ENVIRONMENTAL MANAGEMENT OF LAGOONS FOR SUSTAINING MULTIPLE USES - CASE STUDY NEGOMBO LAGOON

Award Winning Technical Paper presented for Water Resource Development / Water Management Competition sponsored by IWMI and conducted by IESL

by

S.S.L. Hettiarachchi, S.P. Samarawickrama

1. Introduction and Objective of the study

Tidal inlets occupy a unique position on the coast because they form the link between open coastal waters and protected inland waterways. Fisheries, commercial (land based) and residential development at inlets and in their immediate neighbourhood has created the need for technical information to assist in the planning, and for impact assessment to achieve a correct balance between commercial, recreational and environmental interests.

Planning for and reporting on the impact of these developments require a clear understanding of natural changes of inlet stability, together with methods of predicting the manner in which tidal inlets will respond to natural and man-made changes which affect the flow and sediment transportation in the system. This understanding and predictions could only be achieved by conducting detailed hydraulic investigations and modelling of the aquatic system.

The objective of this paper is to describe the investigations which have been conducted to assess the hydraulic regime of the Negombo lagoon inlet on the western coast of Sri Lanka. Results from this study will assist in planning engineering interventions for sustaining multiple uses of this important coastal aquatic system.

2. The Negombo lagoon and its Environment

2.1 The Negombo Lagoon

The Negombo lagoon is a shallow coastal body of water located on the west coast of Sri Lanka (7^0 10' N and 79^0 50' E). It forms an integral part of the Muthurajawela marsh - Negombo lagoon coastal wetland, 6230 ha in extent (Figure 1). The lagoon is approximately 12.5 km in length and its width varies from 0.6 to 3.6 km (Figure 2). Its mean depth is estimated to be approximately 0.65 m and the surface area to be 35 km^2, thus placing its volume to be of the order of 22.5 million m^3. One of the unique features of the lagoon is that its transition to the sea consists of several narrow channels. The total cross-sectional area of the inlet channels is estimated to be 250 m^2 with a length of 2.5 km. This area of transition also serves as a principal anchorage for a large fleet of fishing vessels of different types.

The exchange of water in the lagoon is influenced by the tides from the ocean side and fresh water supply from the inland side. The tide is semi-diurnal and the tidal range in the lagoon varies in the order of 0.07m at neaps to 0.2m at springs, these values being about one third of tide at sea. Thus the volume of water stored and released varies between 2.5 million m^3 and 7 million m^3 per tide. Fresh water enters from the southern end of the lagoon through Dandugam Oya, Ja Ela and several streams from the Muthurajawela marsh. The supply of fresh water varies from virtually zero during the dry seasons to more than 100 cumecs during the rainy seasons.

The lagoon and the entire wetland are separated from the sea by a narrow stretch of land consisting of a very fragile coastal dune system situated on beach rock formed during sea level changes over geological periods of time. The coastal conservation of this dune system plays a vital role in the long term stability of the lagoon.

2.2 Review of development activities and the environment

The Negombo lagoon and its coastal environment has had a long association with tourism and the fishery industry. One of Sri Lanka's leading beach resorts is located north of the Negombo lagoon inlet. The lagoon inlet serves as a principal coastal fishery anchorage for a fleet of fishing vessels and the lagoon estuarine fishery supports at least 3000 families from 26 villages dispersed at the perimeter of the lagoon.

Eng. (Prof.) S.S.L. Hettiarachchi, BSc (Eng.), PhD (Lond), DIC Presently working as Associate Professor of Department of Civil Engineering, University of Moratuwa.

Eng. (Dr.) S.P. Samarawickrama, BSc (Eng.) PhD (Lond), DIC Presently Working as a Senior Lecturer, Department of Civil Engineering, University of Moratuwa.

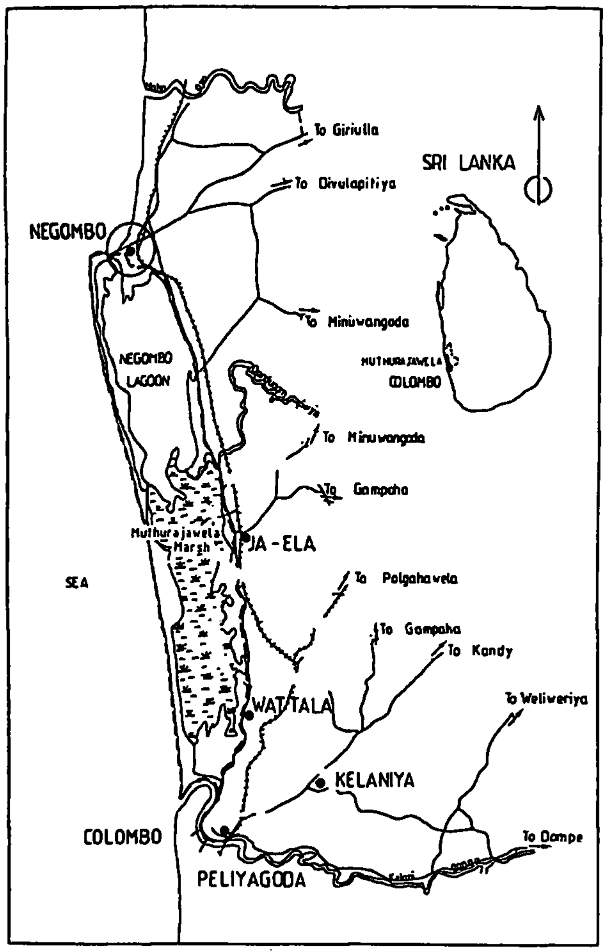


Fig. 1 - Muthurajawela Marsh - Negombo Lagoon

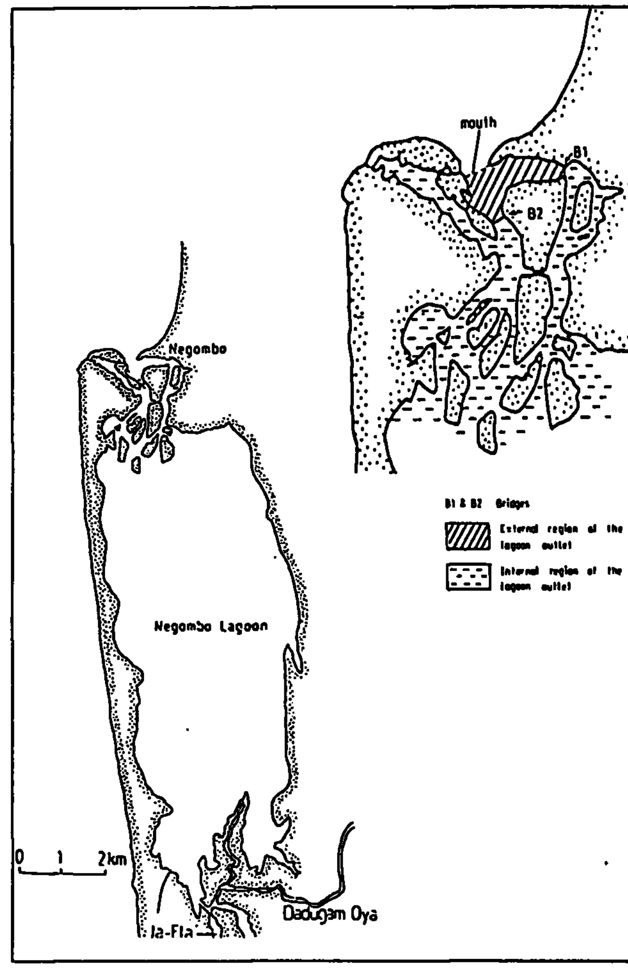


Fig. 2 - Negombo Lagoon

With the development of the tourist industry in the late sixties the beaches of Negombo, extending north of the lagoon inlet upto Maha Oya outlet and beyond, provided ideal frontage for a large number of middle grade hotels. Coastal erosion along this stretch of coastline increased rapidly in the early eighties . The Coast Conservation Department with Danish aid constructed four offshore breakwaters, the first of its kind to be used in Sri Lanka, between the Negombo inlet and the Maha Oya outlet. In order to develop the beaches a certain amount of artificial nourishment was also carried out. A stable beach has now developed in the lee of the offshore breakwaters.

The Negombo anchorage located at the inlet provides operating facilities for about 1300 fishing boats of 17 feet and above, including about 200 offshore boats. However, excessive siltation has taken place in the lagoon resulting in the loss of about 25% of the water area during the last three decades. This has decreased the tidal flow in and out of the lagoon, thus reducing the current velocities during flood and ebb tides which are required to keep the inlet open with sufficient depth for navigation. Since the early 1980s, haphazard expansion of piers and landing points (Figure 3) have contributed towards alterations in the flow patterns leading to sedimentation in the channel segment. Previously navigable areas are obstructed by newly formed sand shoals which also reduce the area available for fishing. Functional seagrass beds have become smothered by sediment deposition. Disposal of waste oil from inboard engine boats have resulted in pollution of water and sediment thereby affecting certain species of fish.

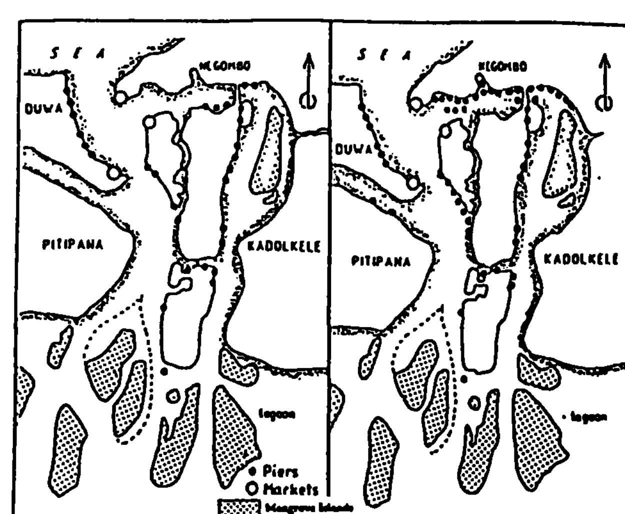


Fig. 3 - Expansion of Piers and Anchorages for Fishing Vessels (3)

Several boatyards are located at the inlet. Due to the effects of siltation, boatyards have progressively encroached into the lagoon inorder to launch the finished crafts with ease. There are many infrastructure facilities which have been located on areas reclaimed by dumping waste.

Due to acute shortage of land for human settlement within the Negombo municipality, landless persons have been reclaiming and building unauthorised dwellings on the inter-tidal sand shoals of the many islands within the lagoon inlet (Figure 4). Such activities affect the hydraulic regime of the lagoon and can restrict circulation as well as contribute to sedimentation problems.

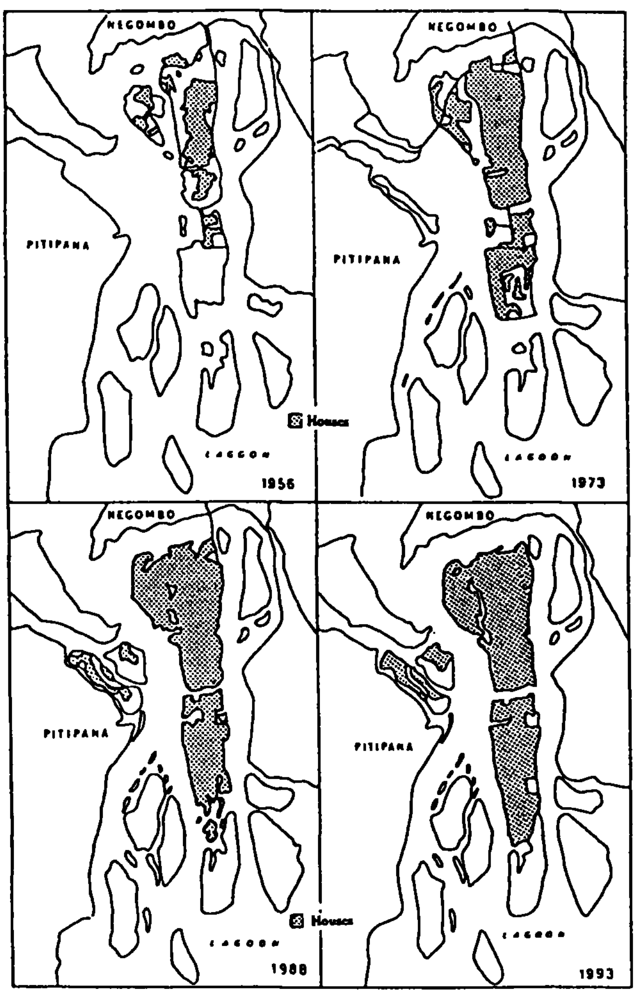


Fig. 4 - Housing Development in the Channel Segment from 1956 - 1993 (3)

Large quantities of solid and liquid waste are dumped at various locations in the lagoon resulting in pollution problems. This results in the loss of vital functional parts of the eco-system including the flow channels and nursery areas. Large scale solid waste disposal is often followed by encroachment with the waste acting as a base for the retention of the top soil.

From the above discussion it is evident that unplanned development along the waterfront, reduction of tidal flow, siltation and pollution are major problems affecting the Negombo lagoon. These have contributed to the overall degradation of the aquatic environment at the tidal inlet and within the lagoon. If this situation continues it could in the long term adversely affect the lagoon environment, in particular, its biodiversity conservation.

To the south of the lagoon lies the Muthurajawela marsh located in a district undergoing a major transformation in terms of land use, population growth, urbanization and densification. The population growth rate in these areas is high, of the order of 2.5% per year, and the projected land requirement for housing is expected to exceed 4000 ha within the first half of this decade. Evidently, without planned management, the existing resource use problems would have aggravated and threatened the existence of this unique eco-system. Therefore the Government of Sri Lanka, through the Board of Investment initiated the preparation of a Master Plan for the Muthurajawela marsh - Negombo lagoon (1) based on a very detailed Ecological Survey (2). These investigations represent the first experience in Integrated Coastal Resources Management in Sri Lanka. Subsequently a Conservation Management Plan was prepared for the Muthurajawela marsh - Negombo lagoon (3) under the Wetland Conservation Project implemented by the Central Environmental Authority.

The foundation of the Master Plan was strategic land allocation by zoning, which addressed the issues of development, ecology and equity. The planning process addressed important problems (Table 2). The Master Plan recommended to establish within the continuous wetland three zones from north to south, namely, a conservation zone, a buffer zone and a mixed urban zone, which occupied 91%, 6.4% and 2.5% area respectively of the continuous wetland. Conservation in the above context was defined as protection and preservation where necessary and sustainable use of physical, biological and cultural resources, including public education and research. Although the governing concept for the management plan for conversation was the interrelationship between the marsh and the lagoon, for all practical purposes zoning of the conservation zone was required. This was particularly so in view of the fact that the area covered by the marsh and the lagoon were under the management of separate agencies. Figure 5 illustrates the proposed zoning for the conservation zone, a strategy which provides adequately for incorporating sustainable development, prevention of externalities and equity.

The Government of Sri Lanka identified the Negombo coastal fishery anchorage as an important site for further development. Having recognised that the principal anchorage in Negombo is located at the inlet of a lagoon which is environmentally very sensi-

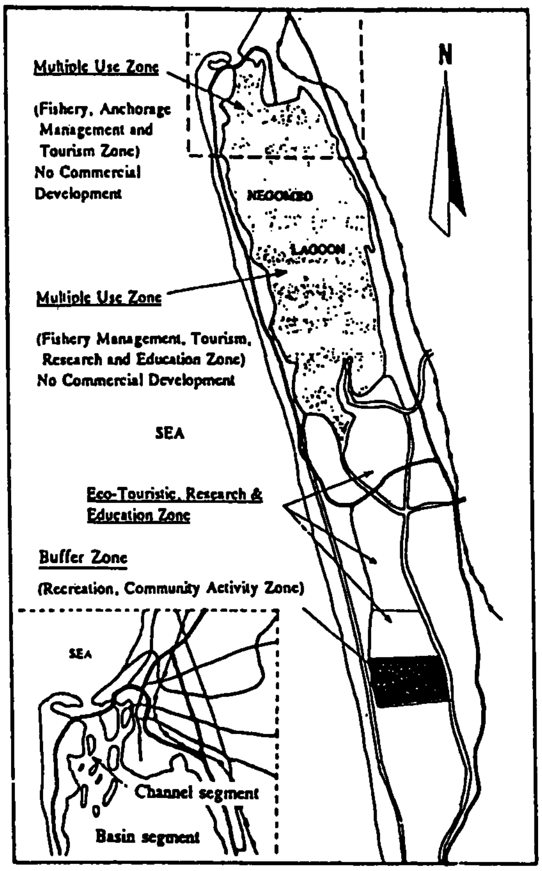


Fig. 5 - Proposed Zoning for the Conservation Zone (3)

tive, it has been accepted that the proposed modifications could have an impact on the stability of the lagoon. In this context there is a need for detailed hydraulic investigations at identifying methods of improving the anchorage at the inlet with minimum structural changes and least impact to the lagoon and the wetland as a whole. Table 1 identifies the different types of information required and the associated risk with typical activities linked to development work within a tidal inlet (4).

In planning development activities it must also be recognised that the Negombo lagoon is a high value resource base and that a large population living in villages surrounding the lagoon depend upon its fishery productivity for livelihood. In this respect there is a need to organise the lagoon fishing community and instil the need for sustainable management of the lagoon resources for the protection of their livelihood as well as for bio-diversity conservation. The marsh-lagoon wetland complex must interact adequately both with the terrestrial watershed and the sea for continuity of its eco-system structure and functions. This identifies important aspects of the hydraulic regime required for the desired ecological balance.

Table 1 - Information Required and Risks Associated With the Development of Tidal Inlets (4)

Activity	Information required	Associated Risk
Dredging for channel maintenance	Locations, quantities, disposal methods, tidal flow, wave action and sediment transportation	Infilling of the tidal inlet and instability of channels
Reclamations associated with harbour and other works	Tidal flow, wave action and sediment transportation	Obstruction to navigation and restriction of tidal flow into the lagoon
Construction of entrance training works	Tidal flow, wave action and sediment transportation	Obstruction to navigation
Coastal erosion and flood defence works	Wave climate, littoral drift, beach stability and sediment budget	Down-drift erosion and instability of channels
Causeways	Effect on tidal compartment and flow patterns	Siltation and restriction of tidal flow
Catchment works (river control, bank stability and drainage)	Tidal flow, sediment transportation and backwater effects	Instability of channels, flooding and change in overall sediment budget
Residential and Industrial development	Rate of erosion and adequate buffer frontage	Erosion of site

Table 2 - Problems Resource use Conflicts and Their Management for the Muthurajawela Marsh and Negombo Lagoon

Problems	Conflicts	Strategies/Policies/Management Plans
Lack of state control on land management	Use of state land for planned urban expansion vs Regularization of encroachment	Acquisition of control of state land and management in a socially equitable manner
Alternative housing	Sand filling for capital intensive development vs Continuing use of the marsh for housing expansion	Formulation of an adequate relocation/ community development package for encroachers
Maintenance of adequate tidal exchange and flushing	Maintenance of channel width and depth vs Loss of opportunity for unauthorized land fill and house construction in the channel segment	Implement boundary demarcation, removal of obstructions to flow and planned dredging
Sedimentation and loss of fishing area	Un-controlled use of watershed vs Loss of eco-system biodiversity	Strategic dredging in the short term and implementation of watershed management in the long term
Controlling discharge of untreated industrial effluents and domestic waste	Loss of opportunity of free discharge of untreated effluents and installation of treatment, charging tariffs vs Loss of eco-system biodiversity	Implementation of cost recoverable waste treatment scheme for industries and discharge of waste by use of a sea outfall
Eutrophication	Loss of opportunity of free discharge of sewage vs Prevention of eutrophication and enhancement of eco-system biodiversity	Control of convenient discharge of sewage and investigations leading to an urban sewage management scheme based on cost recovery measures
Presence of an unplanned fishery harbour	Environmental degredation due to unplanned activities vs Development of an environmentally friendly fishery harbour	Development of a fishery harbour designed to accommodate special considerations relating to the lagoon and the eco-system
Oil pollution	Uncontrolled and free expansion of anchorage facilities vs Loss of eco-system biodiversity	Limiting anchorage facilities on a planned basis, management of anchorage use and adaptation of precautionary measures
Coastal stability	Sand mining and sand pumping from an eroding coastline vs Coastal protection	Use of appropriate technology and identification of coast protection measures
Absence of a flood buffer	Loss of retention area vs Increased flood threat	Enhancement of flood buffer and drainage capacity of the wetland

Table 2 Contd.

Habitat degradation from overfishing	Optimization of eco-system biodiversity, optimizing fishery income and limiting access to the fishery activities vs Loss of income and occupation in the absence of alternatives	Preparation of a fishery management plan with due consideration to socio-economic aspects and sustainability of the eco-system
Lack of employment opportunities	Over exploitation of the marsh and lagoon vs Generation of alternative employment which is less dependent on such resources	Programme to generate alternative employment, depending less on resources of the marsh and the lagoon
Externalities	Extensive development of the marsh and lagoon vs Negative side effects on lagoon fishery and marine species	A zoning strategy and management plan for the lagoon fishery
Loss of biodiversity and natural values	Development vs Ecology	Formulation of a land use zoning strategy which will be an adequate compromise

3. Investigative Study of the Negombo Lagoon

3.1 Approach to the problem

Planning and development activities at the Negombo lagoon inlet and assessing its impact on the environment require as detailed an understanding as possible of the system to be managed. A review of natural conditions and development activities identified some of the problems which affect the lagoon environment. It was clear that siltation of the lagoon and its inlet was a major issue, linked to most problem areas. In this context it was evident that the method of approach adopted should identify the lagoon inlet as an integral part of the aquatic system consisting of the main body of the lagoon on one side and the ocean on the other side. It is important to note that the entire tidal exchange between the ocean and the lagoon is restricted to flow beneath the two bridges identified in Figure 2. The region between the bridges and the mouth is used extensively by fishing vessels and waves from the ocean propagate into this area.

The prediction of siltation and its prevention at tidal inlets are difficult tasks. In order to identify methods of preventing siltation or limiting its impact it is essential to identify and confirm the source of the deposited material, its volume and the processes by which it is moved into the tidal inlet. The processes and quantities of transportation, settlement and accumulation of sediments depend upon the characteristics of the sediments itself and upon the strength and duration of the driving forces of waves, tides and inland drainage (where applicable). Even more important is the impact of combined action of these processes.

Ideally the investigative strategy requires both qualitative and quantitative information leading to a clear understanding of natural changes of inlet stability. It also requires methods of predicting the manner in which the inlet will respond to changes introduced by development activities.The priority need is to assess the likely impact or efficiency of a proposed development or control scheme so that different options can be evaluated objectively one against the other. In order to achieve this objective it is necessary to be able to simulate existing conditions within the system of interest and to predict, in quantitative terms, within acceptable levels of accuracy, the consequences of natural and man-made changes in these conditions. In this context it is recommended to apply reliable mathematical models which is a powerful technique capable of integrating, by means of mathematical equations, the many diverse processes involved in the functioning of aquatic systems, thereby simulating such systems and predicting quantitatively the effects of changes in these systems.

3.2. Components of hydraulic investigations

The hydraulic behaviour of a tidal inlet can be investigated in two stages.

In the first stage an initial but sufficiently detailed assessment of the physical processes occurring at the inlet can be made by studying existing information.

This will include

1) Historical information and data from different investigations carried out in the study area. These include information on previous schemes in the area and their impact on neighbouring regions.

2) Application of semi-quantitative conceptual models that rely on an understanding of the varying processes in the natural systems that affect the hydraulic regime and coastal stability.

3) Using results from case studies of similar situations from which the likely impact of change can be inferred.

In the second stage a greater understanding can be obtained efficiently, by the applications of mathematical models. Once the existing physical processes are fully understood and modelled, engineering interventions for improving the environment can be formulated. The results from further model studies can then be used to assess how well the mitigating measures will work and their impact on the neighbouring environment.

4. Sedimentation at Lagoon Inlets

4.1 Morphological stability of tidal inlets

Estuaries and inlets are governed by tidal action at the sea face and by inland drainage to whichever degree it exists. These are the main independent variables. The boundary shape of the estuarine system is determined by the geomorphology of the land and the properties of the alluvial materials that form the bed and banks of the channels. The geomorphology of an estuarine system is essentially, a fixed boundary condition but the movement of channels as modified by flow can be regarded as a variable boundary of the system. Usually, the overall boundary shape changes only slowly, though there may occur rapid local or short term adjustments.

4.2 Sediment transportation and deposition in varying flow fields and under density gradients

Approaches of fishery harbours and anchorages located at tidal inlets are usually subjected to the combined effects of waves and currents leading to sedimentation. In the presence of appreciable river flow, the differences in density between sea and river water creates density gradients which contribute towards landward movement of fine sediments. Furthermore, sediment in suspension also causes density currents which give rise to sedimentation in regions of still, relatively deep water.

Some of the important aspects leading to sedimentation in tidal inlets can be understood by analysing the mechanics of sediment transport in a flow field with varying velocities (5). It is also noted that sediment can be carried in suspension at much lower velocities than those required for erosion. Consequently fine sand particles may be transported into an estuary on the flood tide to be deposited at slack water into cohesive deposits, but the requirement of a higher erosion velocity on the ebb tide means that sand particles progressively accumulate in cohesive deposits. This in turn produces an armouring effect on the surface of the deposits thus contributing towards greater resistance against erosion. With respect to sedimentation of fine, cohesive sediments it should be noted that the rate of settlement also depends upon the concentration of the sediment in suspension. In the case of non-cohesive granular sand it is important to account for unsteady cyclic nature of tidal flow which causes a lag in response between water velocity and sediment transport.

Wave action can impose a major influence upon sediment motion in an estuary or tidal inlet. Waves with large orbital bed velocities provide a very effective stirring mechanism while orbital motion throughout the water depth, together with breaking waves encourage mixing of suspended material.

When tidal energy is low relative to wave energy, there are situations when wave can still dominate the development of bed formations. For example, there are certain conditions under which inland (river) flows and tidal flows are hardly sufficient to transport sediment on their own strength, but wave action is able to bring sediment into suspension at the tidal inlet or at the river mouth, allowing it to be transported landward by the rising tide and the process of salinity intrusion. It is important to note that even under mild wave conditions, depending on wave period and wave height, it is possible to develop bed velocities which are sufficient to move or bring into suspension sand which would then be deposited by tidal action. The fresh water flowing from the inland areas mixes with sea water to generate a resultant landward circulation close to the bed in key areas transporting sand and silt into the main channel under the combined action of waves and tidal currents.

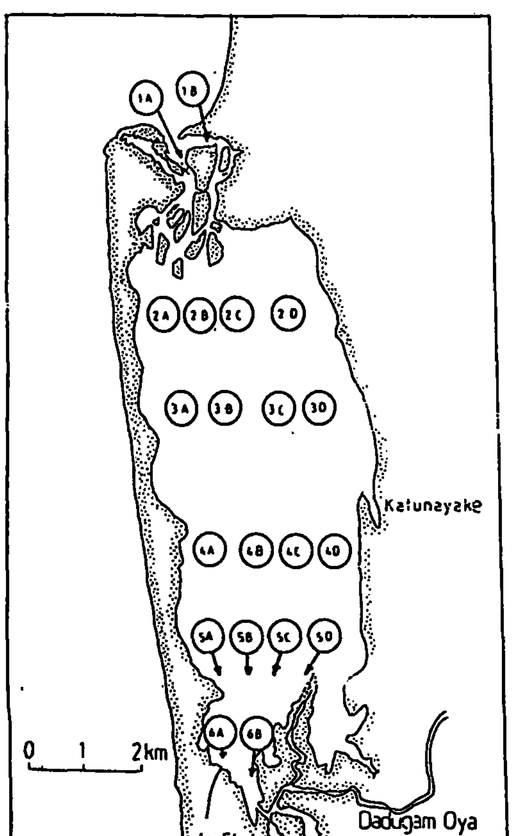
When tidal energy is low relative to river discharge there will exist a degree of stratification of fresh water with accompanying intrusion of salt water underneath. This phenomenon contributes to the deposition of fine sediments and could lead to siltation at crucial locations in fishery harbours located at tidal inlets and along estuaries.

In either partly or well mixed conditions the salt water wedge is not stationary. It will oscillate backwards and forwards with the tide. The intrusion will be apparent mainly from the distributions in velocity and salinity across various planes along the length of the waterway. In well mixed conditions the salinities at the surface and the bed may differ by only 15% - 25%. Such identification data will vary throughout the year as both tides and river discharge vary. But long-term changes can be effected by activities such as deepening the water way for navigational purposes.

5. Summary Of Investigations

Results from three investigations relating to the physical oceanographic characteristics of the Negombo lagoon provided data for an initial assessment of the hydraulic regime of the lagoon and its inlet. These investigations have been undertaken by the National Aquatic Resources Agency (NARA).

The first study (6) referred to the investigation of the distribution and seasonal variation of salinity, suspended matter, siltation, temperature, turbidity, transparency and pH values. This data has been collected over a period of twelve months from March 1989 to February 1990 covering a wide area of the lagoon and its inlet. The twenty data sampling points are illustrated in Figure 6. The sampling points are located along six lines of which the first (near the lagoon inlet) and the sixth (at the end of the lagoon) contain two sampling points per line. The rest of the lines contain four sampling points per line. The distribution of sampling points has given uniform coverage of the area under investigation.



Sampling points for field study (6)
Sampling points for field study (8)
(xl, x2 tide pole, x3 current measurements)

Fig. 6 - Location of Sampling Points and Nomenclature (6, 10)

The second study (7) refers to the Muthurajawela ecological survey in which the results from the first study are further discussed along with additional information.

The third study (8) refers to an investigation relating to the determination of friction coefficients and water exchange for the Negombo lagoon inlet. Of interest to this study are the measurements relating to the water level variations inside and outside the lagoon, the tidal current velocities at the inlet and the river discharges. The measurements have been taken during three periods namely, each extending over 4 days between 31st October 1991 and 3rd January 1992. The periods have been chosen to cover rainy and dry seasons to give widely varying fresh water supply.

In addition to the above three studies, NARA had undertaken a detailed bathymetric survey of the lagoon outlet in 1989.

Information relating to the historical developments and coastal changes around the lagoon inlet are also available (9). The same study also provides information on sediment characteristics of the beaches south and north of the Negombo lagoon inlet.

Information available from the above studies (6,7,8 and 9) were further analysed leading to an assessment of the impact of hydrodynamic processes on the sedimentation in the Negombo lagoon and its inlet by the first author (10). It provides a detailed assessment of relevant processes by studying existing information and supporting field observations.

Results from two investigations on mathematical modelling (11 and 12) of the Negombo lagoon are available. The first investigation (11) is a pilot study of the problem of sedimentation. The second was carried out by the second author (12) to simulate the tide induced hydraulic regime in the lagoon and its inlet. It forms a case study of a wider investigation on the hydraulic behaviour of tidal inlets covering both hydrodynamics of flow and sediment transportation, using advanced mathematical modelling techniques.

6. Analysis of Data and Discussion of Results

6.1 Field investigations

A preliminary analysis of data from field investigations (10) indicates that although a large data bank exists for the Negombo Lagoon, most of the data have been collected not from a view of engineering studies and hence the same cannot be used directly for detailed computations of the hydraulic behaviour of the inlet. The principal shortcomings of the data from an engineering viewpoint are the limited frequency of collection (sampling frequency) and the limitations with respect to the number of points at which the data has been collected (spread of data points).

It is noted that only few sampling points (1A, 1B, 2A, 2B) cover the regions of the lagoon inlet. Of these, the points 1A and 1B are closer to the mouth itself located in the main navigational channels. The points 2A and 2B are within the main body of the lagoon. It would have been of interest if at least four additional sampling points were located within the inlet but outside the main navigational channels. This would have provided information which could have been used for predictions leading to specific siltation patterns in the anchorage itself. It was observed from recent field visits that the areas outside the main navigational channels have been subjected to increased siltation.

In spite of the above limitations, detailed analysis of the data provided sufficient information to identify important aspects of the hydraulic behaviour and the sedimentation processes in the main body and in the inlet of the lagoon. Of the data available, attention was primarily focused on rainfall, salinity, suspended matter, siltation, soil composition and velocity distribution. The latter only being measured at the inlet. The analysis of the data included the study of the variation of individual parameters and the examination of relevant cross-corelationships among them.

Information of the bottom soil analysis at the sampling points was available in the form of percentage of silt and clay against that of sand. In the main body of the lagoon (covered by sampling points other than 1A and 1B) the percentage of silt and clay was in the range 40% to 99% and on most occasions it was well above 50%. The percentage of sand at points 1A and 1B located within the inlet was in the range 23% to 98%. It seems that the inlet is influenced by the sand introduced by the tides. From data available on nearshore sediment characteristics it was observed that the grain size in the immediate vicinity of the lagoon inlet varies from 0.26mm (near Duwa) in the south to a range 0.9-0.45mm in the north.

Examination of the surface and bottom salinity levels indicate the presence of stratified conditions with the bottom layers having a slightly higher level of salinity indicating intrusion of sea water along the sea bed. Salinity distribution patterns indicate the existence of a strong gradient from the head of the estuarine system towards the lagoon inlet. These salinity levels vary from almost complete fresh water conditions (during certain rainy months) to values in the range of 30-35 ppt in the regions closer to the inlet (Figure 7). The position of zero net movement moves across the lagoon from the southern most region to the lagoon inlet.

From this study it is evident that both inland drainage and tidal flow have a pronounced effect on the sedimentation of the main body of the lagoon and its outlet. The impact of inland drainage has a greater effect in the regions within and closer to the head of the lagoon. The tidal flow has a greater effect in the regions within and closer to the lagoon inlet.

Both land drainage and tidal flow introduces sediment laden discharge into the lagoon and the prevailing hydraulic regime encourages a large proportion of the sediment load to settle within the main body of the lagoon and at its inlet. The rainfall and the resulting increase in the sediment load of the inland drainage has a strong impact on the sedimentation processes.

The sediment load introduced by inland drainage from streams and rivers, will settle in areas immediately away from the influence of the discharge plume where the hydraulic conditions will be less dynamic. The high siltation rates at sampling points 4A, 4B, 5A and 5B support this argument. A large proportion of the remaining sediment which is carried towards the lagoon inlet will settle in the region closer to the lagoon inlet. This includes the areas covered by the sampling points 2A and 2B and the complex area of transition north of these two points. Since the natural transition to the sea consists of several narrow channels it is likely that the sediment can get trapped in this region. A proportion of the sediment load introduced by the tides will also settle in these regions. The fluctuating tidal velocity regime supports the sedimentation process.

Unauthorised reclamation taking place around the islands in the inlet has further aggravated the problem by affecting the flushing ability of the lagoon.

It is apparent that the ebb flow will transport the sediments in suspension as well as those on the bed, out of the inlet into nearshore regions. It is also possible that re-suspension of material and its transport will take place during the ebb flow. In this context it is noted that fine sand particles may be transported into an estuary on the flood tide to be deposited at slack water into cohesive deposits, but the requirement of a high erosion velocity on the ebb tide means that sand particles progressively accumulate in cohesive deposits. This in turn produces an armouring effect on the surface of the deposits thus contributing towards greater resistance against erosion. This effect is particularly relevant to situations where tidally induced water variations are small in both absolute and residual motion terms, low enough to permit suspended sediment to settle on the bed.

From the analysis of field data it is evident that the lagoon including the main body and the inlet will be progressively subjected to sedimentation due to the settlement of sediment load from inland drainage and tidal flow. The region of the lagoon inlet, with its complex geometry, acts as a sediment trap and it could be expected that sedimentation in this region will continue to increase in the future.

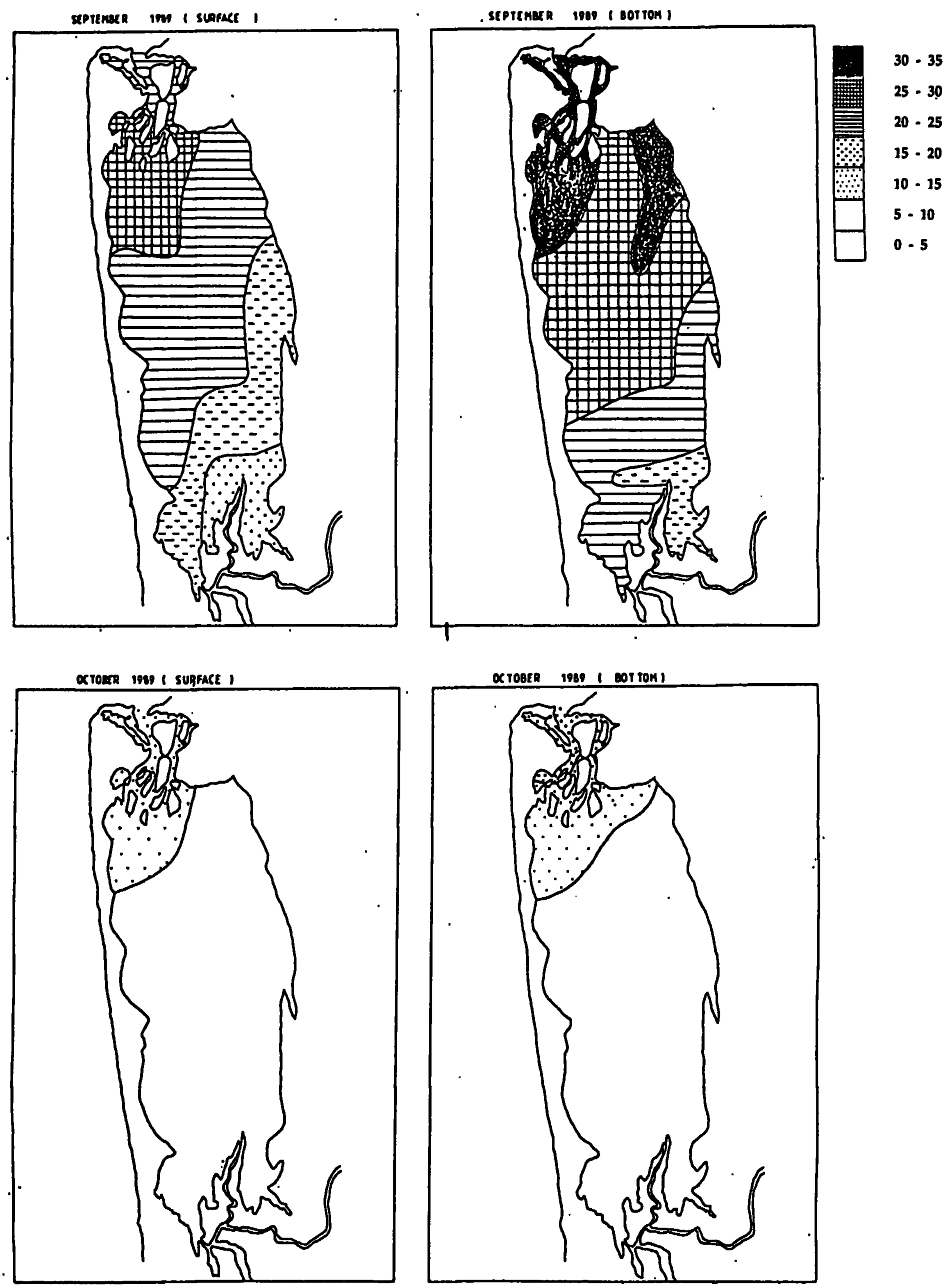


Fig . 7 - Salinity Variation at the Surface and at the Bottom in September 1989 (6,10)

6.2 Mathematical Modelling

Selected results from the mathematical model study on the simulation of the tide induced regime in the lagoon (12) are discussed in this paper.

A depth averaged, finite difference numerical model was developed and used to predict water surface elevation, velocity fields and residual movements in the lagoon. The conservation equations of mass and momentum were solved using the well documented Alternating Direct Implicit (ADI), Finite Difference technique which was second order accurate in space and time. In the momentum equations the effects of the earth's rotation, bed friction, turbulent diffusion and convective accelerations were included.

The region of the Negombo lagoon simulated in the model was defined by a finite difference mesh of 199 by 66 grid points, with an equal grid spacing of 71.43m in both directions. As in the case with all numerical models, the placement of the boundaries and the conditions there greatly influence the solution process. An average tidal range of 0.6m was used for this study. The depth contours of the lagoon and previously measured water elevations were available for the seaward boundary (11 and 10). In the absence of field measurements for the bed roughness characteristics along the lagoon reach, Manning's of 0.03 was considered appropriate for this study. A small time step of 69.94 seconds was used to overcome numerical instability problems, which might have arisen because of the complicated geometry of the application.

Figure 8 represents the computational domain used for the study. Seven important locations within the computational domain were selected to represent the outputs of the variation of surface elevation and velocity.

Only a few field measurements of surface elevation and velocity were available for comparison with those predicted by the mathematical model. Figure 9 illustrates a comparison between measured and predicted surface elevation at a point inside the lagoon. It also illustrates the measured external tidal fluctuations. The agreement between the measured and predicted results is encouraging, particularly in view of the coarseness of the grid and the consequent difficulty of representing a complex bathymetry at discrete points. Difficulties in assessing bed roughness without detailed field data, the exclusion of wind-induced motion and surge effects from the mathematical model have contributed to the differences between the measured and predicted values.

Figures 10 and 11 illustrate the graphical outputs of the spatial velocity fields produced during the second tidal cycle at mean water level on flood tide. Figure 12 shows the residual movements, the net displacement of water over a complete tidal cycle, of selected points.

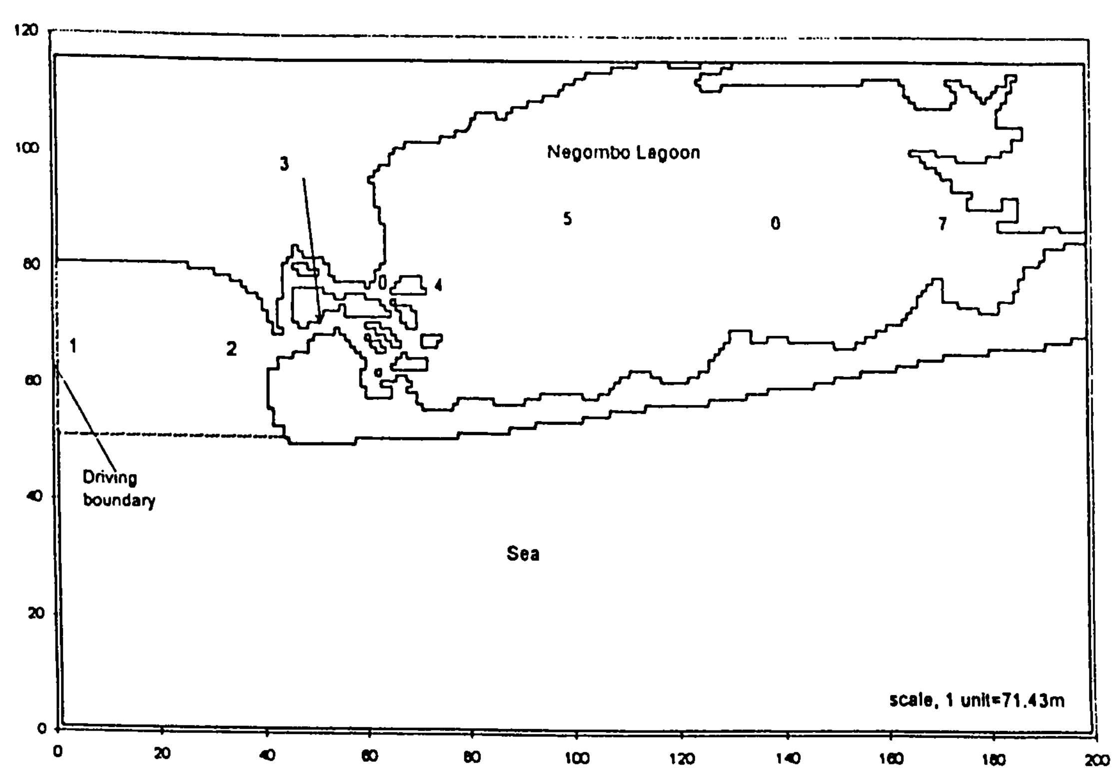


Fig. 8 - Computational Domain Showing the Driving Boundary and Output Points (12)

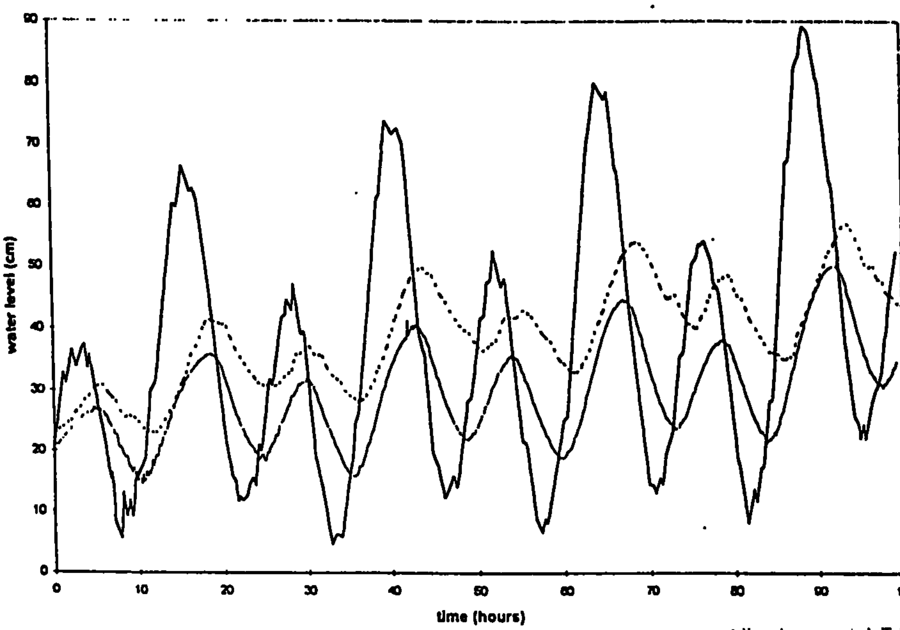


Fig. 9 - Measured and Predicted Surface elevation (12)

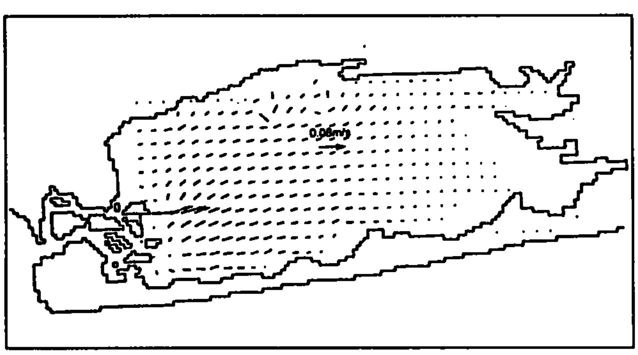


Fig. 10 - Velocity Vector Plot in the Lagoon at Mean Water level on a Flood Tide (12)

(Vector scale given by separate arrows

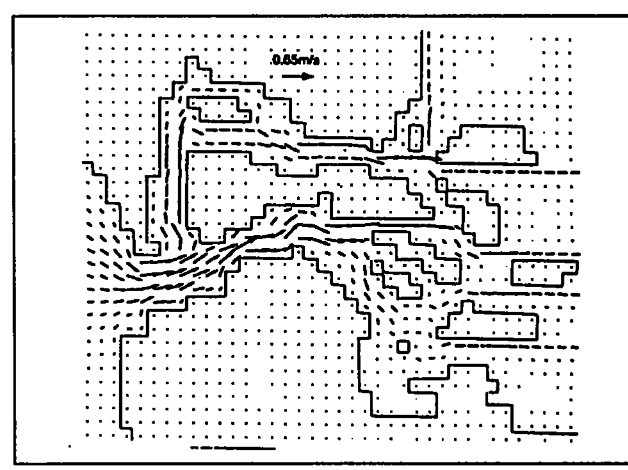


Fig. 11 - Velocity Vector Plot at the Lagoon Inlet at Mean Water level on a Flood Tide (12)

(Vector scale given by separate arrows

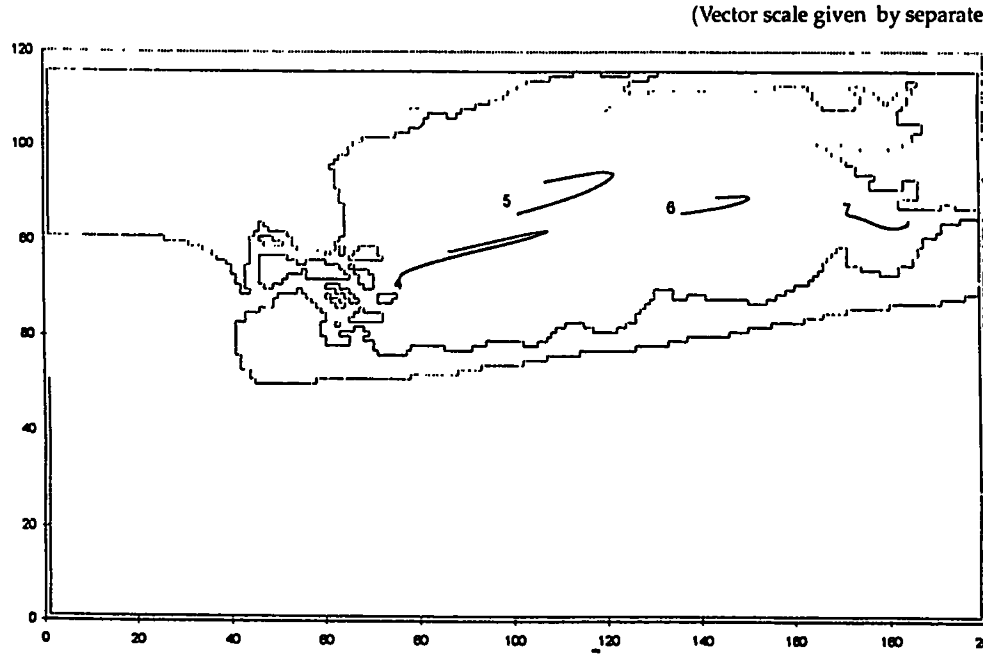


Fig. 12 - Residual Movements at selected Points Over one Complete Tidal Cycle

Some discrete velocity measurements were available at the lagoon inlet and these indicated a maximum of around 0.6 m/sec. The numerically predicted maximum value was 0.5 m/sec. When considering the comparatively large grid used to represent the narrow entrance channels and the other approximations, the comparison is good. Even though no measured data were available to validate the predicted residual movements, the results shown in Figure 12 is encouraging. At the far end of the lagoon the water movement was relatively small. However it is noted that river discharge is not included in this study.

Results from modelling of sediment transport indicate that continuing changes of depth in the narrow entrance / exit channels of the inlet would be expected with the formation of flood and ebb tide deltas. Detailed analysis reveals that sediment movement initializes around a velocity of ± 0.32 m/sec. With an increase in velocity the suspended load rate increases rapidly compared to the bed load. However, the tidal velocities in the lagoon are not high enough to generate a significant amount of suspended sediment movement. Bed load transport rate is higher than the suspended load transport rate at lower velocities. With an increase in velocity the suspended load rate increase at a higher rate than the bed load rate. It has to be noted that the ratio of suspended to bed load transport rate depends not only on the velocity but also on the ratio of roughness height to depth (ks/h) ratio. With an increase in $k_s$lh, the ratio of suspended to bed load ratio decreases.

With reference to a location at the mouth of the inlet, variation of maximum sediment rate with particle diameter for mean water levels on the flood and ebb tide revealed that the bed load transport rate increases with reduction of particle diameter to about 0.1 mm and then begins to decrease as expected. There is no significant effect of the reduction of particle size on the suspended load rate down to 0.2 mm but below this value the suspended load rate increases rapidly. It is noted that there is a significant effect of particle size for sediment transport predictions, in particular, below a median particle size of 0.2 mm.

Selection of a sinusoidal tidal input instead of actual semi-diurnal tidal variation may have introduced some errors in sediment transport predictions, especially considering the sensitivity of tidal range to sediment transport predictions. Inspite of this limitation the results are of immense benefit in predicting the behaviour of the lagoon and in particular its entrance.

From the results of this study it is observed that the tidally-induced water variations within the lagoon are very small in both absolute and residual motion terms and this would be low enough to allow suspended sediments to settle on the bed. Thus it can be expected that a substantial proportion of the suspended sediment load introduced to the lagoon via inland drainage and the tides will settle on the bed. The water depths in the lagoon will continue to reduce which, together with limited circulation of water may lead to the degradation of water quality with consequent impacts on marine species and fishing.

7. Concluding Remarks

This paper has identified the importance of the Muthurajawela marsh - Negombo lagoon wetland and its environment, on one hand as a unique eco-system rich in biodiversity and on the other hand as source of multiple resources being exploited by the stakeholders. The paper highlights the need for coastal aquatic systems to be managed for sustaining multiple uses and for the community to be safeguarded against the adverse effects of their unconstrained action.

In the above context the paper has illustrated the relevance and applicability of mathematical models in the investigation of the hydraulic behaviour of lagoons and their environmental management. Mathematical models can be used effectively to study the impact of different hydraulic regimes and to predict likely changes which will take place due to development activities and other action.

Investigations confirmed that unauthorised landfill, unplanned development along the waterfront, siltation, reduction of tidal exchange and flushing, discharge of industrial effluents and municipal waste and overall pollution of the environment are major problem affecting the Negombo lagoon. These problems and their impacts have a close interrelationship with the hydraulic regime which can be simulated by mathematical modelling. It also enables the prediction in quantitative terms the consequences of natural and man made changes in these conditions. In this context the paper has identified important findings relating to the dynamics of flow, sediment transportation and siltation. If the coastal fishery anchorage at the lagoon inlet is to be developed it would be necessary to extend the modelling work at identifying methods of improving the anchorage with minimum structural changes and least environmental impact to the unique eco-system.

From the investigations carried out it is evident that both inland drainage and tidal flow have a pronounced effect on siltation of the main body of the lagoon and its inlet. The tidally - induced water variations within the lagoon are very small and this would permit the suspended sediments to settle on the bed. Thus it can be expected that a substantial proportion of the suspended sediment local introduced to the lagoon via inland drainage and the tides will settle on the bed. The water depths in the lagoon will continue to reduce and combined with limited circulation of water may lead to the degradation of water quality with consequent impacts on marine life. The introduction of further pollutants under poor conditions of circulation will aggravate the situation further. The findings clearly support planned engineering interventions to sustain multiple uses of the lagoon. Failure to do so will affect the biodiversity of the eco-system and the resource users will be deprived of long term sustainable benefits. In implementing planned engineering interventions for the environmental management of the lagoon it is necessary to educate the resources users and adopt a participatory approach with the support of the community and all stakeholders.

8. References

1. Master Plan of Muthurajawela Marsh andNegombo Lagoon Greater Colombo Economic Commission (GCEC) Eurocosult 1991.

2. Environmental Profile of Muthurajawela and Negombo Lagoon. Ed. Samarakoon, J. and van Zon, H. GCEC, Sri Lanka and Euroconsult, Netherlands. March 1991.

3. Conservation Management Plan - Muthurajawela Marsh and Negombo Lagoon. Wetland Conservation Project, Central Environmental Authority, Sri Lanka and Euroconsult, Netherlands. October 1995.

4. The hydrology and geomorphology of tidal basins. Smith, D.B. in The closure of tidal basins. Ed. van Aalst, W. Delft University Press, Netherlands. 1984.

5. Hydraulic behaviour of estuaries McDowell, D.M. and O'Connor, B.A. McMillan Press, 1977.

6. Dynamics of some Physical Oceanographic Characteristics of the Negombo Lagoon. Wickramaratne, W.S., Niwas, J.M., Samarakoon, S.J.R. and Selladurai, M. Research Report, Oceanographic Division, NARA, 1992.

7. Report on the Muthurajawela Ecological Survey.Wickramaratne, W.S., Niwas, J.M., Wijeratne, E.M.S. and Guruge, K.S. Research Report, NARA, 1992.

8. Studies of Tidal Choking and Water Exhange in Negombo Lagoon, Sri Lanka. Wickbom, L. Fisheries Development Series 67, SWEDMAR, 1992.

9. Coastal changes of the Negombo Lagoon Outfall and the Kaluganga Estuary Madduma Bandara, C.M., Gamage, P.W. and Wilson, W.N. Coast Conservation Department, Sri Lanka, 1987.

10. Sedimentation in the Negombo Lagoon outlet Hettiarachchi, S.S.L. Research Report, University of Moratuwa, 1995.

11. Sedimentation in the Negombo Lagoon outlet Terwel, L. and Vermeulen, J. Research Report of the Delft University of Technology conducted in collaboration with the University of Moratuwa, September 1994.

12. Long-term Tide and Wave-induced a Sedimentation at a Lagoon Entrance Samarawickrama, S.P. PhD Thesis, Department of Civil Engineering, Imperial College, London, August 1999.