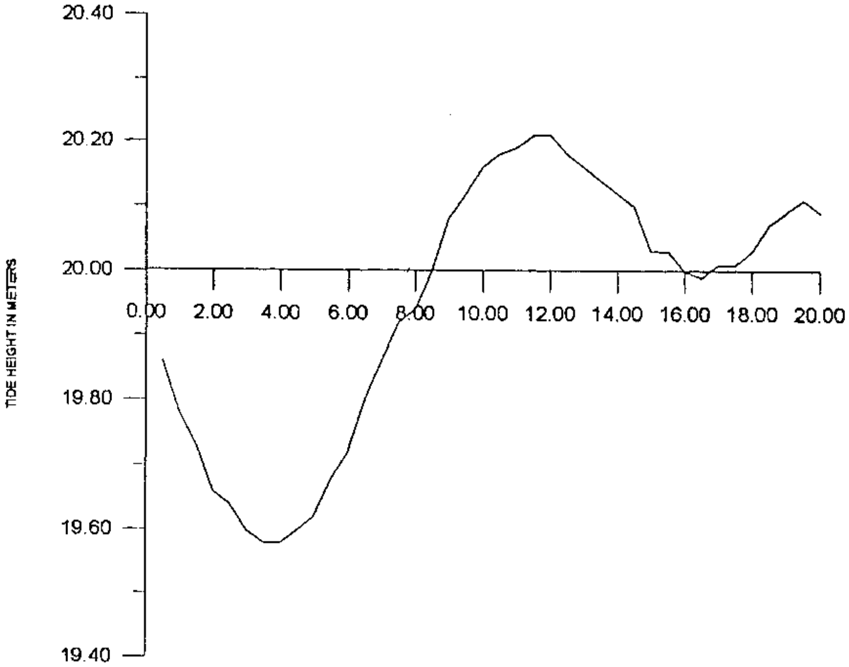


FIG. 5 : TIDE USED TO SIMULATE PRE-MONSOON HYDRODYNAMICS

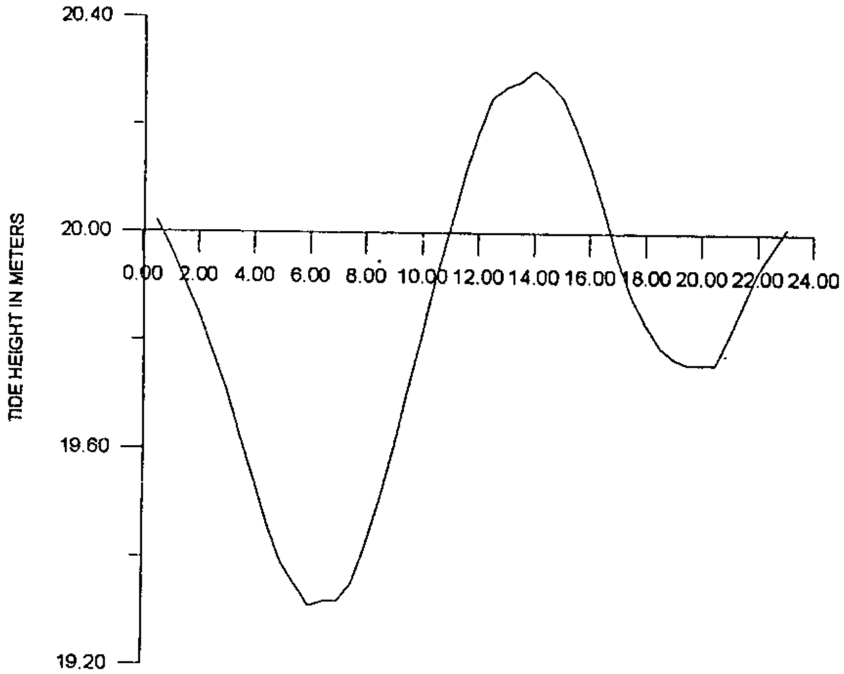


FIG. 6 : TIDE USED TO SIMULATE POST-MONSOON HYDRODYNAMICS

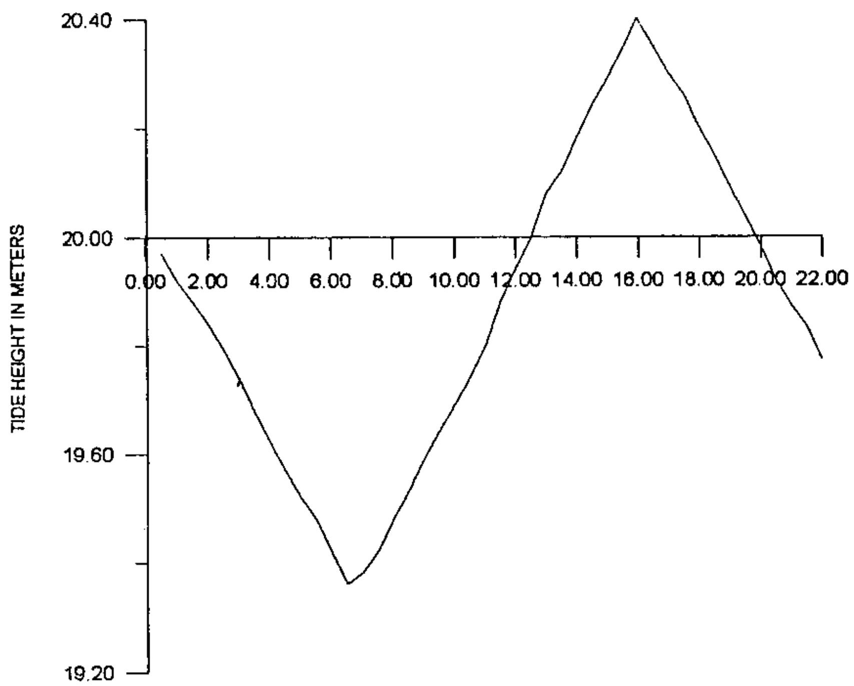


FIG. 7 : TIDE USED TO SIMULATE BUND FLOW

5.0 ANALYSIS OF RESULTS AND CONCLUSIONS

The two dimensional finite element surface water model FESWMS-2DH has been applied for the Cochin harbour and approaches. The model has been calibrated and validated, prior to the application, for the study area, by adjusting the model parameters such as roughness coefficient, kinematic eddy viscosity, and boundary conditions. Fresh water inflow from rivers, tide, and wind forces are used to simulate the estuarine hydrodynamics.

Three FLOMOD runs have been performed as below:
(a)Pre-Monsoon Environment
(b)Post-Monsoon Environment
(c)With Thannirmukkam Bund Flow

Each of these runs produced flow data which consisted of velocities in X and Y directions; and depth and water surface elevations at each node points. For getting graphical outputs, these flow data were used in running ANOMOD program. These outputs were used to visually inspect the flow pattern and the variation of flow at different node points, for unsteady (tide) flow. Time history reports were prepared for the 11 current meter stations.

5.1 ANALYSIS OF RESULTS

Pre-monsoon scenario: Since the inflows from both the rivers are not significant, estuarine dynamics is mainly depending on the tidal waves. During the 20 hr. tide period, flow was found to be mostly from sea to estuary. Average flow profile is given in Fig. 8. Velocities at node points were found to be of very small in magnitude.

Monsoon scenario: During monsoon season, mouth of the estuary is experiencing maximum variations. Discharge from both the rivers will also get enhanced because of large flow from upstream. So the whole estuary will be highly disturbed. Flow tides and ebb tides are intermittent in the estuary. An average flow pattern is shown in Fig. 9. It can be seen that the mouth is affected by large velocity currents.

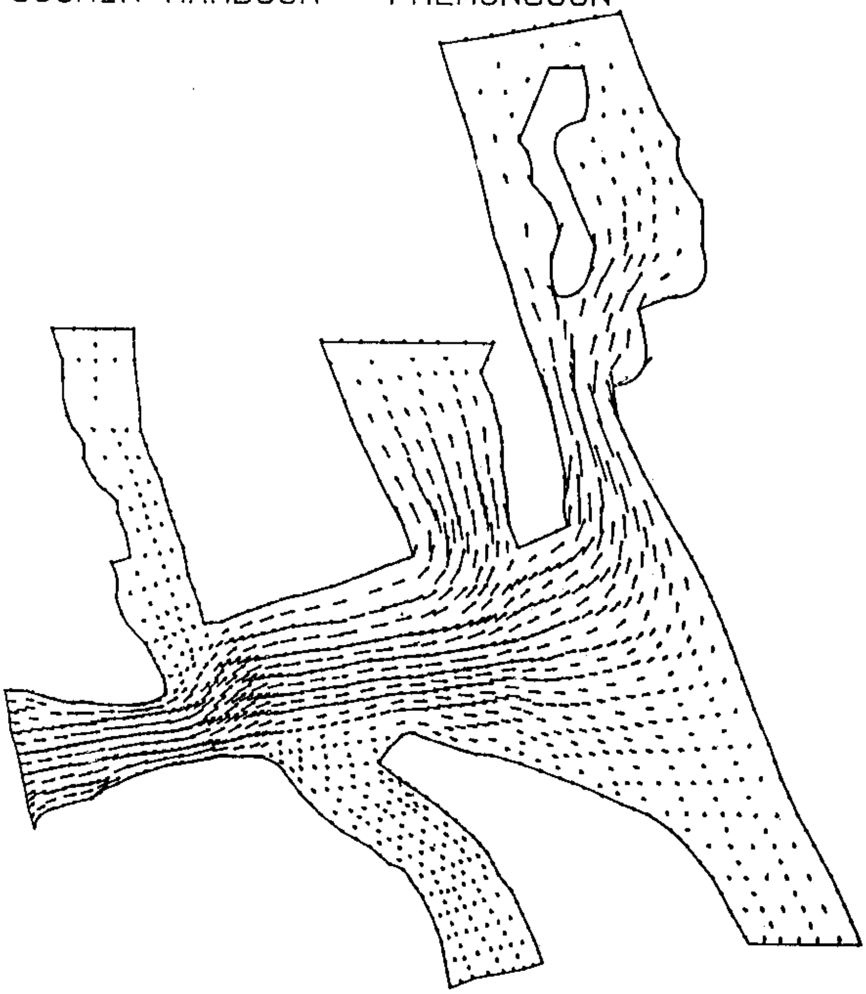


FIG. 8. VELOCITY DISTRIBUTION FOR PREMONSOON FLOW

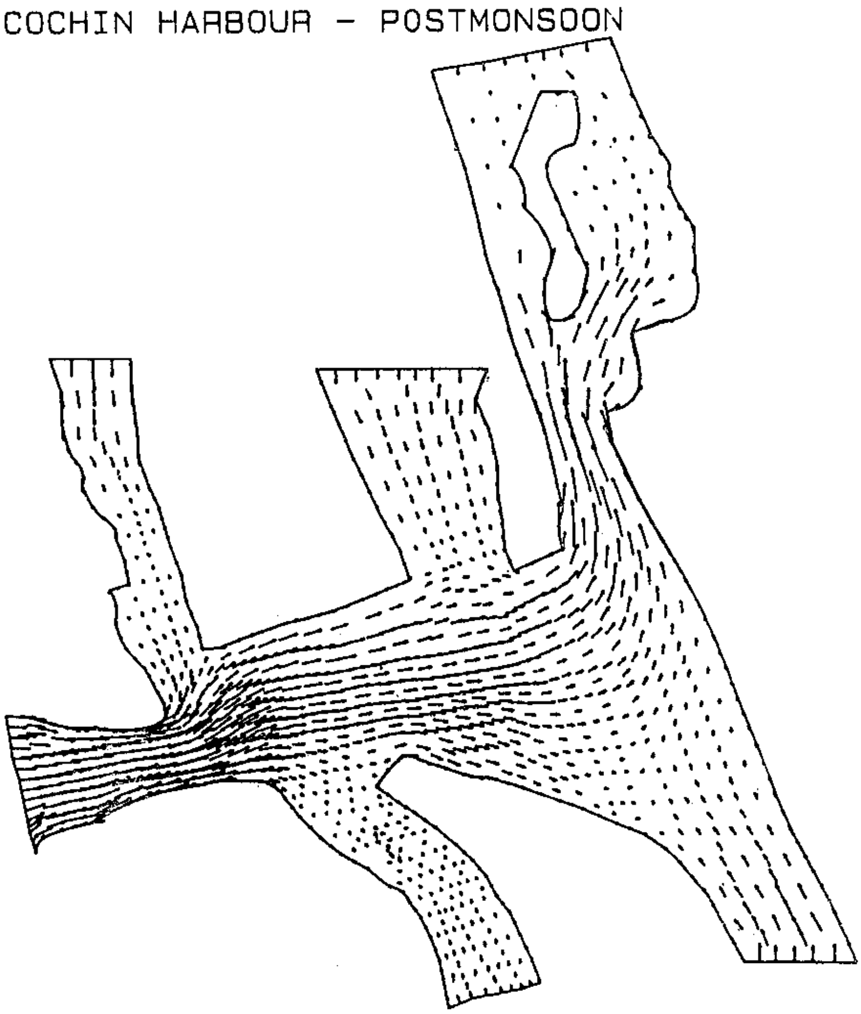


FIG. 9. VELOCITY DISTRIBUTION FOR POSTMONSOON FLOW

With Bund flow: When the monsoon gets stronger, all the rivers discharges huge amount of water to sea through various estuarine or backwater systems. Kuttanad area of Kerala is protected from flooding by Thannirmukkam bund. During heavy monsoon, the authorities allow the water to pass through the bund. This will largely affect the hydrodynamics of the study area. Because of this large flow from Southern side of the study area, flow of water is generally from estuary to sea. This can be seen from Fig. 10.

Variation of time dependent velocities and depth of water at some of the current meter stations are given in **annexure**. Since these current meter stations are situated very near to the mouth of Cochin estuary, pattern of depth variation resembles the tidal curve used for the simulation. Although magnitude and direction of velocities differ from station to station, its pattern also show similarity. Comparison of observed and simulated current velocity values for 11 current meter stations are given in Table 1.

TABLE 1: Comparison of Observed and Simulated current velocities (in m/sec.)

Station (Node no.)	Pre-Monsoon		Post-Monsoon		With Bund Flow	
	Observed	Simulated	Observed	Simulated	Observed	Simulated
1 (23)	0.058	0.043	0.101	0.096	0.132	0.126
2 (57)	0.052	0.049	0.102	0.099	0.135	0.131
3 (60)	0.055	0.051	0.113	0.109	0.145	0.142
4 (62)	0.053	0.048	0.110	0.105	0.14	0.136
5 (126)	0.070	0.066	0.129	0.132	0.187	0.186
6 (124)	0.062	0.065	0.138	0.141	0.179	0.183
7 (122)	0.060	0.062	0.128	0.130	0.135	0.140
8 (176)	0.074	0.071	0.157	0.154	0.195	0.193
9 (178)	0.082	0.079	0.181	0.179	0.231	0.227
10(180)	0.080	0.081	0.184	0.186	0.234	0.238
11(388)	0.053	0.050	0.124	0.122	0.160	0.156

Note:
Pre-Monsoon velocity values are for a tide height of 0.18 m, at 12.50 hrs.
Post-Monsoon velocity values are for a tide height of 0.12 m, at 16.00 hrs.
Bund Flow velocity values are for a tide height of 0.15 m, at 18.50 hrs

COCHIN HARBOUR - BUND

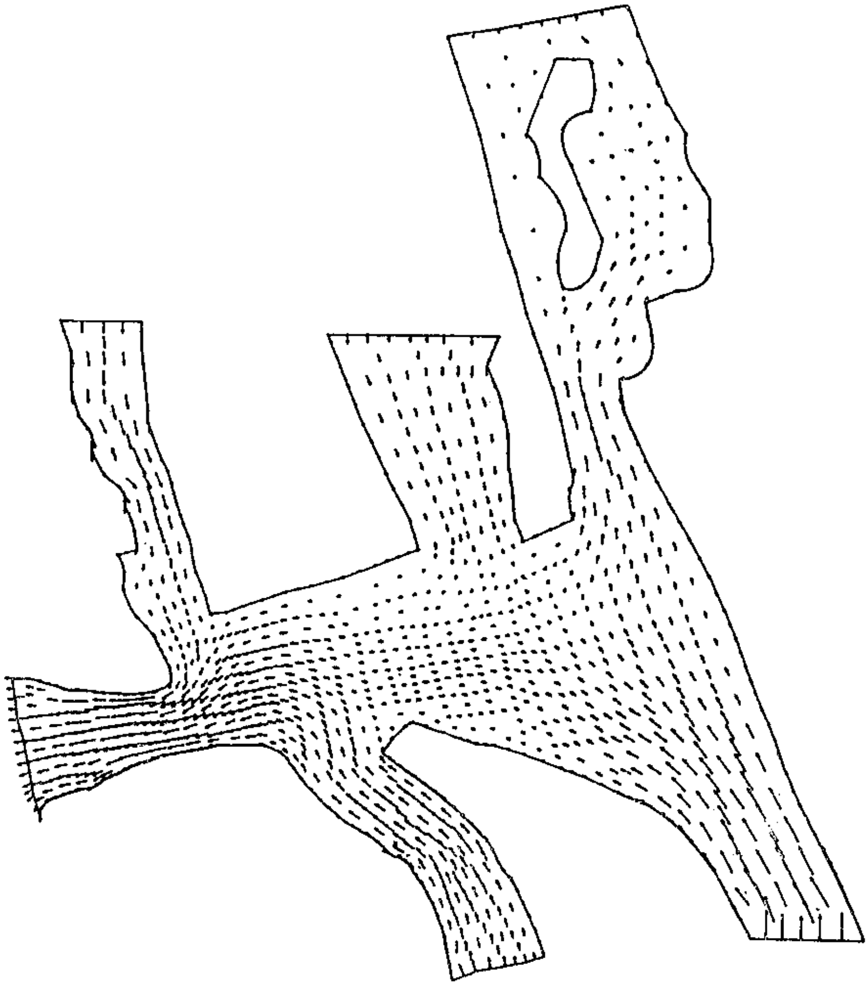


FIG. 10. VELOCITY DISTRIBUTION FOR BUND FLOW

5.2 CONCLUSIONS

From the calibration and application of FESWMS-2DH to an Indian estuary, the following points can be specified as conclusions.

1.Calibrated model has been applied to simulate the hydrodynamics of the estuary for different combinations of tides, winds and fresh water inflows, and it is found that the results are comparable with the observed current pattern within the estuary.

2.Slight variations in kinematic eddy viscosity will not affect the output from FLOMOD module, significantly. But changes in Manning roughness coefficient have a significant effect on the velocity components.

3.A thorough field survey is required before the application of the model, since accurate estimation of model parameters and their variation along the study area is of utmost importance for effective modeling.

4.Current meter stations should be available at various parts of the study area, for an efficient model calibration and validation.

5.Since different estuaries are having different physico-chemical, biological, and meteorological conditions, generalisation of model parameters is not possible. Detailed studies should be conducted for each estuary, for better understanding about the estuary and its hydrodynamics.

ACKNOWLEDGEMENTS

The author takes this opportunity to express his gratitude to Dr.A.N.Balachand, Professor, and Sh.K.Ajith Joseph, Research Scholar; Physical Oceanography & Meteorology Division, School of Marine Sciences, Cochin University of Science & Technology, KOchi, for supplying necessary data, and extending all necessary helps, for this study, for data collection and during his stay at CUSAT.

He is thankful to Sh.P.K.Agarwal, SRA; Sh.Jiweshwar Sinha, Scientist; and Sh.T.Thomas, SRA, of Regional Centre, Sagar, for their support, during his deputation to RC Sagar, where most of the preliminary works of this study has been performed.

Special thanks are also to Sh.S.Chandra Kumar, for data preparation; Sh.N.K.Lakhera, for preparing tracings; and to all his other colleagues for their cooperation during lengthy computer sessions.

CHANDRAMOHAN T.

REFERENCES

1.Abbot,M.A., and Cunge,J.A., 'Two Dimensional Modelling of Tidal Deltas and Estuaries', in Unsteady Flow in Open Channels, Ed. by Mahamood,K., and Yevjevich,V., Water Resources Publications, Colorado, USA, 1975.

2.Chandramohan,T., 'U.N.D.P. Project Report on Hydrological Data Processing and Analysis for Studies Related With water Surface Profiles, Geographical Information System, and Two-Dimensional Finite Element Modeling in Estuarine Hydrodynamics', Roorkee, 1993.

3.Chatterjee,A.K., 'Estuarine Improvement-Numerical Simulation', in Proceedings of the National Seminar on Estuarine Management, Trivandrum, 1987.

4.Cochin University of Science and Technology, 'Abstract Report on the Research Work Carried Out Under U.G.C. Assisted Programme', Cochin, 1987.

5.Froelich,D.C., 'FESWMS-2DH Users Manual', Publication No. FHWA-RD-88-177, Federal Highway Administration, April 1989.

6.James,E.J., 'Studies on Estuarine Hydrodynamics of the South-West Coast of India', in Proceedings of the National Seminar on Estuarine Management, Trivandrum, 1987.

7.Joseph,J., and Kurup,P.G., 'Tidal Response and Circulation of Cochin Estuary', in Proceedings of the National Seminar on Estuarine Management, Trivandrum, 1987.

8.King,I.P., and Norton,W.R., 'Recent Applicatons of RMA's Finite Element Models for Two-Dimensional Hydrodynamics and water Quality', in Proceedings of International Conference on Finite Elements in Water Resources, London, 1978.

9.Lee,J.K., Froehlich,D.C., Gibert,J.J., and Wiche,G.J., 'Two-Dimensional Finite Element Model Study of Backwater and Flow Distribution at the I-10 Crossing of the Pearl River, Lousiana', U.S.G.S., Water Resources Investigation Reprt, 82-4119, 1983.

10.Lee,J.K., and Froehlich,D.C., 'Review of Literature on the Finite Element Solution of Equations of Two-Dimensional Surface Water Flow in the Horizontal Plane', U.S.G.S. Circular 1009, 1986.

11.Masch,F.D., and Shankar,N.J., 'Circulation in Shallow Estuaries', in Proceedings IAHR International Symposium on River Mechanics, Thailand, 1973.

12.Nair,K.V.K., 'Managements of Estuaries-Problems and Prospects', in Proceedings of the National Seminar on Estuarine Management, Trivandrum, 1987.

13.Navon,I.M., 'A Review of Finite Element Methods for Solving the Shallow water Equations', Proceedings International Conference on Computer Modeling in Ocean Engineering, Venice, 1988.

14.Norton,W.R., and King,I.P., 'A Finite Element Model for Lower Granite Reservoir', water Resource Engineers, Inc., san Deigo,1973.

15.Pinder,G.F., and Gray,W.G., 'Finite Element Simulation in Surface and Subsurface Hydrology', Academic Press, New York, 1977.

16.Reddy,J.N., 'An Introduction to the F. E. Method', McGraw-Hill, New York, 1984.

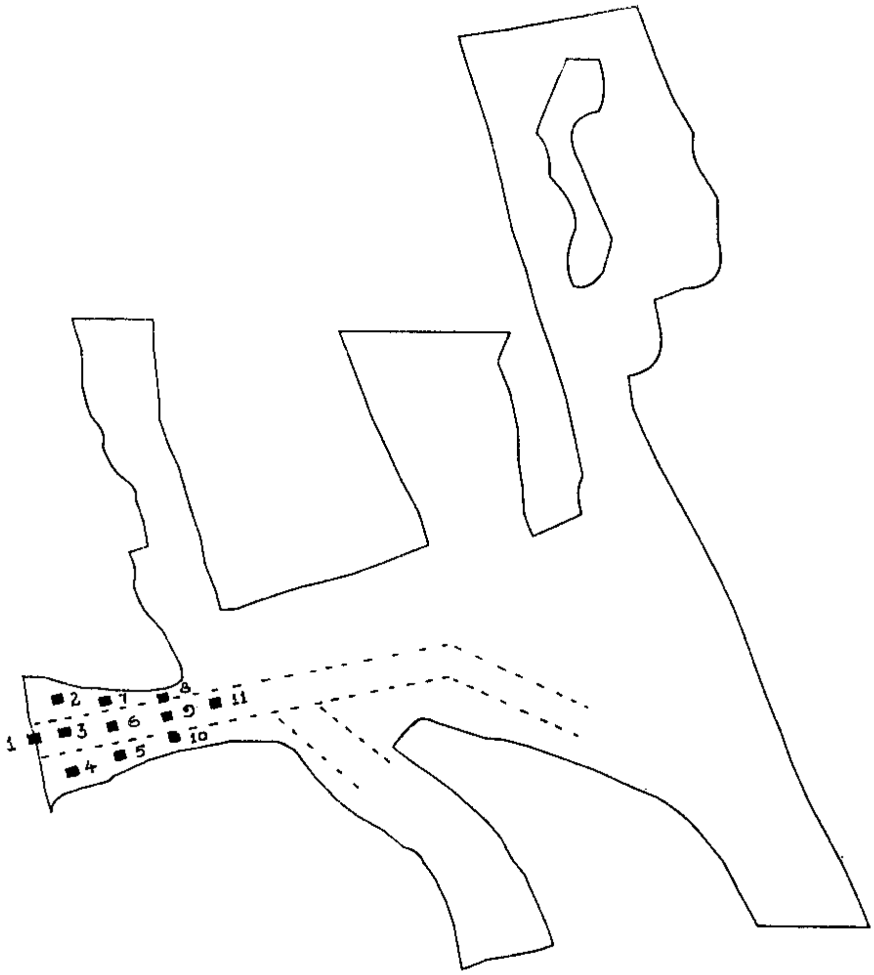
17.Shuy,E.B., 'Tidal Flow Profiles Along a River estuary Discharging into a consrticted Bay', in Proceedings of Sixth International Conference on Finite Elements in water Resources, 1986.

18.Vierira,J.R., 'Finite Element Models for the Study of Estuaries, Lagoons and Coastal Seas', Proc., 5th Int. Con. on Finite Elements in Water Resources, Vermont, USA, 1984.

19.Walters, R.A., and Cheng,R.T., 'A Two-Dimensional Hydrodynamic Model for a Tidal Estuary', in Proceedings of Second International Conference on Finite Elements in Water Resources, London, 1978.

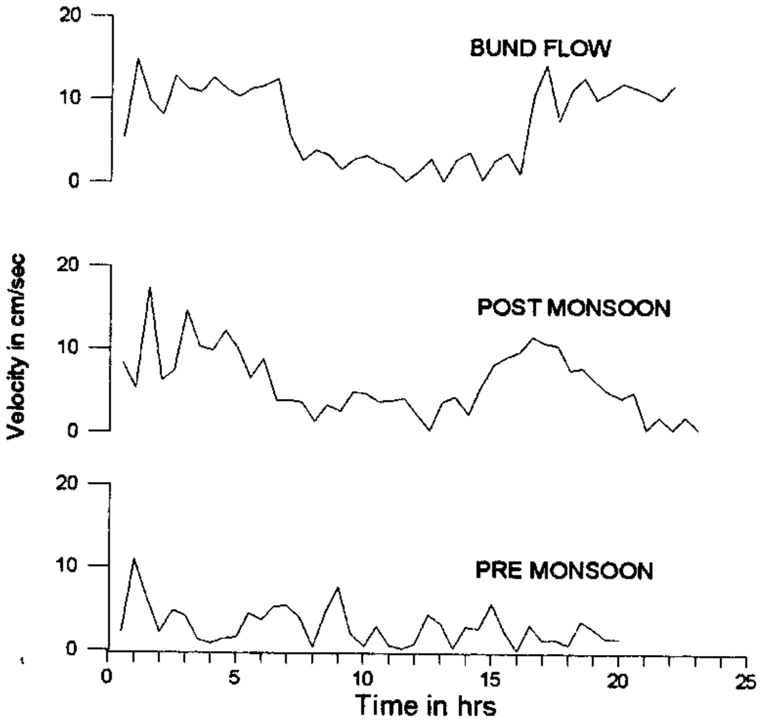
20.Wang,J.D., and Connor,J.J., 'Mathematical Modeling of Near Coastal Circulation', Report No.200, Ralph M. Parsons Laboratory for water Resources and Hydrodynamics, M.I.T., Cambridge, 1975.

ANNEXURE



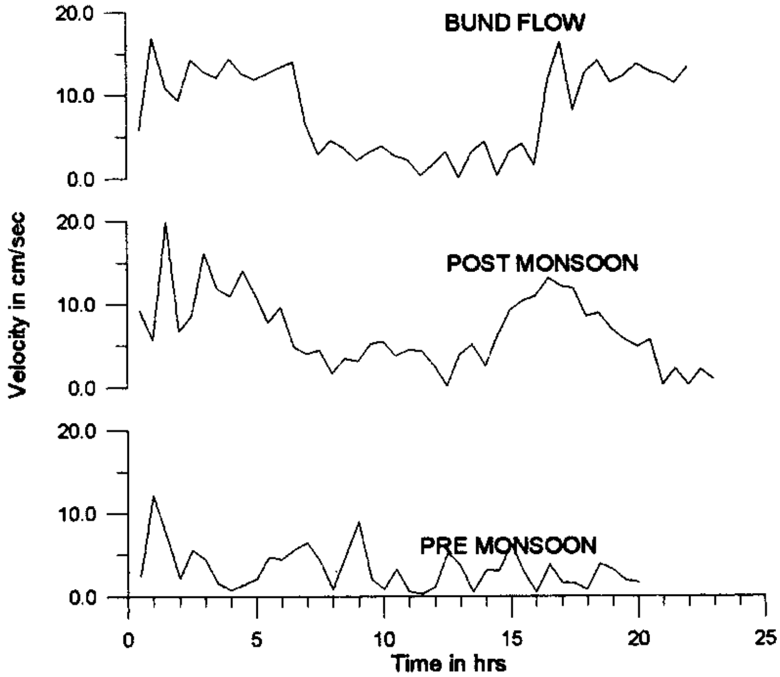
LOCATION OF CURRENTMETER STATIONS

STATION 1



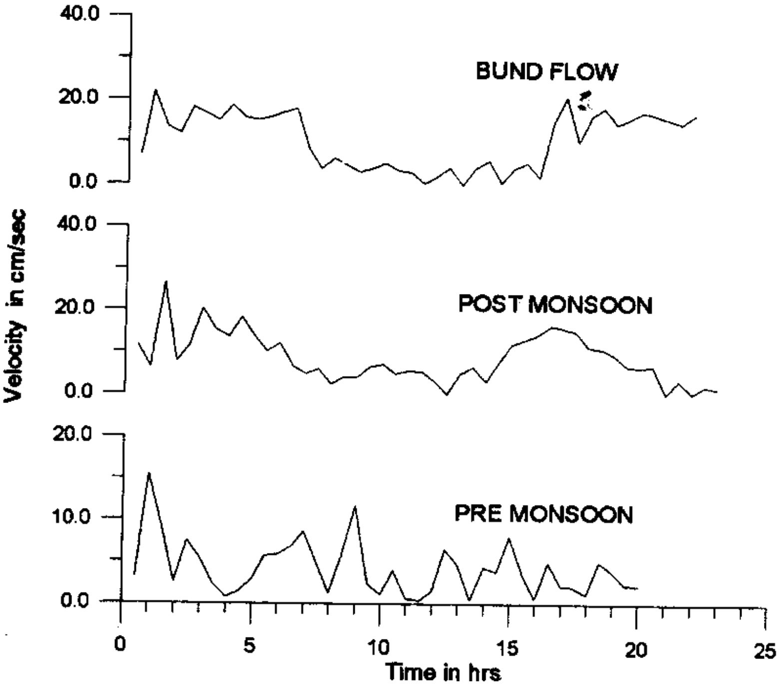
20
10
0
BUND FLOW
20
10
0
POST MONSOON
20
10
0
PRE MONSOON
Velocity in cm/sec
0
5
10
15
20
25
Time in hrs

STATION 3



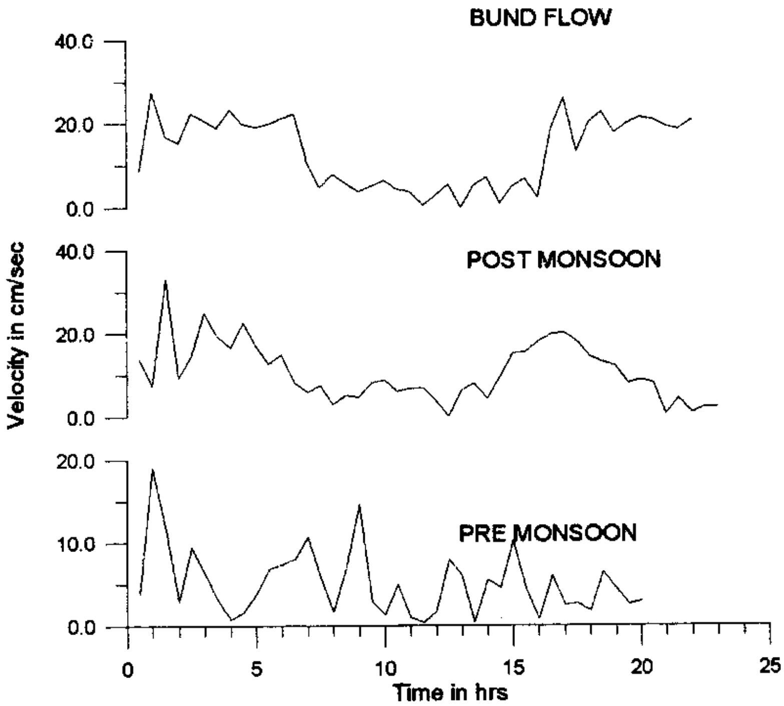
BUND FLOW
POST MONSOON
PRE MONSOON
Velocity in cm/sec
Time in hrs
20.0
10.0
0.0
0
5
10
15
20
25

STATION 6



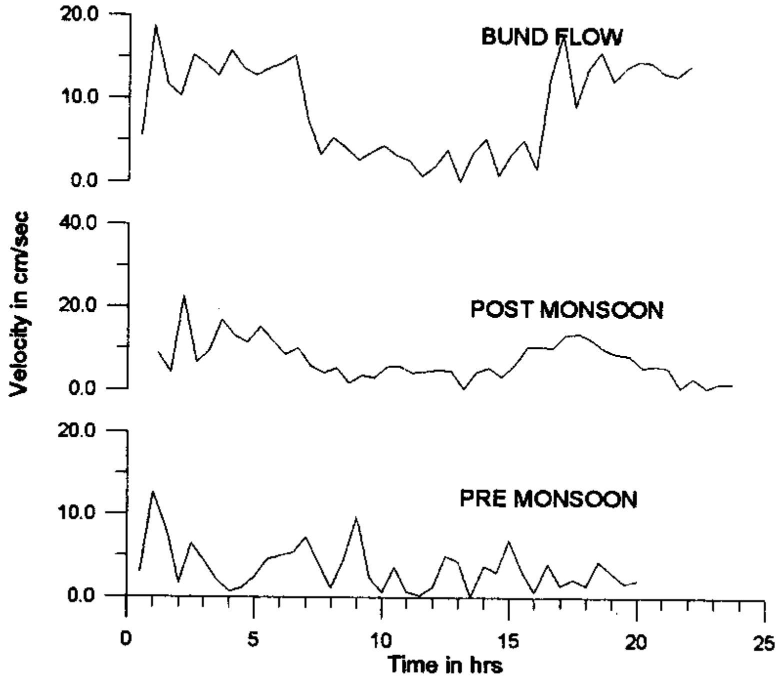
40.0
20.0
0.0
BUND FLOW
40.0
20.0
0.0
POST MONSOON
20.0
10.0
0.0
PRE MONSOON
Velocity in cm/sec
0
5
10
15
20
25
Time in hrs

STATION 9



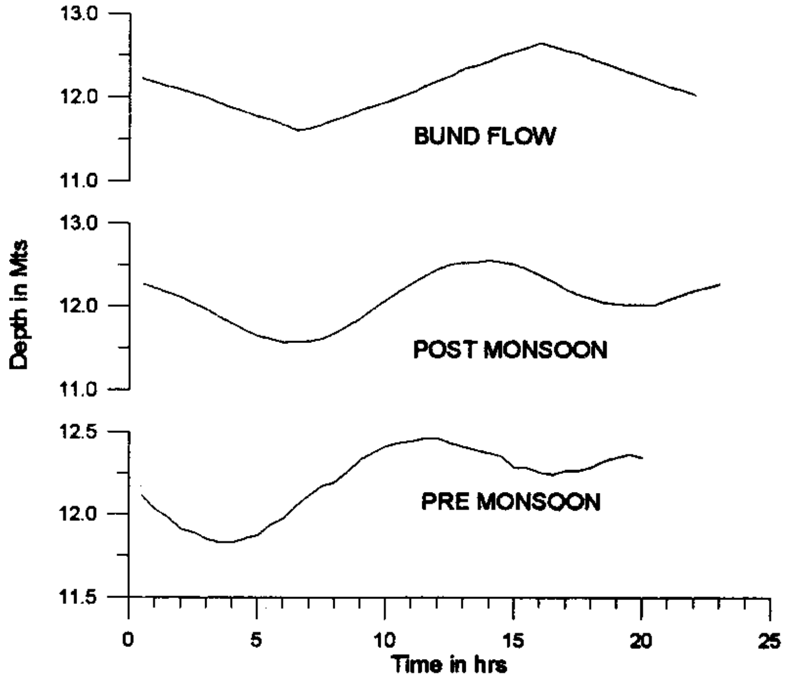
BUND FLOW
POST MONSOON
PRE MONSOON
40.0
20.0
0.0
40.0
20.0
0.0
20.0
10.0
0.0
Velocity in cm/sec
0
5
10
15
20
25
Time in hrs

STATION 11



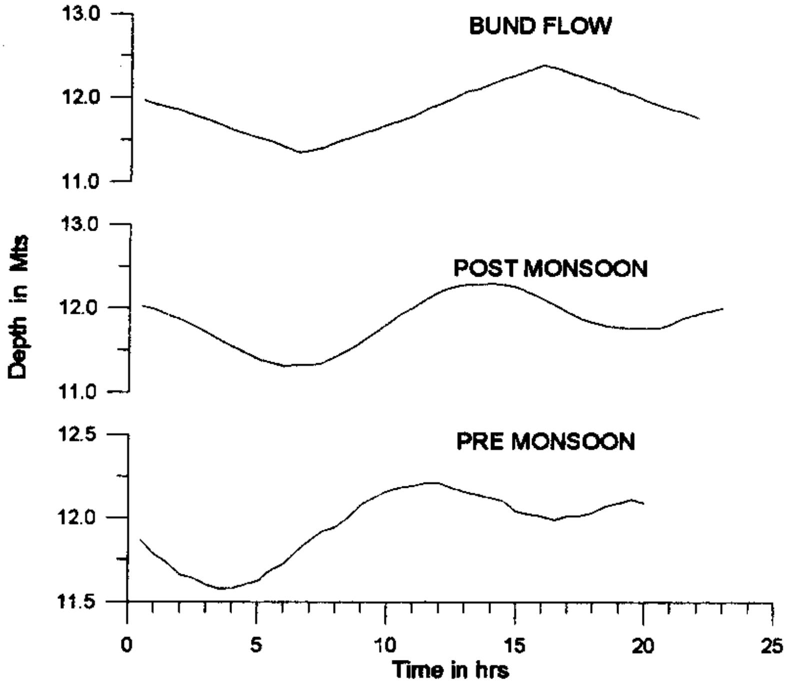
20.0
10.0
0.0
BUND FLOW
40.0
20.0
0.0
POST MONSOON
20.0
10.0
0.0
PRE MONSOON
Velocity in cm/sec
0
5
10
15
20
25
Time in hrs

STATION 1



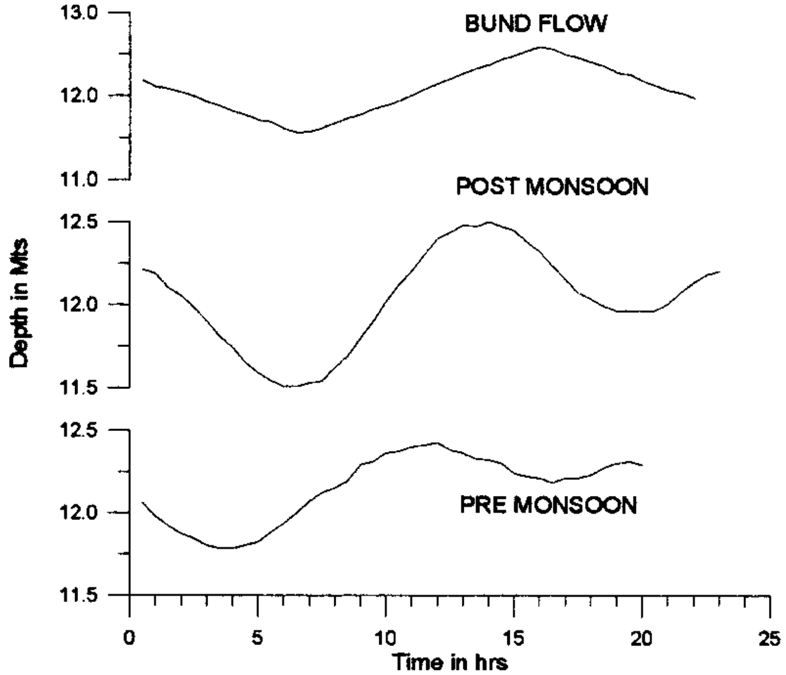
13.0
12.0
11.0
BUND FLOW
13.0
12.0
11.0
POST MONSOON
12.5
12.0
11.5
PRE MONSOON
Depth in Mts
0
5
10
15
20
25
Time in hrs

STATION 3

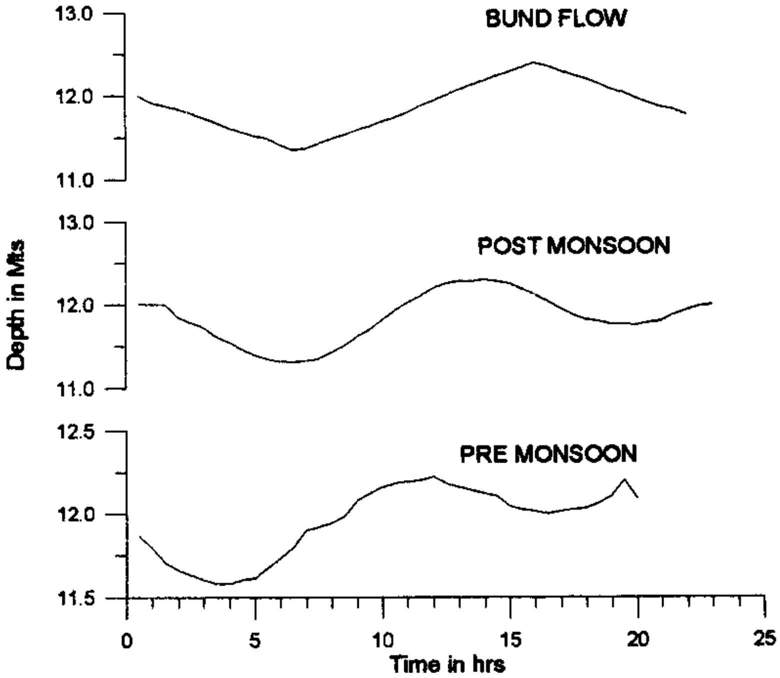


BUND FLOW
POST MONSOON
PRE MONSOON
13.0
12.0
11.0
13.0
12.0
11.0
12.5
12.0
11.5
Depth in Mts
0
5
10
15
20
25
Time in hrs

STATION 6

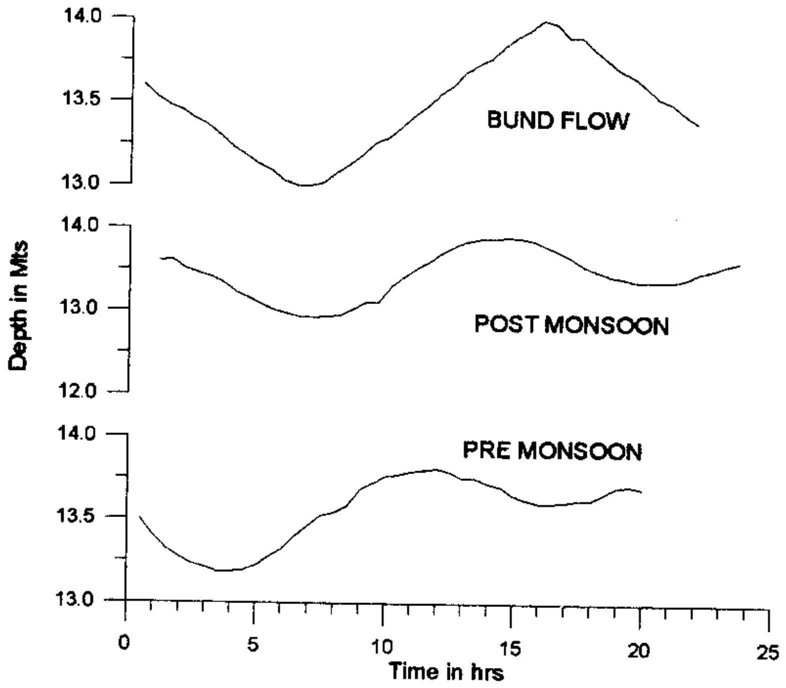

BUND FLOW
POST MONSOON
PRE MONSOON
Depth in Mts
Time in hrs
13.0
12.0
11.0
12.5
12.0
11.5
12.5
12.0
11.5
0
5
10
15
20
25

STATION 9



BUND FLOW
POST MONSOON
PRE MONSOON
Depth in Mts
Time in hrs
13.0
12.0
11.0
13.0
12.0
11.0
12.5
12.0
11.5
0
5
10
15
20
25

STATION 11



14.0
13.5
13.0
BUND FLOW
14.0
13.0
12.0
POST MONSOON
14.0
13.5
13.0
PRE MONSOON
Depth in Mts
0
5
10
15
20
25
Time in hrs

DIRECTOR	: S.M. SETH
TECHNICAL COORDINATOR	: G.C. MISHRA
HEAD	: B. SONI
STUDY GROUP	: CHANDRAMOHAN T.