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# Sediment Transport in Alluvial Tidal Rivers

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**Abstract :** *Prototype experimental, qualitative and quantitative emperical model may be rewardingly extended to explain morphological variations in an alluvial tidal waterway due to transport of sediments. The use of the methods have been suitably supported by studies on the estuary of the Hooghly in the state of West Bengal, India - perhaps the only estuary in India investigated for sediment transport in a planned well-organised manner.*

## 1. Introduction

Sediment transport processes in alluvial channels have been engaging the attention of the hydraulic expertise over the last several decades and would continue to do so. This is over-whelmingly appreciated for tidal water ways where the pattern of sedimentation is determined by the interaction of a wide array of independent variables. A simplistic approach requires the identification of the predominant parameters influencing movement of sediments by synthesising planned information from hydrographic survey charts, hydrological and meteorological observations. It is proposed to present the characteristics of tidal rivers and discuss the methods to evaluate sediment transport to the extent possible in context to the simple case of "well-mixed" estuaries. The methods may be modified and extended to estuaries of different orders of "mixing" demanding ingenuity of approach.

## 2. Tidal Waterways

### 2.1 Waterway

A tidal waterway is often called an estuary. An estuary is a semi-enclosed coastal body of water which has free connection with the open sea and within which sea water is measurably diluted with fresh water derived from drainage.

Earlier investigations of marine and littoral environments were mostly concerned with textural and morphological changes in response to wind induced waves and tidal currents. With the development of estuarine hydraulics, investigations on the interaction between tidal, fluvial waters and waves governing various forms of circulation gathered momentum. Even to-date, however, understanding remains in a state of "flux". This is so as the regime of a tidal portion of a river is essentially a manifestation of a complex interaction of the different parameters with their differing degrees of predominance generating a time-dependent "mixing" characteristic within the estuary governing the sedimentation process. While conception remains probabilistic, any assessment involves assumptions.

### 2.2 Principal Parameters in Sedimentation Process (R & D Report, 1986)

#### 2.2.1 Fluvial Water

Quantities of fresh water entering estuaries depend on the climate, physiography, geology and vegetation cover of the hinterlands. Estuaries with large and varied catchment areas may receive smoothened discharges with seasonal peaks. Sudden peaks cause sand movements in waves.

2.2.2 The Tides

In contrast to the largely unpredictable inflow of fluvial water from the upstream into the estuary, the incursion of tidal waters is mostly regular and predictable altering according to the procession of spring and neap tides occasionally modified by storms and sustained variations in barometric pressure. Strong tides occur in March and September influencing remarkably the pattern of sediment movement. Again considering the Bay of Bengal, commencement of strong southerly breeze from February onwards raises the mean sea level in summer and monsoon months. Tides are weak in winter months, strong between February and May, relatively weak in monsoon. Tides are semi-diurnal in lower latitudes and diurnal in higher.

2.2.3 Salinity Intrusion

Variation of salinity introducing horizontal and vertical gradients of dense water is a typical characteristic in an estuary setting up "Circulatory" and "mixing processes". A complete range of salinities from fresh water to sea water is always found with the meeting of fresh water and sea. Vertically, character of the water changes within extremes. With the super-imposed flood and ebb tides, salinity variations are often remarkable within a small area. These variations are local and transient. However, they have a profound effect on sediment movement. Generally, vertical salinity difference less than 5 ppt renders the estuary "well-mixed" and amenable to quantitative estimation of sedimentation within empericism.

2.2.4 Wind and Waves

Wave induced sediment movement occurs following the motion of waves due to a "raised" sea. The waves generate orbital velocities over the bed setting bed sediments in motion. Their direction of incidence and intensity as a function of angle of approach to the flow, height, wave length determine the processes of movement of sediment. This is one of the least understood of modern sedimentary dynamics.

2.2.5 Coriolis Force

The coriolis force - an inherent dynamism imposed by the rotating earth - is alleged to have a permanent effect on the curvature of channels in a wide estuary. Thus the circulation pattern of the estuary determining the sediment transport is influenced by this force. Again, this acts differently in the northern and southern hemispheres. The radius of curvature of the channel in the outer estuary of the Hooghly was computed as 18 km. to balance the coriolis force. The estuary exhibits such radii.

## 3. Sediment Transport in a tidal waterway

It is always rewarding to visualise the interaction of flow and the bed sediments for a concept of the sediment movement. While freshet flow is unidirectional, it is initially retarded in the upper reaches of the estuary and becomes oscillating as the tides predominate. In such a case, the mixing of the fresh water with the sea water becomes complete in the vertical direction. If the freshet discharges are very high overcoming the tidal forces, the discharge flows unidirectionally towards the sea over the tides and a "stratified" or "partially mixed" estuary emerges.

### 3.1 Source of sediments (Biswas, 1977)

The sources of sediments in estuarine transport could be—

— Primary
— Secondary

Primary sources are those from which sediment commences its journey into the tidal section. The secondary sources are those involving movement of materials within the estuary. The importance of the sediment added from the river varies with time and certainly from one waterway to another. The rate of erosion of terrestrical materials, and, therefore, the yields of sediment entrained by river are controlled by such multivariate parameters as relief, lithology, climate and human interference. All tidal waterways receive perhaps some sediment through the sea as well. This source is, however, not easily established. The usual methodology to identify such sediment is by artificial or natural tracer analyses. The temporary or final distribution of sediment type in an aquatic environment is a result of "hydraulic sorting" and "deposition".

### 3.2 Interaction of flow and sediment

The pattern of bed movement in a tidal waterway is very revealing. Naturally, information can be derived only through studies in a glass-walled flume and through an echo sounder mounted on a vessel. Investigations have shown that with the turn of the ebb tide, the sand bed of the channel is covered by dunes built by the high sustained velocity during ebb. These dunes are covered by small ripples originating during the ebb. As the flood flow from the sea sets in towards the "landward" direction of the flood. With higher velocities, the ebb ripples disappear. Flood dunes emerge, larger than the ebb dunes. With fall in flood velocities, smaller ripples and dunes form over the larger dunes. The pattern of sediment movement is always out of phase with the velocities. Velocities are off phase with the water level in the time co-ordinate. Fig. 1 demonstrates the phenomenon of phase difference in the hooghly estuary. (Biswas et al, 1991). In a tidal river of movable bed, the bed configuration at no time corresponds to the instantaneous flow condition. The accelerating and deaccelerating flow in either direction introduces further "inertial" effects. Laboratory experiments cannot exclusively reproduce the prototype phenomenon due to differences in dimensions of bed forms in flumes and large and deep flows. Evaluation of transport is often sought within the conception of unidirectional flow.

### 3.3 Evaluation of sediment transport

The tidal flow is "unsteady gradually varied". Transportation, deposition and erosion of sediments in such an environment should always be assessed as rather a "resultant" phenomenon over a period of time, instead of very short durations of an hour or a day as in unidirectional flow. It is the net erosion or deposition or transportation covering a period of several tidal cycles which determine the "morpho-sediment regime" of a tidal waterway.

— Three methodologies are available in the state of the art of evaluation presently, viz.,

- — Prototype experimental model
- — Qualitative model
- — Quantitative model

#### 3.3.1 Proto-experimental

The methodology involves estimation of direction, intensity and extent of movement of sediments through injection of natural or radio active tracers. Natural tracer may be dyed sediments of the river. Radio active tracers utilise activated glass beads with a size distribution similar to that of the bed of the waterway. The radio isotope Scandium 6 with a half life of 3 months is used. A typical result of a study in the Hoogly at 160 km. downstream of Calcutta appears in Figs 2 and 3. The isotope was "point" injected during the "flood tide" to infer on the predominant direction of movement of dredged spoil dumped extensively over the area of injection from the navigation channel located about 7 km. to the west. The tracking was after one month of the injection i.e. 60 tidal cycles. It appears that—

- — predominant movement is upstream
- — net rate of movement is 1000m upstream
- — longitudinal dispersion of sediments predominate over lateral dispersion

With more simultaneous data on velocities, a quantitative estimate may also be attempted.

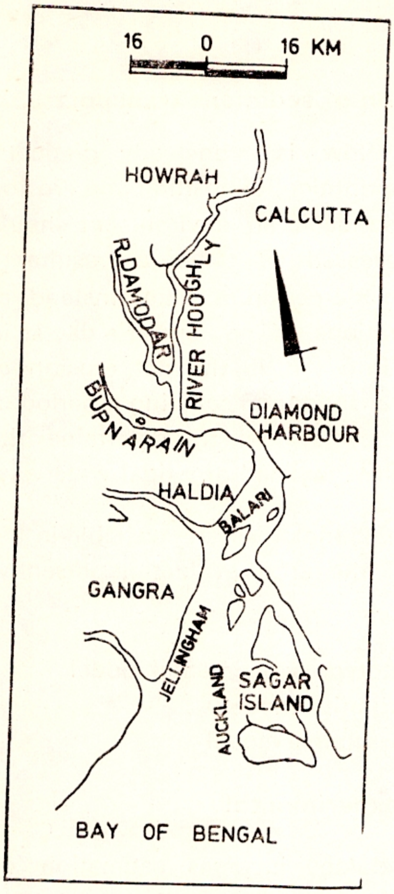


FIG. 1.1 INDEX PLAN

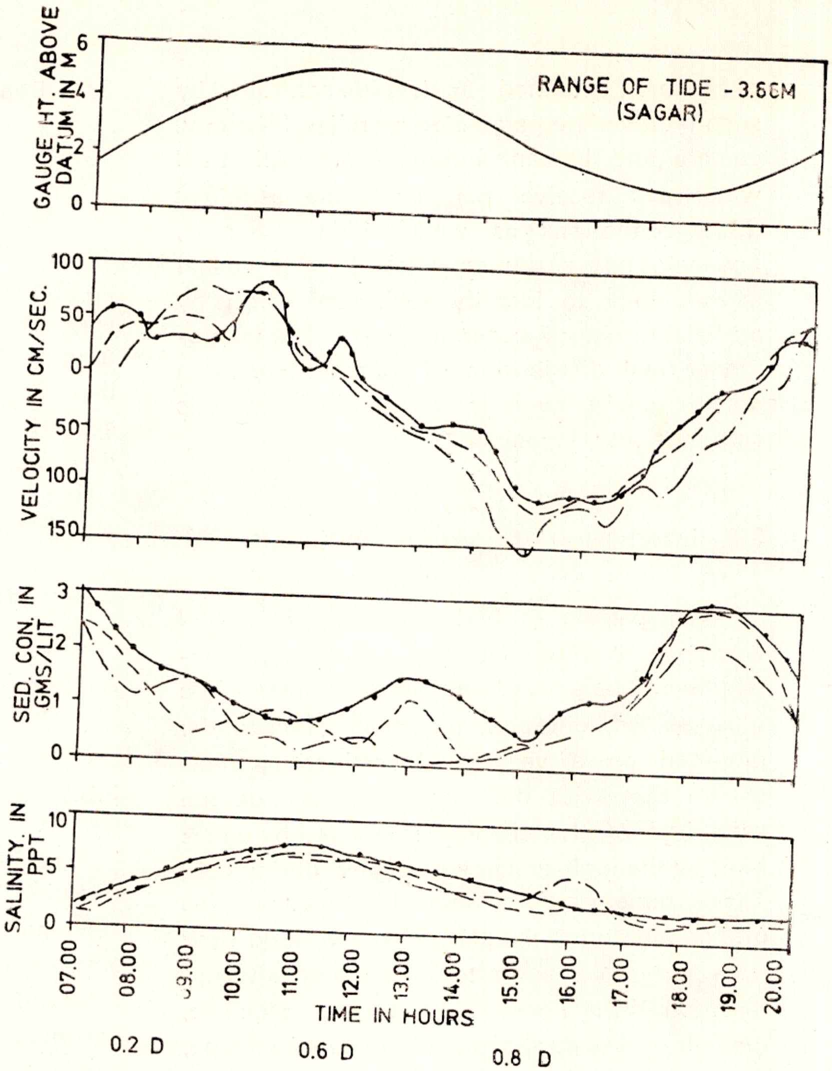


Fig. 1.3 Time Variation of Velocity Sediment Concentration and Salinity

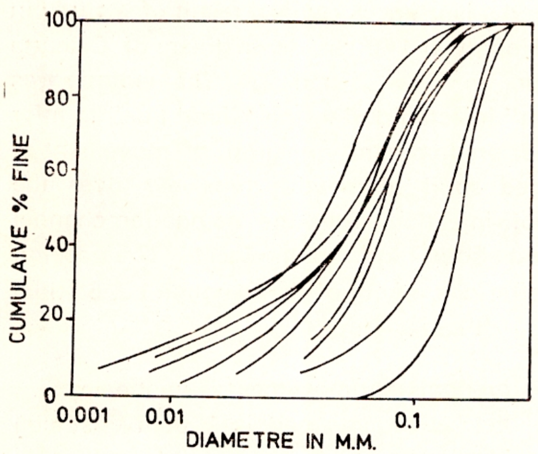


Fig. 1.2 Size Distribution of bed Material in the Estuary

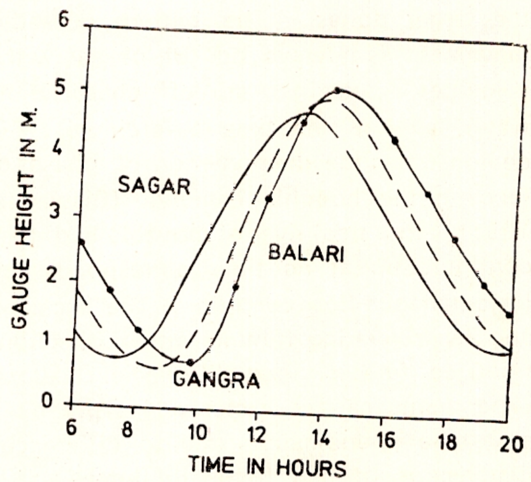


Fig. 1.4 Tide Curves at Estuary

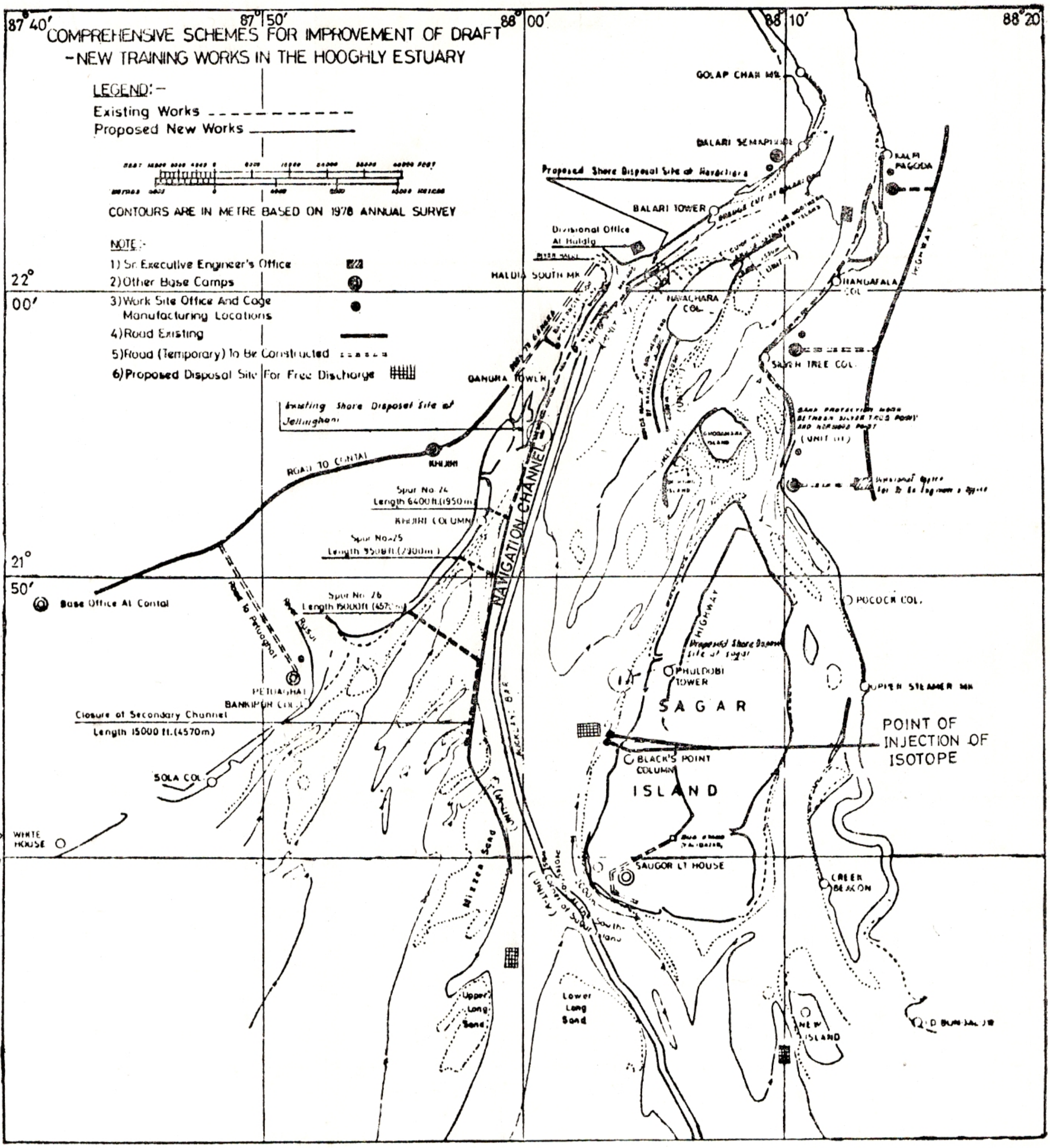


Fig. 2 Outer Estuady of the Hooghly

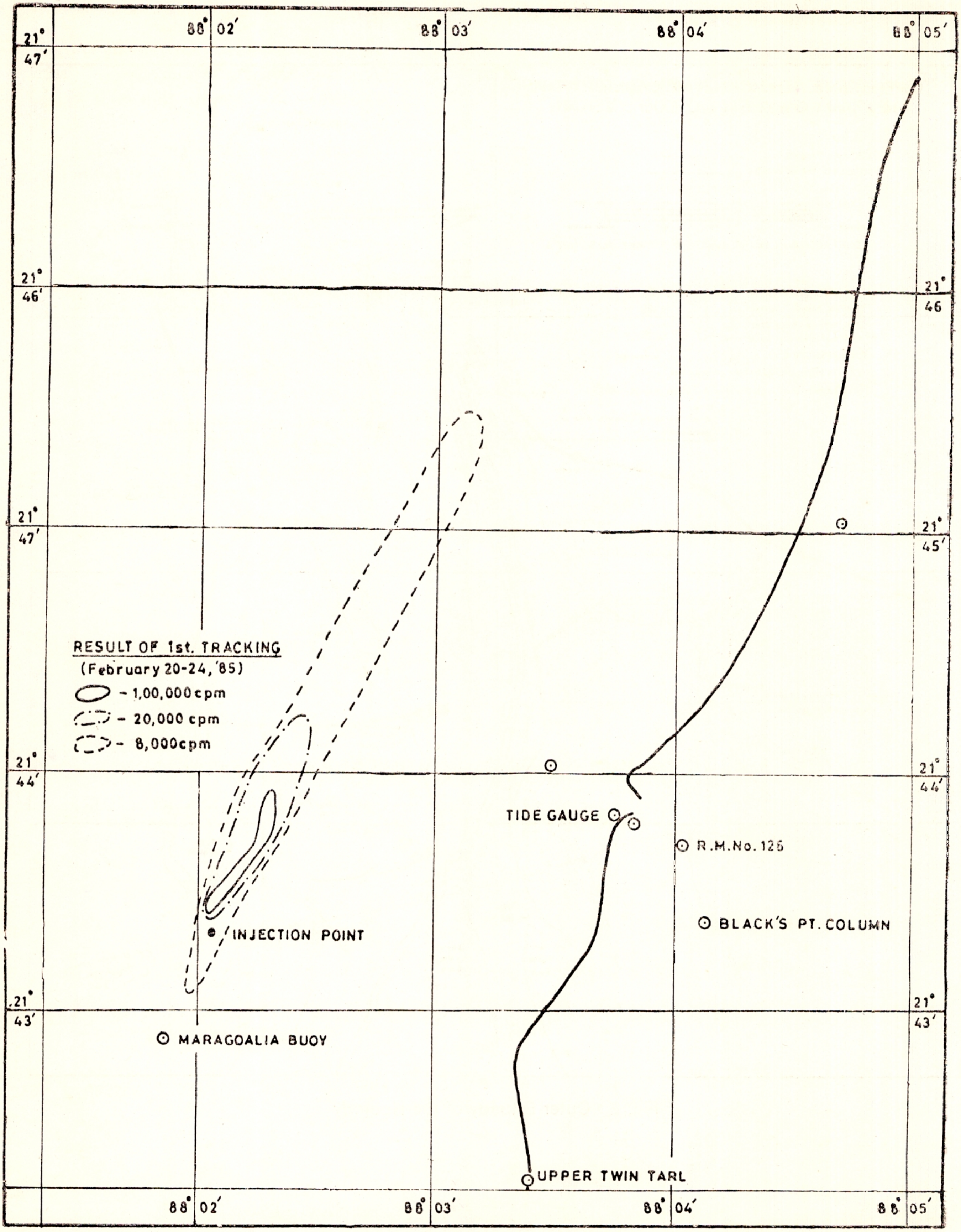


Fig. 3 Radiotracer Study in Hooghly Estuary

### 3.3.2 Qualitative model

Quantum of sediment in motion with the flow may be expressed as an exponential of the velocity of flow as follows :

$$q_b = V^n \quad \ldots \quad (1)$$

where $q_b$ : bed load transport per unit width per second

$V$ : mean velocity of flow during flood or ebb

$n$ : exponent

The relationship follows the Einstein-Brown model and also the sixth power law of stream competence. Predominance of transport is expressed as—

$$P_F = \frac{\int_{O}^{T_F} (V_F)^6\, dt.}{\int_{O}^{T_F} (V_F)^6\, dt + \int_{T_F}^{T_E} (V_E)^6\, dt} \quad (1)$$

where $P_F$ : Flood tide predominance

$V_F$ : depth average flood velocity

$V_E$ : depth average ebb velocity

$T_F, T_E$ : times of high water and low water slacks

A flood predominance diagram at a station on the Hooghly estuary, State of West Bengal is shown in Fig. 4 (Nag et al, 1969). Velocities were obtained from 1-D numerical model.

### 3.3.3 Quantitative model

#### 3.3.3.1 Sediment transport measurements

Valuable information on quantitative estimate of sediment transport may be had from planned hydrological measurements on velocities (V) sediment concentration (S) and water levels along the estuary at selected stations. Quantitative estimate of movement is

$$q_s = VDS \quad \ldots \quad (2)$$

where $D$ = depth of flow.

REPRODUCED FROM THE PROCEEDING OF THE INTERDISCIPLINARY SYMPOSIUM ON THE BHAGIRATHI-HOOGHLY BASIN, CAL. UNIV, INDIA, PP-95

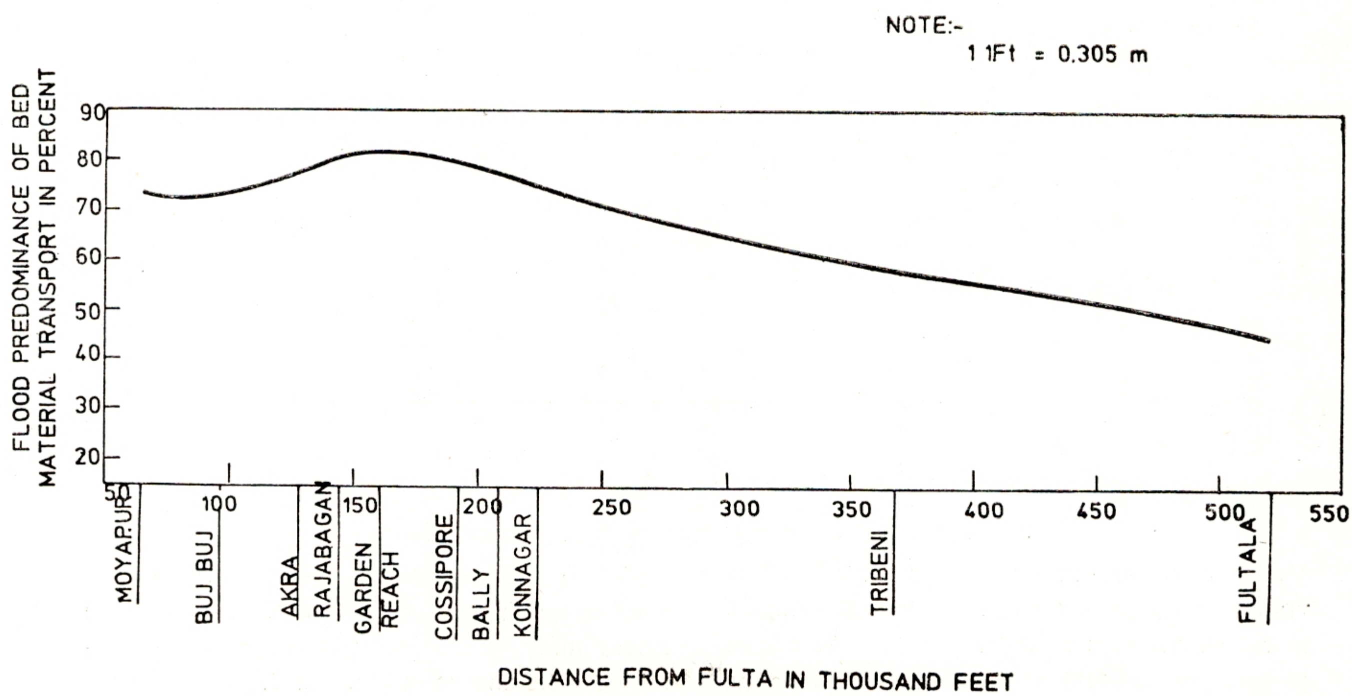


Fig. 4 Flood Predcminance of bed material Transport Tide : 4th May 1962 Range at Saugor-15′-5″

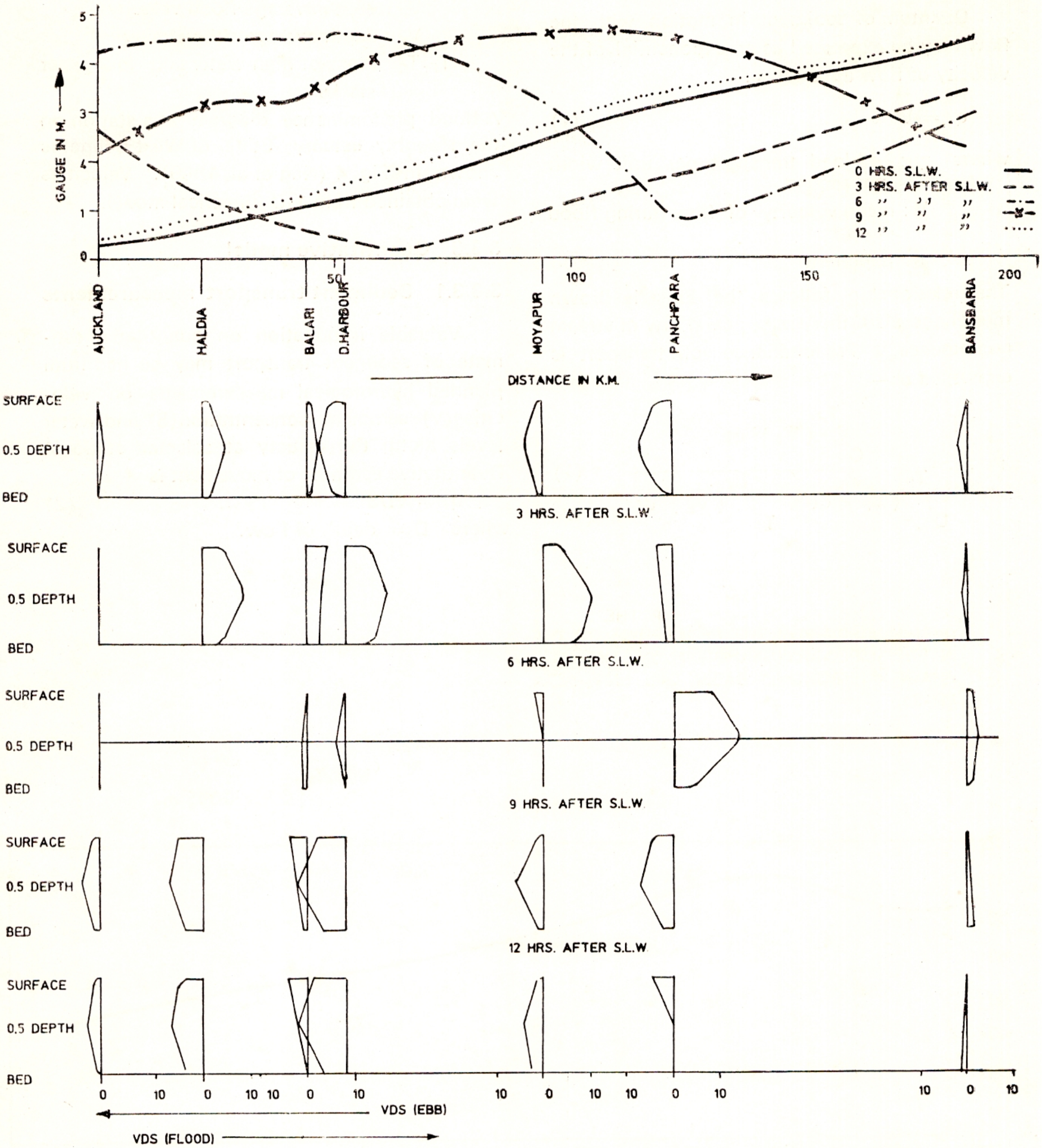


Fig. 5 Pattern of Sediment Movement in Hooghly Estuary

Methodology of measurements may be by "point" samples or "depth-integrated" samples with simultaneous recording of velocities (Biswas et al, 1991). The method gives the transport of sediments in suspension and is useful in estuaries with overwhelming movement of sediment in suspension. Results from a case study for the Hooghly spread over several years are shown in Fig. 5 & 6.

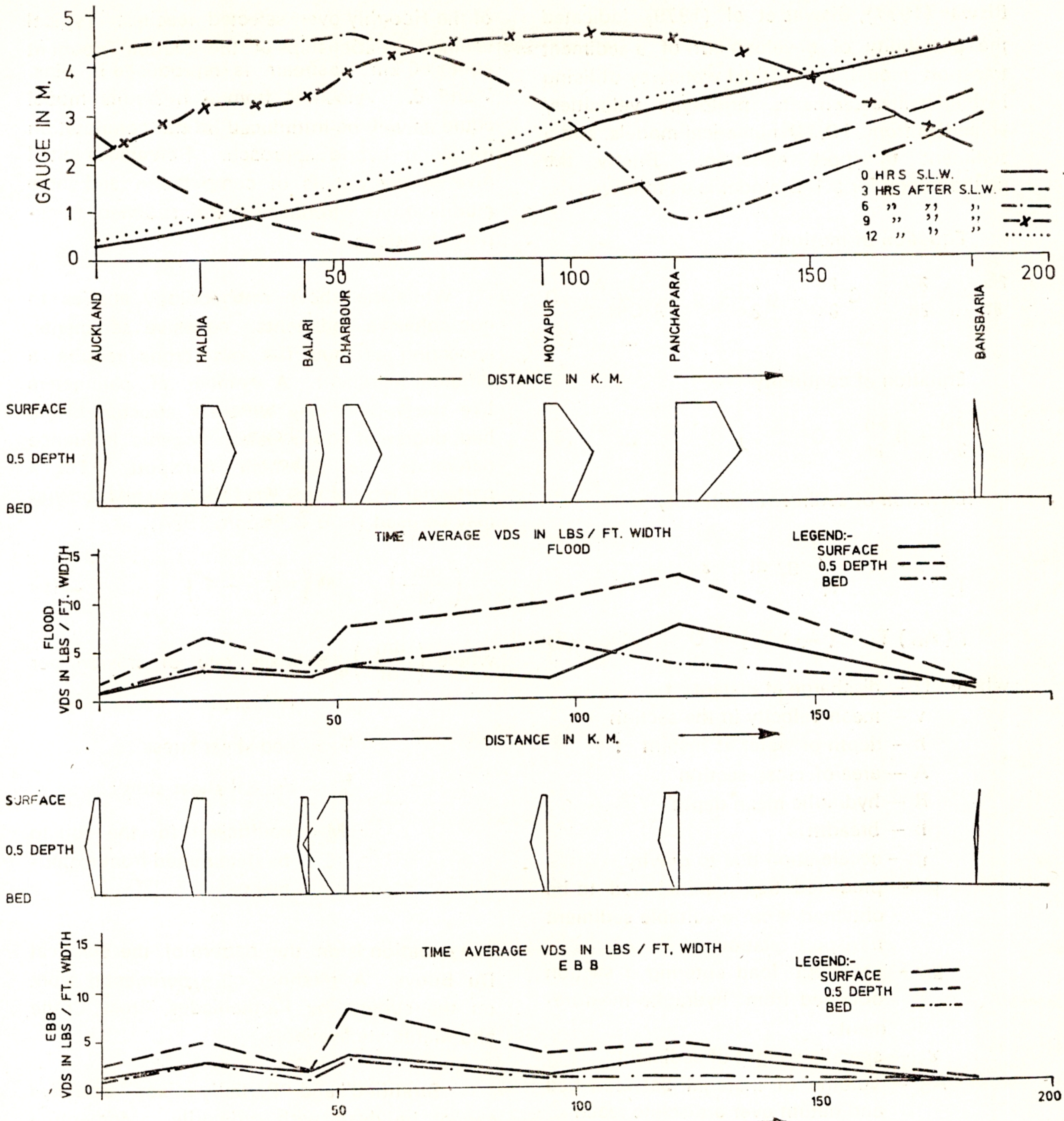


Fig. 6 Time Average Sediment Movement During A Tidal Cycle in Hooghly Estuary

### 3.3.3.2 Simulation models (Biswas et al. 1987)

Application of simulation principles to physical phenomena in environments of manifestation of a wide array of interacting parameters involve the numerical, hydraulic and electric analogue models through selected relationship and mathematical equations representing the phenomenon. Biswas et al (1974), Biswas (1977), Biswas et al (1979) indicated the possibility of development of a sediment transport model for a tidal waterway utilising hydraulic measurements, prototype velocities/ velocities from 1D/2D numerical models, and a sediment transport equation. Briefly, the methodology for a 1-D model is as follows :

Equation of motion

$$\frac{\partial Q}{\partial t} + V\frac{\partial Q}{\partial x} + Q\frac{\partial v}{\partial x} + g\frac{\partial h}{\partial x} + g\frac{Q \mid Q \mid A}{A^2C^2R} = O \quad \ldots \quad (3)$$

Equation of continuity

$$\frac{\partial Q}{\partial x} + b\frac{\partial h}{\partial t} = O \quad \ldots \quad (4)$$

Equation of sediment continuity

$$\int_{T_1}^{T_2} g_m' \, dt - \int_{T_1}^{T_2} g_c' \, dt + \gamma_s$$

$$[ ( A_D ) T_2 - ( A_D ) T_1 ] = O \quad \ldots \quad (5)$$

where Q — discharge at instant t
v — mean velocity in the section
h — depth of water at instant t
A — area of cross-section
R — hydraulic mean depth
b — breadth
g — acceleration due to gravity
$g_c'$ — predicted bed material load to be obtained from a suitable sediment transport relation
$g_m'$ — sediment load entering a section obtained from hydraulic mearurements
$\gamma_s$ — specific weight of sediment
$A_D$ — volume of material between bed and datum over a discrete reach

$T_1$, $T_2$ — time limits of model operation.

Using the Einstein's relationships for sediment transport to compute g'c in Eq. 5 with velocities from the numerical model (Eq. 3 & 4) and from hydraulic measurements, it was possible to compute deposition over the bed of the estuary of the Hooghly over selected reaches. Typical sediment relationships at the Station Tribeni at about 60 km. upstream is reproduced in Figs. 7 and 8. Velocities from a hydraulic model could as well be introduced in the computation involving hybrid approach. References cited give briefly details of computation and some modifications introduced in the sediment transport equations.

While the above methodology applies to non-cohesive sediments, cohesive sediments, appearing as mud flat out crops require a different treatment. A number of parameters like the type of clay minerals, structure of the bed, degree of consolidation organic influence determine the sediment transport. For a particular type of soil, the following relationship may be used (R & D Report, 1986).

$$\left(\frac{dm}{dt}\right)_e = M\left(\frac{T_b}{T_c} - 1\right) \quad \ldots (6)$$

where $\left(\frac{dm}{dt}\right)_e$ = mass rate of erosion per unit area

$T_b$ = bed shear stress

$T_c$ = critical shear stress

M = coefficient for the soil to be determined from experiments.

The equation is on the pattern of the classical Du Buoys. A plethora of experimental work on the subject by Partheniades, Cross, Crone and Mehta are available.

"Stratified" and "Partially mixed" estuaries cannot be dealt with ordinarily, Momentum and continuity equations need be solved for upper and lower layers connectad by an inter facial shear stress (Mc, Dowell and O'Connor, 1977). It is felt that specific problems of sediment transport in such estuaries may be solved through extensive hydraulic measurements to calibrate numerical models.

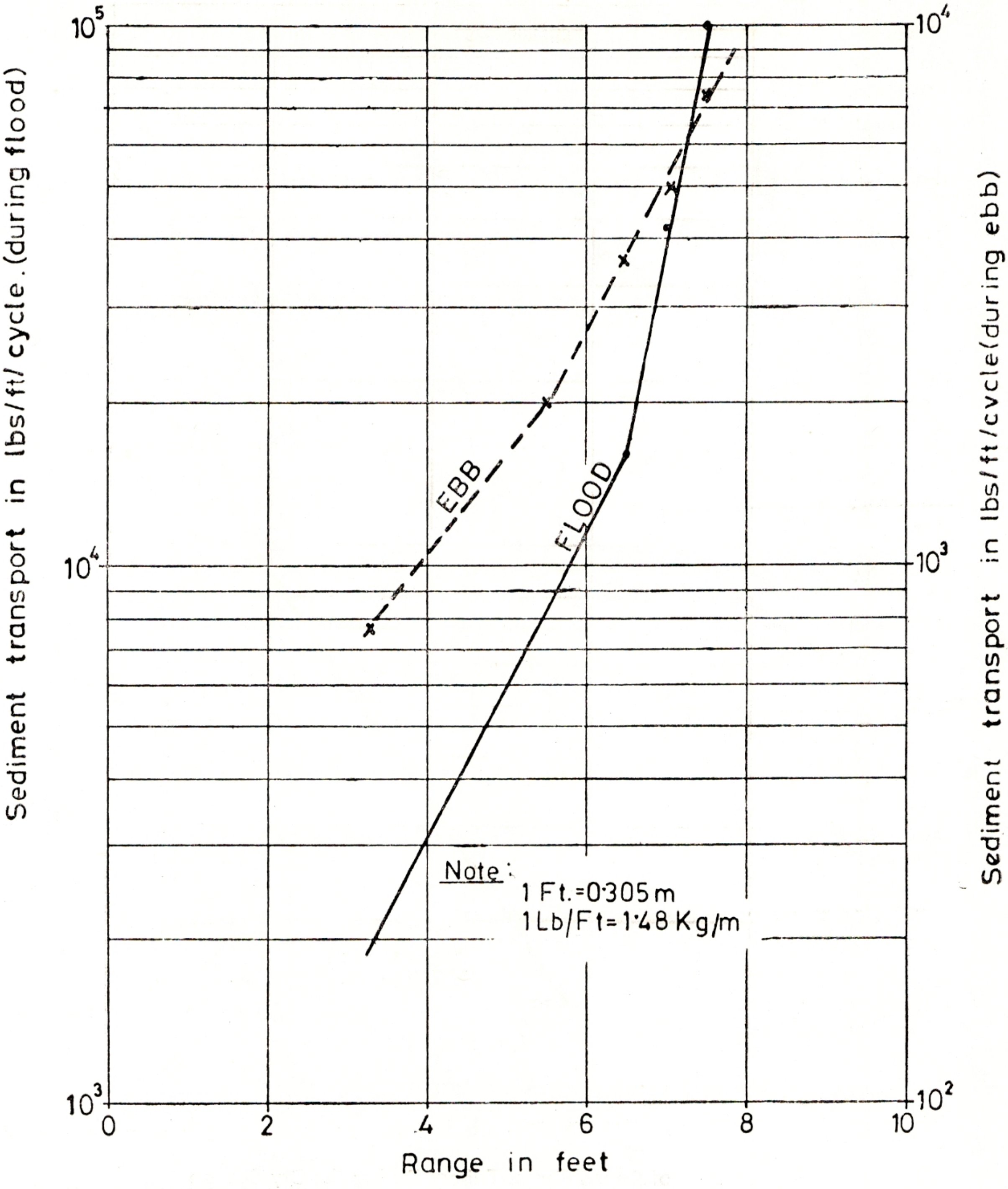


Fig. 7 Rating Curve Measured Sediment Load-Vs-Range From Observation at Tribeni

3.3.3.3 Sediment Transport due to waves

Within a tidal waterway, sediment transport following only wave action occurs near the "slacks"; otherwise, it is always the combination of waves and currents. The short period waves approaching the waterway from the sea get distorted under the influence of estuarine currents. Waves may approach oblique to or a thwart to or in unision with the direction of

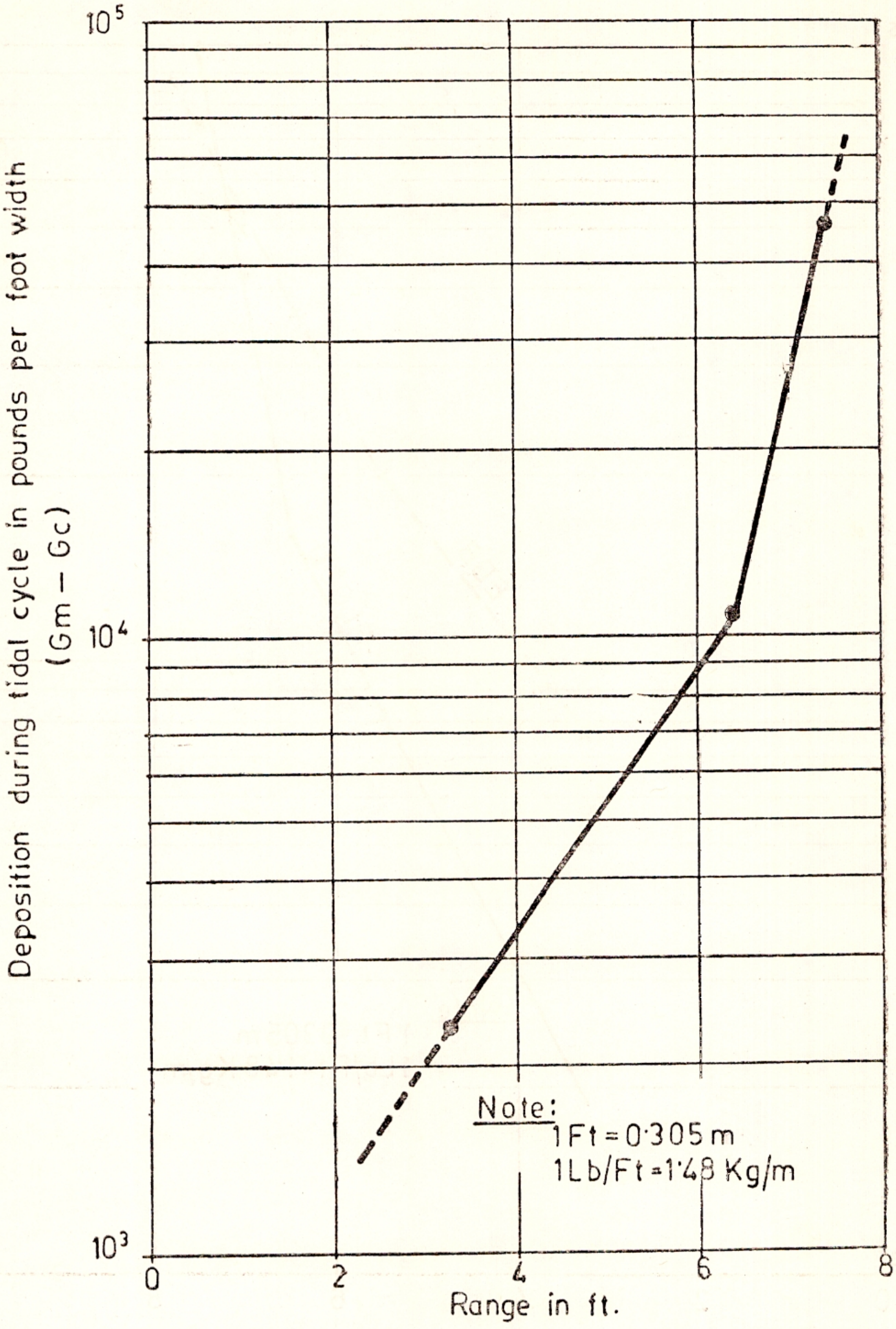


Fig. 8 Rate of Deposition at Tribeni During the Dry Season

the currents. All these conditions may occur over the same tidal cycle. Sediment transport due to currents and waves may be computed separately and then synthesised, Einstein-Brown type relationship may be adopted (Per Brunn, 1978).

While waves have to be considered in sediment transport in large open estuaries, they have little significance in large open estuaries, they have little significance in deep narrow estuaries (Mc Dowell and O'Connor, 1977).

## 4. Discussion

It has to be recognised that an alluvial tidal waterway is perpetually in the stage of seeking adjustment with the hydrological and meteorological dynamism. Its morphology is continually under "short" term seasonal changes viz. monsoon and summer and "long" term variation due to coastal changes and global changes in mean sea level. It is important to conceptionally visualise the pattern of sediment circulation erosion and deposition, specially for public utility services like navigation, provision of jetties, location of water intakes and the like. Presentation so for clearly suggests the following in context to sediment transport :

— A phaselag exists between sediment concentration, velocity and water level at any instant;

— At no time, tidal flow occurs over a bed formation corresponding to the velocity of flow at that instant;

— Coefficient of resistance remains in a state of continuous variation;

— Application of existing sediment transport relation for uniform unidirectiohal flow is possible over discretised time internals;

— The net change i.e. deposition or scour over the bed is relevant for any assessment than rate of sediment transport.

— Degree of mixing of salt water from the sea and the fresh water from fluvial discharge generate specific types of estuaries. Sedimentation pattern is governed by the degree of mixing;

— Non-cohesive/cohesive character of the bed sediment also govern the sedimentation pattern;

— Waves superimpose their effects on the tidal current dominated sediment transport. In isolation, sediment transport due to waves may be analysed through existing transport relations with modification.

## 5. Resume

Mechanism of net sediment transport on an alluvial tidal waterway may be realised through qualitative and quantitative methods. It is essential to precede these investigations through a detail hydro-metero-morphological analysis, A conception has to emerge on the "short" and "long" term changes in the waterway. A judicious synthesis of the study with that of sediment transport can then allow a picture of the circulation, deposition and scour pattern to emerge. The well-documented studies of the estuary of the Hooghly illustrates such an approach (Biswas, 1983).

## References


1. Biswas, A.N, (1977) : "Morphological changes in an alluvial channel due to sedimentation processes with reference to the Bhagirathi-Hooghly river system in the Indo-Gangetic Delta", Ph.D. Thesis, Jadavpur University, Calcutta, p. 79.

2. Biswas, A.N. (1983) : "Geo-hydro-morpho metry of the Hooghly Estuary". Jl. of Inst. of Engrs. (India), Vol. 66, Part Cl 2, September, p. 61-73.

2. Biswas, A.N. and Chakraborty, A (1974) : "Sediment Transport in a Tidal River", Jl. Hyd. Div. Am. Soc. C.E Vol. II, Hy II, Nov. pp. 1677-1689.

4. Biswas, A.N., Chatterjee, A K. and Mazumder, N.C. (1987) : "Simulation studies for Alluvial Estuarine Improvement" Jl. of Irrig. and Power, Special issue, Diamond Jubilee p. 61-74.

5. Biswas, A.N. and Ghosh, S.N. (1991) : "Suspended load measurements in Alluvial Channels", Workshop lead paper on Sediment Measurements by CBIP, Hyderabad.

6. Biswas, A.N., and Mitra, B (1979) : Assessment of Resholaling in a Dredged cut in a Tidal Alluvial Waterway, J. of Irrig. and Power, July, p. 319-328.

7. McDowell, D.M. and O'Connor, B.A. (1977) : "Hydraulic Behaviour of Estuaries" published by the Macmillan Press Ltd., London, pp. 112.

8. Nag, S.K. and Sen, A (1969) : "Mathematical model for the upper reaches of the Hooghly River", Proc. 39th Annual Research Session, CBIP, Ahmedabad, India, Vol. 1B, July, 1969, pp. 198-207.

9. Per Brunn (1978) : "Stability of Tidal Inlets" : Elsevier Scientific Publishing Company, New York, p. 220.

10. R & D Report on "Assessment of Siltation in Artifically Developed Shipping Channel in estuaries with reference to the Eastern Coast (1986)", study sponsored by Ministry of Shipping and Transport, prepared by Hydraulic Study Deptt., Calcutta Port Trust, India with compilatien by Dr. A.N. Biswas. Chief Hydraulic Engineer, p. 6-13.