NUMERICAL MODELLING OF SEDIMENT TRANSPORTATION IN THE NEGOMBO LAGOON, SRI LANKA

by

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Abstract

The paper describes the application of a numerical model to predict sediment transportation in Negombo Lagoon, Sri Lanka. This is a continuation of the work published in the June, 1997 edition of Journal of Institution of Civil Engineers, Sri Lanka on the prediction of water-surface elevations, the two-dimensional tide induced velocity field and the residual currents in the Negombo Lagoon. The sedimentation process of the lagoon and the lagoon inlet/exit is discussed here in detail.

1.0 Introduction

Negombo lagoon is a shallow coastal body of water located on the west coast of Sri Lanka (N and E). The lagoon is approximately 12.5km in length and its width varies from 0.6 to 3.6 km. **Figure 1**. Its mean depth is estimated to be approximately 0.65m and the surface area to be 35km^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 250m^2 with a length of about 2.5km.

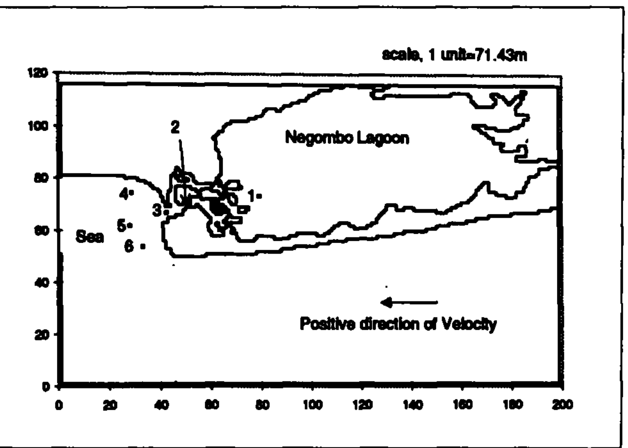

Fig: 1 Plan view of the Negombo lagoon showing out put points

The exchange of water in the lagoon is influenced by the tides from the ocean and fresh water supply from inland. 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 the tidal range at sea. Thus the volume of water stored and released varies between 2.5 million m^3 and 7.0 million m3 per tide. Fresh water enters from the southern end of the lagoon through several small streams. The supply of fresh water varies from virtually zero during the dry seasons to more than 100 m^3/s during the rainy seasons.

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. The reduction of the tidal flow could, in the long term, further adversely affect the lagoon environment. The objective of this study is to predict the sedimentation process of the lagoon and the future behaviour of the lagoon inlet. Empirical formulae developed by Van Rijn, 1984, were implemented in the present model to predict sediment transport due to tidal currents.

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2.0 Model Developments

2.1. Hydrodynamics

A depth averaged, finite difference numerical model was used to predict velocity fields in the Negombo lagoon, refer 1997 paper Institution of Civil Engineers, Sri Lanka. 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 all included.

The numerical solution procedure involved the establishment of a regular mesh of square grids over the area of interest, with the conservation equations being expressed in an implicit finite difference form. The resulting simultaneous equations, together with the known hydrodynamic conditions at the open and closed boundaries, were then solved by the method of Gauss elimination and back substitution to give the water surface elevations and the two mutually perpendicular depth averaged velocity components in the horizontal plane for each "wet" square.

2.2. Sediment Transportation

The sediment transport module of the numerical model uses depth averaged velocity predictions of the hydrodynamic module as input and calculates bed load and suspended load transport rates. A large amount of bed load transport rates, measured in flume and field conditions, was selected from the literature by Van Rijn to verify his bed load formula, Van Rijn(1984). Four hundred and eighty six sets of river data were used to verify the prediction of total load transport rates with 76% of the predicted transport rates within a factor 2 of the measured values.

2.2.1. Bed - load transport formula (Van Rijn,1984)

The bed-load transport rate is given by :

$$q_{b,c} = 0.25\, u^{1*}{}_{,c}\, d_{50}\, T^{1.5} / D^{*0.3} \qquad (1)$$

In which

$q_{b,c}$ bed load transport (m^2/s)

$u^{1*}{}_{,c}$ = $(g^{0.5}u)/C^1$ - grain related bed - shear velocity (m/s)

D^* = $d_{50}\,[(s-1)g/v^2]^{1/3}$ - particle parameter (-)

T = $(\tau^1_{b,c} - \tau_{b,cr})/\tau_{b,cr}$ -bed shear stress parameter (-)

$\tau^1_{b,c}$ = $\mu\,\tau_{b,c} = \rho g[u/C^1]^2$ - effective bed shear stress (N/m^2)

C^1 = $18\log(12h/3d_{90})$ - grain related Chezy coefficient ($m^{0.5}/s$)

h = water depth (m)

s = ρ_s/ρ - relative density (-)

u = depth averaged velocity (m/s)

d_{50}, d_{90} - particle diameters of bed material (m)

v- kinematic viscosity (m^2/s)

$t_{b,cr}$ = $(\rho s-\rho)\, g\, d_{50}\,\theta_{cr}$ - critical bed shear stress according to Shields (-)

2.2.2. Suspended load transport formula (Van Rijn,1984)

The suspended sediment transport rate is given by :

$$q_{s,c} = F\,u\,h\,c_a \qquad (2)$$

In which

c_a = $0.015\,(d_{50}/a)\,(T^{1.5}/D^{*0.3})$ - reference concentration (-)

F = $[(a/h)^{z'}-(a/h)^{1.2}] / [(1-a/h)^{z'}(1.2-Z^1)]$ - shape factor (-)

z^1 = $z + \psi$ - suspension number (-)

z = $w_s/(\beta k u^*{}_{,c})$ - suspension number (-)

ψ = $2.5(w_s/u^*{}_{,c})^{0.8}(c_a/c_0)^{0.4}$ - correction factor related to turbulent damping and hindered setting (-)

w_s = $(10\upsilon/d_s)\{[(1+0.01(s-1)gd_s^3)/\upsilon^2]^{0.5}-1\}$ - particle fall velocity (m/s)

d_s = $[1+0.011(\sigma_s-1)(T-25)]d_{50}$ -representative particle size of sus. sediment,

d_s = d_{50} for T>=25(m)

β = $1+2(w_s/u^*{}_{,c})^2$ - ratio of sediment and fluid mixing coefficient ($\beta_{max} = 2$)

σ_s = $0.5[(d_{84}/d_{50})+(d_{50}/d_{16})]$ - gradation coefficient of bed material (-)

d_{16}, d_{50}, d_{84}, d_{90} - particle diameters of bed material (m)

θ_{cr} = $0.24\ D^{*-1}$ If $1 < D^* <= 4$

θ_{cr} = $0.14\ D^{*-0.64}$ If $4 < D^* <= 10$

θ_{cr} = $0.04\ D^{*-0.1}$ If $10 < D^* <= 20$

Shields Curve

θ_{cr} = $0.013\ D^{*0.29}$ If $20 < D^* <= 150$

θ_{cr} = 0.055 If $D^* > 150$

$u^*{}_{,c}$ = $(g^{0.5}u)/C$ - current related overall bed -shear velocity (m/s)

C = $18\log(12h/k_s)$ - overall chezy coefficient ($m^{0.5}/s$)

$q_{s,c}$ - current related suspended load transport (m^2/s)

k_s - overall bed roughness height (m)

g - acceleration of gravity (m/s^2)

a - reference level (m) : ($a=k_s$, $a_{minimum}=0.01h$) (-)

k - Von Karman constant (-)

c_0 = maximum concentration = 0.65

2.2.3. Total Load Transport

The total transport of bed material particles can be obtained by addition of the bed load and the suspended load.

$$q_t = q_{b,c} + q_{s,c} \quad (3)$$

3. 0 Solution Grid and Boundary Conditions

The region of the Negombo lagoon simulated in the mathematical 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.

In modeling the tidal currents in the Negombo Lagoon it was necessary to introduce a time-varying water surface elevation at the open seaward boundary. The velocity parallel to this driving boundary was set equal to zero, as were the velocities along the non-driving boundaries. The velocity components at right angles to the non-driving boundaries were also set equal to zero. For the seaward boundary previously measured water elevations were available, (Hettiarachchi,1995) and the average offshore tidal range of 0.6m was used for this study. Depth contours of the Negombo Lagoon were available, (Terwel & Vermeulen,1995) and water depths at each grid point were obtained using those contours. No appropriate field measurements were available to indicate bed roughness characteristics within the lagoon or its narrow entrance/exit channels. The model was therefore tested for various values of Manning's n, and n=0.03 was found to be most 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.

Results of an investigation of the nearshore sediment characteristics off the mouth of the Negombo Lagoon were available. Figure 3 illustrates the variation of median grain size(mm) at locations south and north of the lagoon entrance; the sampling sites are also illustrated in the same figure. From these studies it is observed that the grain size in the immediate vicinity of the Negombo Lagoon outfall varies from a minimum of 0.26mm in the south to a range of 0.45mm to 1.00mm in the north. No measurements were available on sediment characteristics inside the lagoon, however the bed material is understood to be of smaller diameters than the coastal sediments, as would be expected. The coastal region near to the lagoon mouth, is fed by the Kalani River to the south and by Maha Oya to the north, which results in larger grain sizes. A median particle size of 0.1mm was used for this study, being the grain size corresponding to minimum shear-stress to initiate its motion.

4.0 Discussion of Results

The model was run on all occasions for six complete tidal cycles, with the results of the first half cycle being disregarded since the model needed some time to dissipate the errors introduced at the commencement of each simulation.

Figure 2 gives the variation of velocity magnitudes with time at selected locations. The selected locations are given in **Figure 1**. **Figures 4** and **5** give the variation of velocity, bed load and suspended load transport rates with time, at locations 2 and 3 respectively. The model results for location 2 predict a very small outward movement of sand from the lagoon compared to inward movement, whereas those for location 3 predict relatively high outward movement compared to lesser inward movement. According to the predictions, the reduction of depths in narrow entrance/exit channels would be expected to continue.

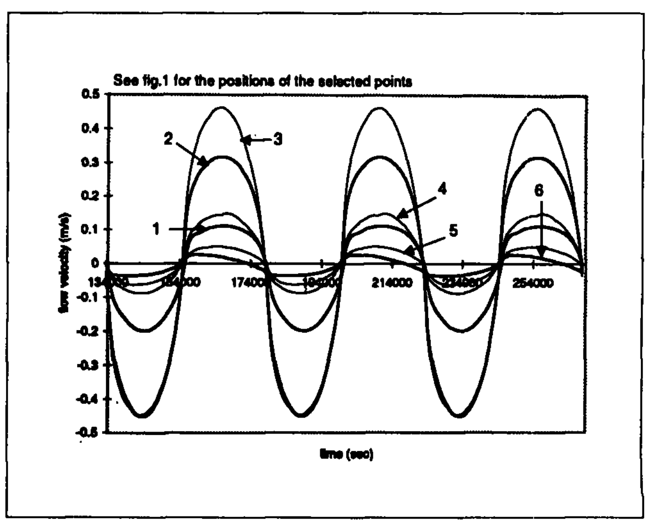

Fig 2: Velocity Magnitude vs Time

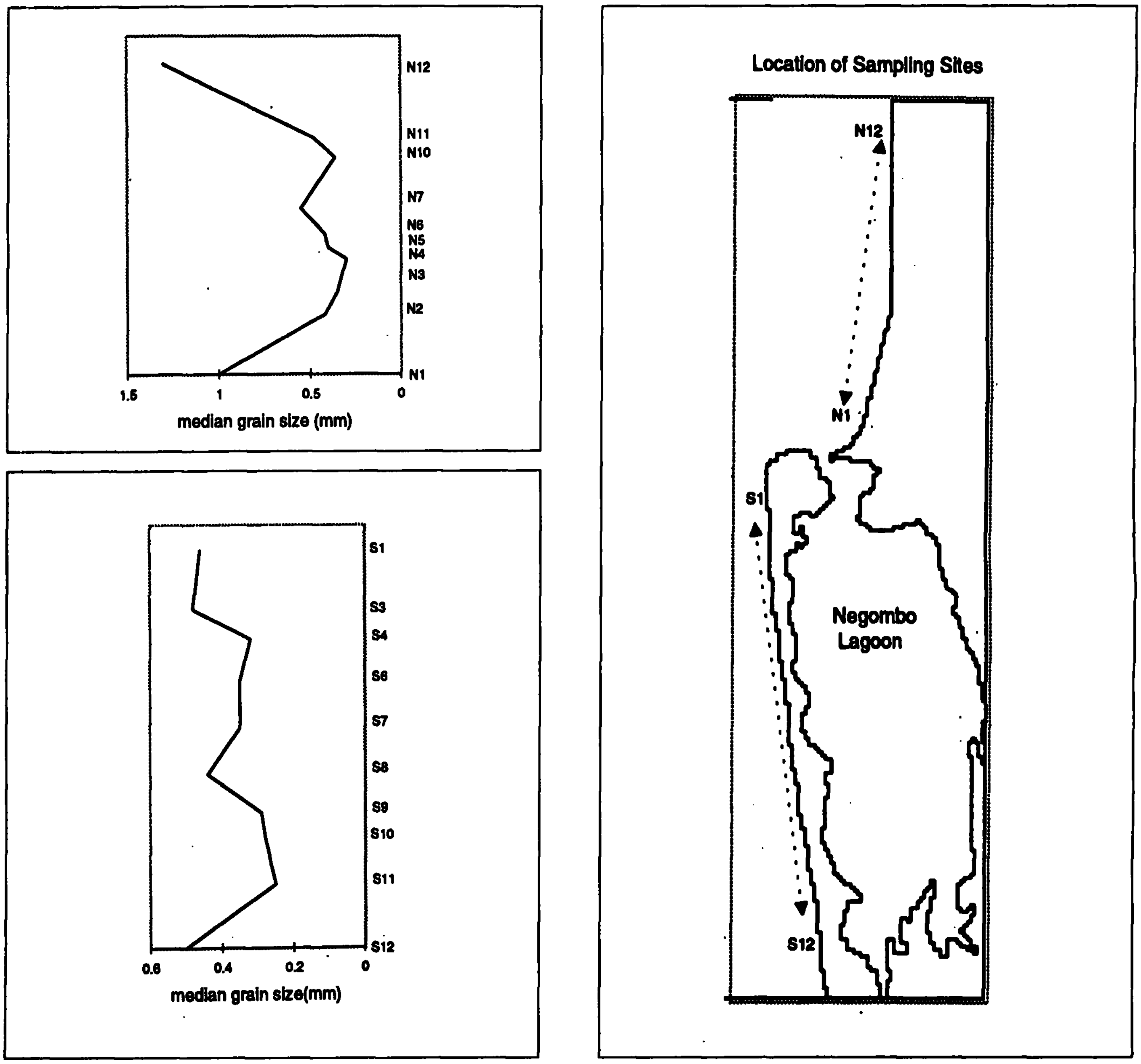

Fig 3: Variation of grain size characteristics, south and north of Negombo lagoon outfall

Figure 6 gives the variation of sediment transport rate with velocity. As can be seen, sediment movement begins around the velocity of (0.32 m/s. With the increase of velocity the suspended load rate increases rapidly compared to the bed load. Even though the suspended load rate increases rapidly with the velocity, the tidal velocities of the Negombo Lagoon are not high enough to generate a significant amount of suspended sediment movement. Figure 7 gives the variation of ratio of suspended to bed load transport rate with suspension number. High values of qs/qb indicate a higher suspended load transport rate compared to the bed load transport rate for all tidal velocities.

Figures 8 and 9 give the variation of maximum sediment transport rate with particle diameter at location 3, for mean water level on the flood tide and mean water level on the ebb tide respectively. The bed load transport rate increases with the reduction of particle diameter to about 0.1mm and then begins to decrease. There is no significant effect of the reduction of particle size on the suspended load rate down to 0.2mm but below the 0.2mm suspended load rate increases rapidly. All predictions quoted previously assumed a median particle diameter of 0.1mm. As can be seen from figures 8 and 9, there is a significant effect of particle size for sediment transport predictions, especially below the median particle size of 0.2mm.

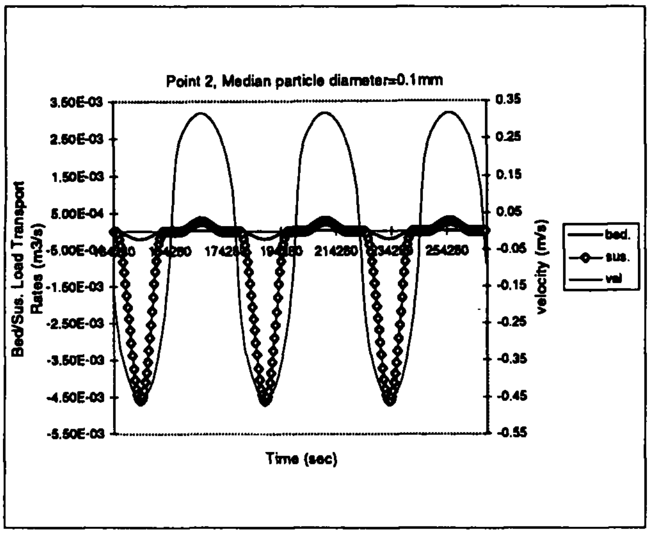

Fig 4: Variation of Velocity, Bed load and Suspended load Transport Rates with Time

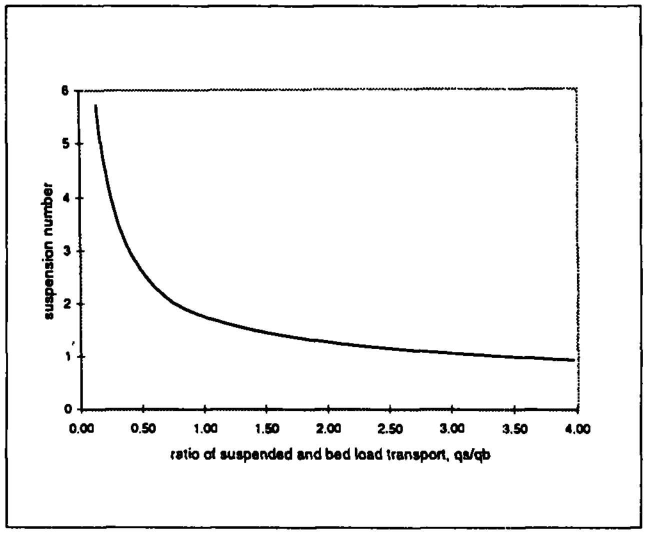

Fig 7: Variation of the Radio of Suspended to Bed Load Transport with the Suspension Number

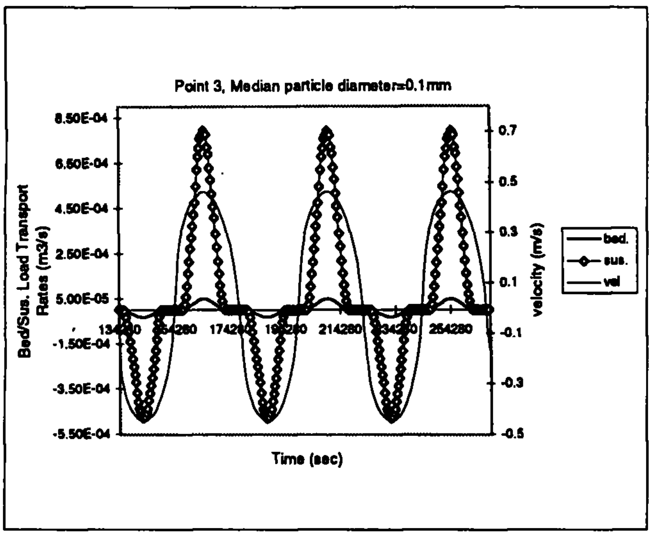

Fig 5: Variation of Velocity, Bed load and Suspended load Transport Rates with Time

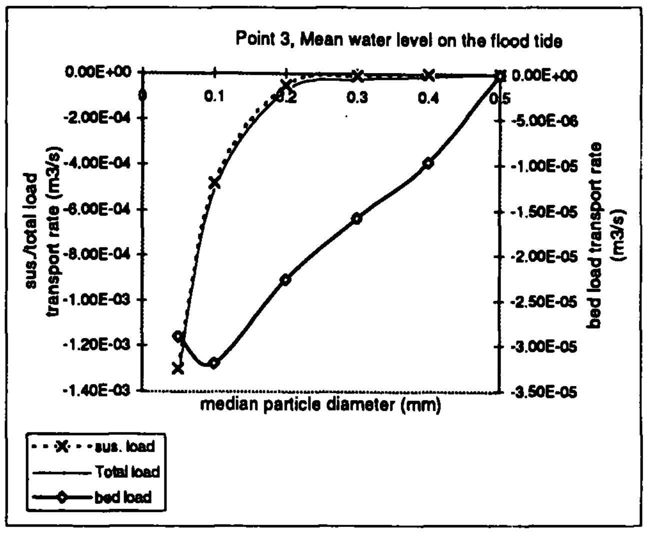

Fig 8: Variation of Maximum Sediment Transport Rate with Particle Diameter

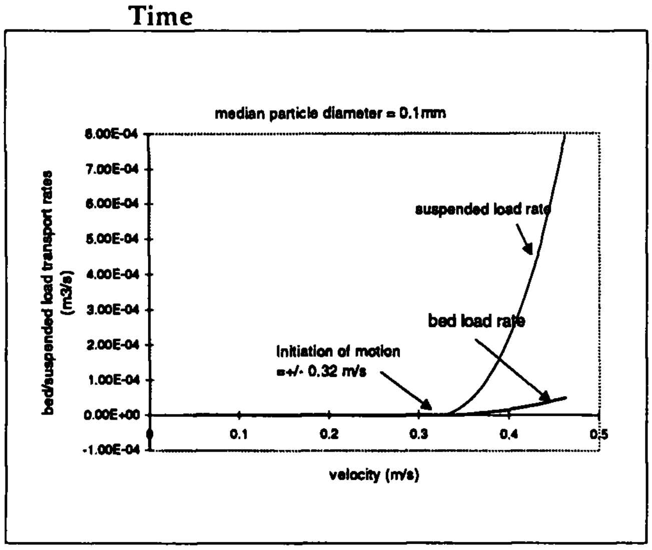

Fig: 6 Variation of Sediment Transport Rate with the Velocity

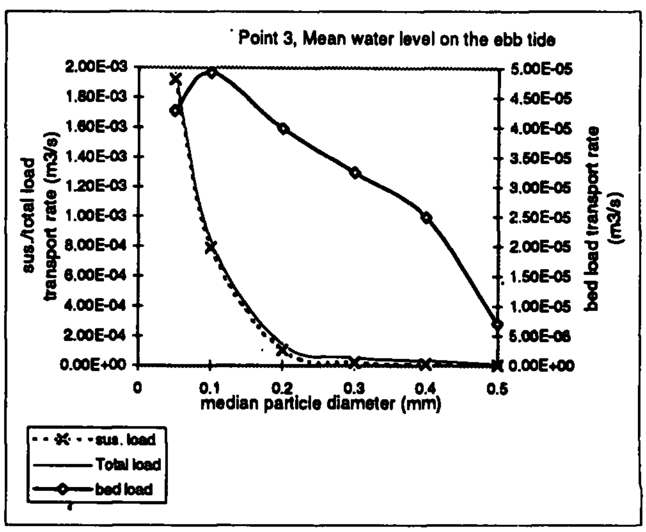

Fig 9: Variation of Maximum Sediment Transport Rate with Particle Diameter

Figures 10 and 11 give the variation of maximum sediment transport rate with tidal range at location 3, mean water level on the flood tide and the mean water level on the ebb tide respectively, negative rates directing transport into the lagoon and positive rates out of the lagoon. A mean tidal range of 0.6m was used for this study, which was obtained as an average value from the measured data. It can be seen from the figures that a change of (0.1m in tidal range from the mean value of 0.6m gives (75%-100% variation of sediment transport predictions.

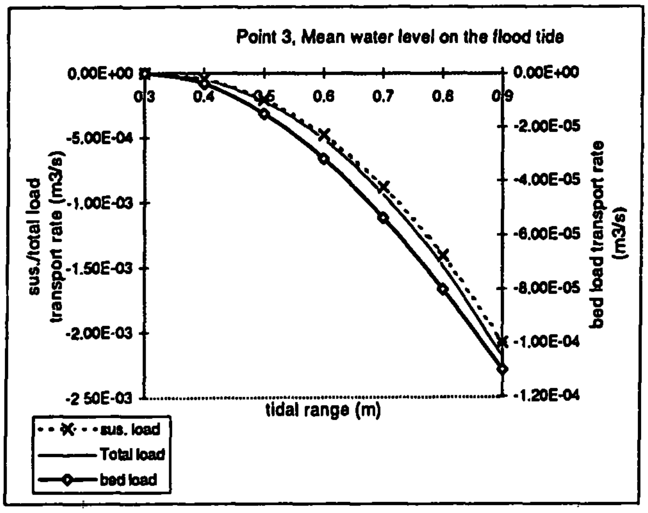

Fig 10: Variation of Maximum Sediment Transport Rate with the Tidal Range

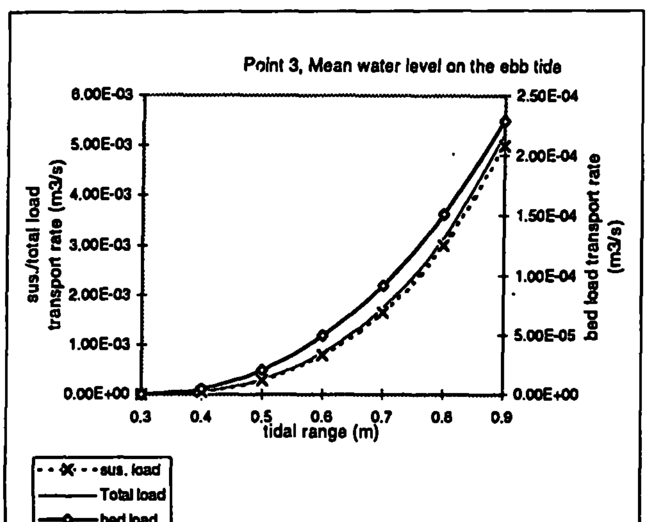

Fig 11: Variation of Maximum Sediment Transport Rate with the Tidal Range

Selection of a sinusoidal tidal input instead of the actual semi-dinural tidal variation may have introduced some errors in sediment transport predictions, especially considering the sensitivity of sediment transport predictions to tidal range. Even though the lack of adequate input data may have introduced some errors in model predictions, the results are thought to be very valuable in the prediction of the future behaviour of the lagoon entrance/exit and the lagoon itself.

It can be seen that the tidally-induced water variations within the lagoon are very small in both absolute and residual motion terms, low enough to allow suspended sediments to settle on the bed. Sediment movements were predicted only in locations 2 and 3, figure 1. Location 1, just inside the lagoon mouth and locations 4,5 & 6 at lagoon exit did not experience any movement of sediments due to tidal velocities. Thus it can be expected that the water depths in the lagoon will continue to be reduced which, together with limited circulation of water, may lead to a degradation of water quality with a consequent impact on fishing. Even though the lagoon exit (locations 4,5 & 6, figure 1) did not experience any sediment movement due to tidal action, it would be expected that the area may experience significant sediment transportation due to wave action. This latter factor is the subject of a study presently in progress.

5.0 Conclusions

Based on numerically predicted tidal velocities in the entrance and within Negombo Lagoon a sediment transport model has been developed to provide information on the potential changes in bed levels in these areas. For sediment diameter of 0.1mm the prediction indicate a continuing reduction in water depths in the narrow entrance/exit channels. This will have significant influence on navigation and, importantly, on the exchange of water between the lagoon and the open sea. This could result in degradation of water quality within the lagoon, with serious consequences.

The models provide realistic values of velocity and sediment transport but there is a lack of coherent full-scale data for the site. Given the importance of the Negombo-Lagoon in socio-economic terms a properly designed field study to provide validation data for the prediction presented in the paper is considered to be fully justified.

6.0 Acknowledgments

This work constitutes part of the second author's Ph.D. studies at Imperial College with financial support from the Association of Commonwealth Universities which is gratefully acknowledged as in the leave of absence granted to him by the University of Moratuwa. Further work will consider the sediment transport processes due to tide-wave interaction.

The core numerical model was developed by Dr. K. Anastasiou, Imperial College and the full scale data was made available by Dr. S.S.L. Hettiarachchi, University of Moratuwa to whom the authors extend their thanks and appreciation.

7. 0 References

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