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# A PRELIMINARY INVESTIGATION OF FINE SEDIMENT DYNAMICS IN CUMBARJUA CANAL, GOA

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## ABSTRACT

A preliminary field investigation was carried out in a 10 km reach of Cumbarjua Canal, Goa, where the sediment is in the fine size range, and the flow is primarily tide-induced. Results based on observations made during February, 1980, suggest that in fair weather, under typically moderate tides, the suspended sediment concentrations are low, and the shearing rates in the flow are low to moderate. Aggregation of the flocculated kaolinitic sediment occurs, but the aggregates have low settling velocities of the order of $10^{-4}$ m/sec. The rate of sediment transport is generally low as well. There appears to be a net transport of sediment from Zuari River towards the Tonca-Surlafenda region where consolidated shoals have formed. Wind-induced waves play a significant role in contributing to the suspended sediment load.

*Key-words* : Fine sediment, dynamics, Cumbarjua.

## INTRODUCTION

An important aspect of estuarial management is the ability to estimate the rates of scour and shoaling in areas of critical concern including dredged canals, waterways and harbor basins where an undesirable degree of sedimentation often occurs. The sedimentary regime of these water bodies is often characterized by the presence of fine, cohesive sediments which are transported in suspension. Laboratory investigations pertaining to the basic aspects of fine sediment transport have yielded useful descriptions of the transport behavior of these sediments (Mehta, Parchure, Dixit and Ariathurai, 1982; Hayter and Mehta, 1982). Unfortunately, adequate prototype information is generally lacking, and there is a need to obtain comprehensive sediment-related data in comparatively well-defined tidal water bodies.

The development of a field measurement programme at the National Institute of Oceanography, Goa, for the purpose of improving upon currently available estuarial sediment-related data was the primary motive behind the present investigation. Cumbarjua Canal, Goa, which was selected for this purpose, offers three basic advantages. These are: (i) it has a reasonably well-defined, two-dimensional geometry and a tide-dominated flow regime, (ii) the bottom sediment is predominantly in the fine size range, and (iii) it is at a commutable distance from the Institute. The canal (Fig. 1) is used by ore

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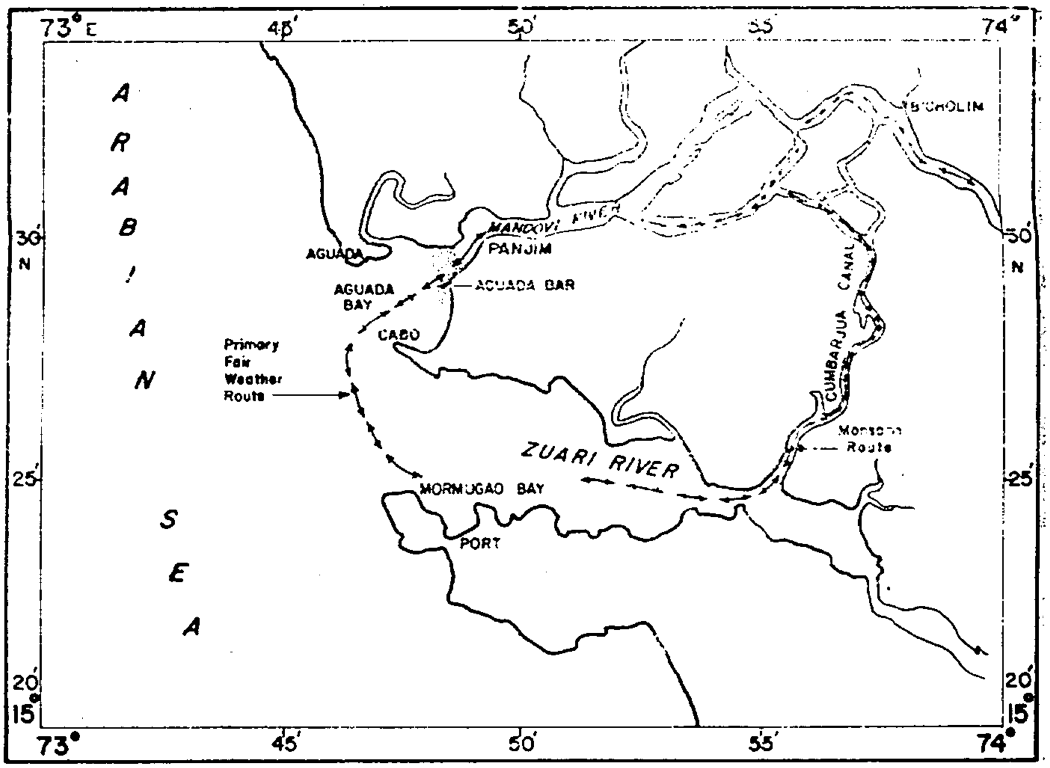

Fig. 1. Cumbarjua Canal, Goa.

carrying barges during monsoon when the fair weather route through Mandovi River via Aguada Bar (to the port of Mormugao) is closed to vessel traffic (Mehta and Bruun, 1981; Mehta and Bruun, 1983). The hydrodynamic regime of the canal has been studied previously (Das, Murty and Varadachari, 1972; Rao, Cherian, Varma and Varadachari, 1976). The present effort was mainly concerned with sediment movement in a 10.4 km reach of the canal from Tonca to Banastarim (Fig. 2). The data were collected in February, 1980. These included a hydrographic survey, flow discharge measurements, bottom sediments and an observation period of approximately 10 hours over which tides, currents, suspended sediment concentration and wind were measured simultaneously at four stations (Fig. 2). Results of the investigation are summarized here; details are given elsewhere (Mehta and Hayter, 1981).

## RESULTS AND DISCUSSION

### *Canal characteristics*

With reference to Fig. 2, the canal width decreased from 320 m at Tonca to 100 m at Banastarim. The corresponding mean depths were 2.5 m and 3.7 m, and the maximum depths were both equal to 6.1 m. The dimensions of the four cross-sections are given in Table 1. A portion of the canal had

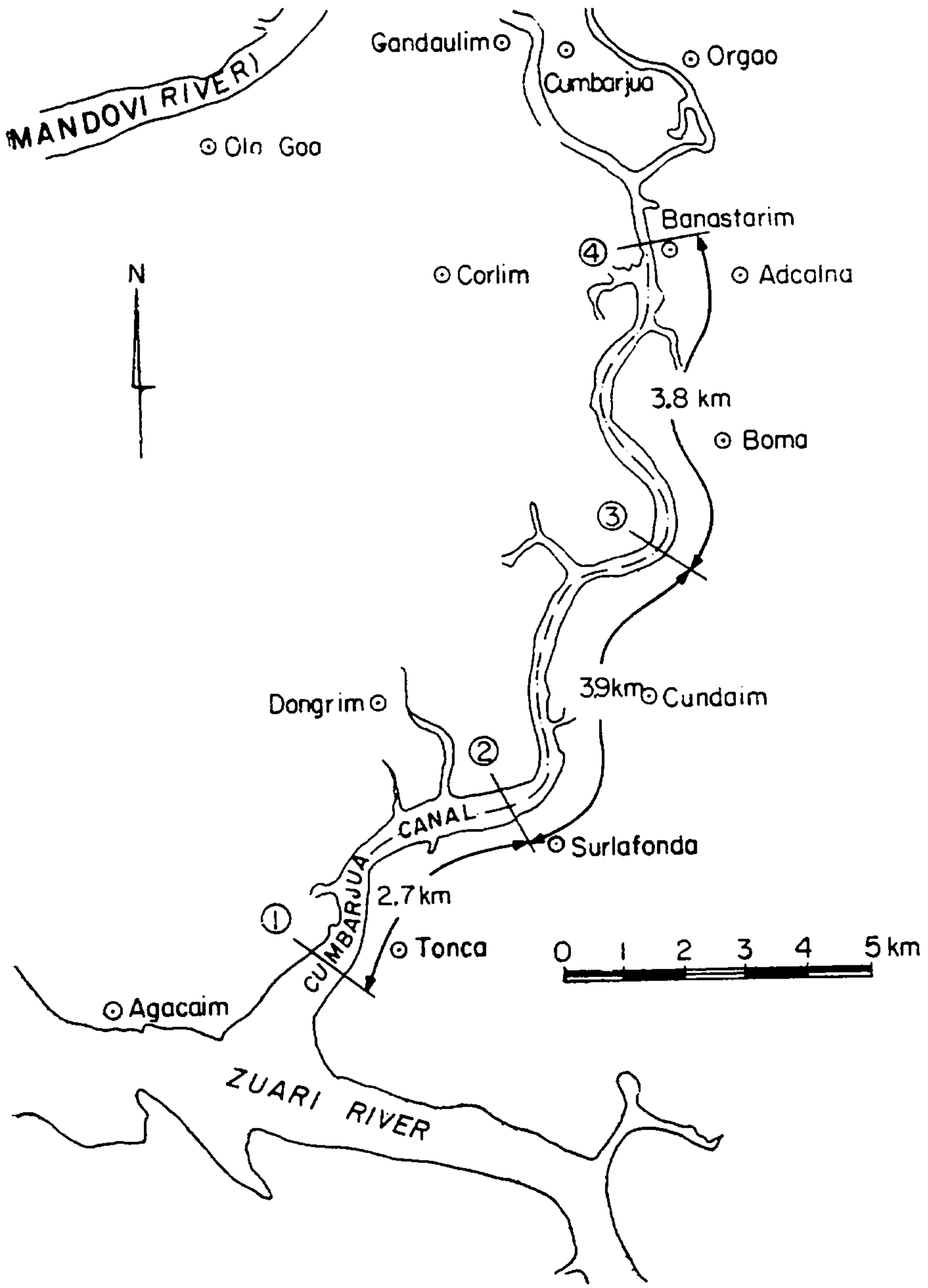

Fig. 2. Canal reach investigated together with station locations.

Table I. Dimensions of four canal cross-sections relative to selected mean tidal datum.

| Section | Mean Depth (m) | Maximum Depth (m) | Width (m) | Area ($m^2$) |
|---|---|---|---|---|
| 1 | 2.5 | 6.1 | 320 | 800 |
| 2 | 3.3 | 7.1 | 150 | 495 |
| 3 | 2.6 | 4.3 | 200 | 520 |
| 4 | 3.7 | 6.1 | 100 | 370 |

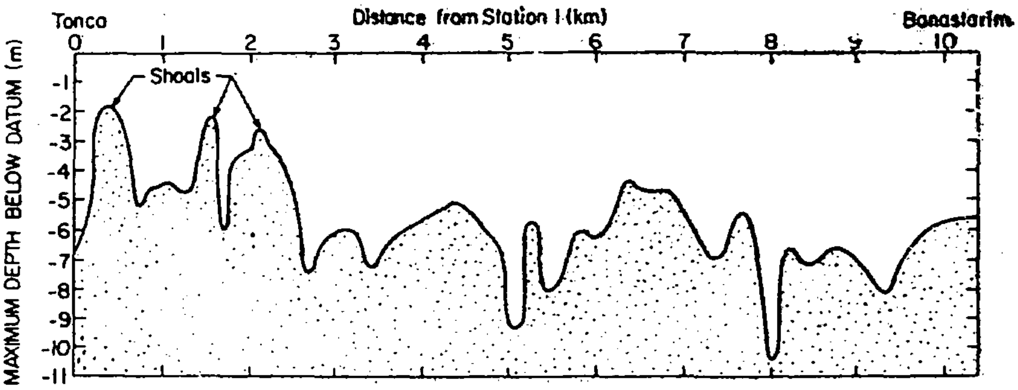

Fig. 3. Centerline depth profile between stations 1 and 4.

been dredged some time prior to the investigation to accommodate larger (1,000 DWT) barges. Fig. 3 shows the centreline depth profile of the 10.4 km reach between stations 1 and 4. Significant shoals occurred in the segment between stations 3 and 4. These shoals did not, in general, extend laterally across the entire width of the canal. Thus the observed depths over the shoals should not be construed as the controlling depths in the navigable channel, which did not everywhere run along the canal centreline. Along the entire canal (at low tide when the muddy banks were exposed), small holes made by various types of burrowing macroorganisms were observed. Apart from the fact that these organisms tend to actively participate in the reworking of the benthic sediments, the resulting perforated bed surface could be expected to increase the bottom roughness. Increased roughness enhances the form drag and hence the energy dissipation at the bed. Experimental evidence indicates that burrowed bed surfaces are generally more erodible than beds without burrowing (Rhoads and Young, 1970).

The sediment consisted predominantly of kaolinite plus illite, montmorillonite, quartz and some organic matter (7% by weight). The size distribution was primarily in the fine range, i.e., clay plus silt (Fig. 4). The remaining fine sand portion which constituted less than 5% by weight of the sediment near the upstream end of the study segment, i.e., Cundaim-Banastarim increased somewhat in the direction from Banastarim to the Zuari end of the canal.

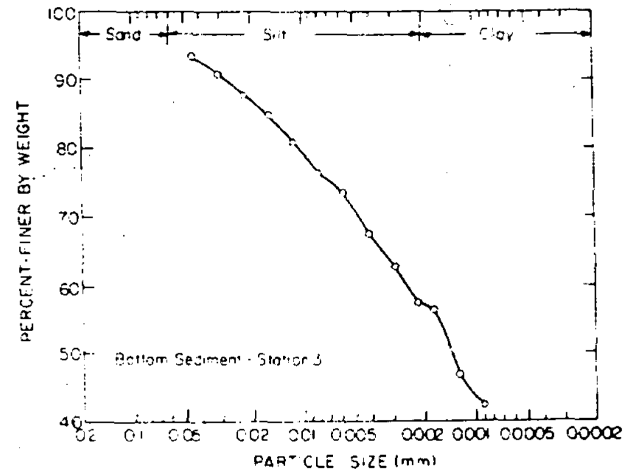

Fig. 4. Grain size distribution of the bottom sediment at station 3. near Cundaim.

The fluid was slightly basic, with pH 7.8. The salinity in the canal varies from near-zero levels in monsoon to as much as 36 ppt during fair weather (Rao, Cherian, Varma and Varadachari, 1976). The annual temperature variation is moderate (27° C – 32° C), and is not likely to be a significant factor governing sediment transport in the canal.

*Canal sediment transport*

The field investigation, together with an interpretation of the earlier studies revealed an interesting tentative description of the sediment transport regime in the canal reach, as noted below.

*Fair weather regime :* The fair weather (November–May), hydrodynamic regime is characterized by moderate tides of the order of 1 to 2 m and low freshwater flow. Fig. 5 shows tidal measurements obtained on February 27, 1980, at the four stations. The tidal range on this day was 1.4 m. In fair weather, the flow is generally mixed vertically, but a small longitudinal-gradient of salinity which typically decreases by 2 to 4 ppt over the reach, tends to occur (Rao, Cherian, Varma and Varadachari, 1976). The salinity (23 to 36 ppt) is well above the limit ( ∼ 10 ppt) below which particle flocculation is influenced by the amount of salt present (Krone, 1963). Under bed shear stresses induced by the prevailing tides, the bottom sediment appears to be fairly resistant to erosion. This observation is suggested by the occurrence of comparatively low suspended sediment concentrations of orders ranging from 10 to 100 mg/l throughout the year (Rao, Cherian, Varma and Varadachari, 1976). It is likely that the bed shear strength increases rapidly with depth due to consolidation, and that the sediment at 1 or 2 cm depth below the bed surface is resuspended perhaps only during spring tides, or when the flow is influenced by storm events. The sediment in suspension is primarily bed material

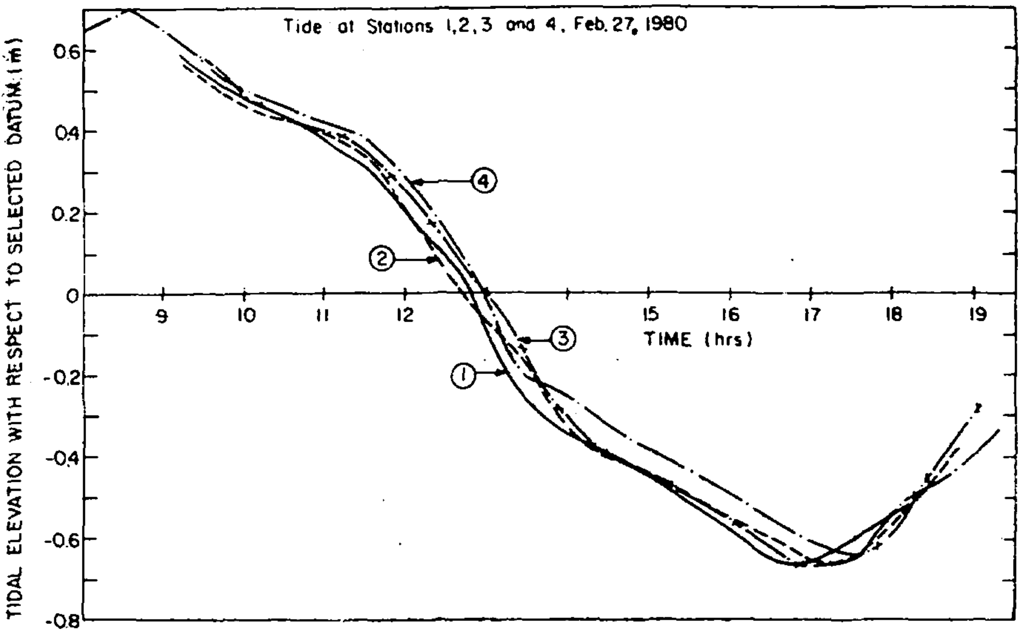

Fig. 5. Tide measurements at stations 1, 2, 3 and 4 on February 27, 1980.

with the exception of colloidal clay particles as well as a portion of the organic material which appears to remain in suspension at all times.

*Aggregation and shearing rates:* When the salt concentration in the fluid exceeds 1-2 ppt, fine sediments become cohesive. This is due to the predominance of attractive electro-chemical forces on the surfaces of these particles which possess relatively large specific surface areas i.e., surface area per unit weight (van Olphen, 1963). When subjected to repeated collisions, cohesive sediment particles form aggregates, with each aggregate consisting of thousands or even millions of individual clay particles.

In general, shearing associated with local velocity gradients is important as a collision mechanism in estuaries with relatively low suspended sediment concentrations such as Cumbarjua Canal. Given the collision mechanism, a range of aggregates of various orders are formed, with each order characterized by a given aggregate density and shear strength. Zero order aggregates are tightly packed units, and increasing order implies more loosely packed structural arrangements of decreasing density and rapidly decreasing shear strength. The shear strength and the density of each order are determined by the local velocity gradient-induced shear field, the type and availability of sediment, and the ionic composition of the suspending fluid. For a given sediment and fluid, the prevailing shearing rates in the flow will control the highest order of aggregation that can occur in the system. This is because while shearing promotes aggregate growth through collisions, it also limits the shear strength by breaking up aggregates whose strength is lower than that of the shear stress determined by the prevailing shearing rate. For example, in experiments using a specially designed viscometer in which the rate of flow shear was controlled, a kaolinitic sediment from Brunswick Harbor, Georgia, U.S.A., yielded aggregates ranging in order from 0 to 3 (Krone, 1963). The corresponding shear strengths were found to be 3.40, 0.41, 0.12 and 0.062 N/m$^2$. Thus the shear strength of the third order aggregate was less than 2% of that of the zero order aggregates.

Except during slack water, it is likely that the available sediment in the canal rapidly aggregates in a near-bed fluid layer where comparatively high shearing rates typically prevail. Such a near-bed layer tends to be saturated with aggregates of the lowest order that can be sustained in the layer (probably zero-order in the present case). During the period of increasing velocity when resuspension of the bed deposit occurs, the near-bed layer will gain sediment from the bed by erosion, and will at the same time lose sediment to the fluid column above, where the rate of shearing is lower and therefore higher order aggregates can form.

The rate of internal shearing in the fluid, G, averaged over the turbulent time-scale is obtained from

$$G = \frac{(f/8)^{3/4}\, u^{3/2}}{(k\nu)^{1/2}\, h^{1/2}} \left( \frac{1}{z/h} - 1 \right)^{1/2} \qquad (1)$$

where $z$ = elevation above the bed, $f$ = Darcy-Weisbach friction factor, $u$ = flow velocity, $k$ = Karman constant, $\nu$ = kinematic viscosity of the fluid and $h$ = depth of flow (Mehta and Hayter, 1981).

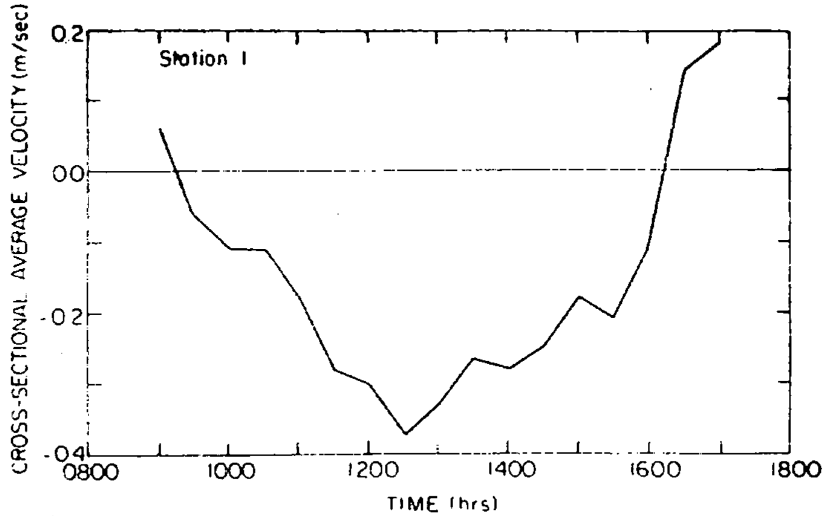

Fig. 6. Cross-sectional average velocity variation with time in canal at station 1.

Figure 6 shows the time-variation of the cross-sectional average flow velocity at station 1 based on measurements obtained on February 27, 1980 (Mehta and Hayter, 1981). The corresponding shearing rates, G, at relative elevations z/h = 0.1, 0.5 and 0.9 are given in Fig. 7. These computations are based on values of f = 0.046 (derived from measurements), k = 0.3 (for sediment-laden flows), $v = 1.06 \times 10^{-6}$ m2/sec, h = 2.5 m plus tidal variation according to Fig. 5, and the cross-sectional average flow velocity (Fig. 6). The shearing rates were comparatively low throughout most of the water column. Using the depth-averaged velocity in the deepest part of the cross-section instead of the cross-sectional average velocity, a maximum value of G = 14 $\sec^{-1}$ at z/h = 0.1 was estimated, as compared with G = 9.4 from Fig. 7 (Mehta and Hayter, 1981). Both the G values are relatively low.

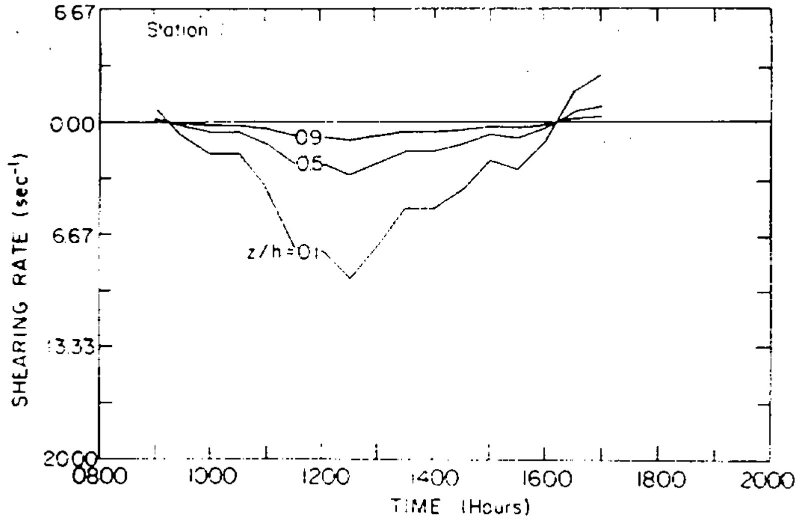

Fig. 7. Shearing rates in the canal at relative elevations z/h = 0.1, 0.5 and 0.9 at station 1.

At station 4, the G values were slightly higher. At z/h = 0.1, a maximum value of G = 34 $\sec^{-1}$ was estimated in the deepest part of the cross-section (as opposed to G = 16 $\sec^{-1}$ based on the cross-sectional average velocity). Since the day on which observations were made may be considered to represent a typical fair weather season, it may be concluded that, in general, shearing rates in the canal reach are low to moderate during fair weather. Higher shearing rates (e.g. well in excess of 30 $\sec^{-1}$ ) often occur in larger estuaries such as Savannah Harbor (Krone, 1972).

Krone (1963) showed that the maximum shear, $\tau$, on an aggregate surface due to drag from rotation induced by flow shear can be calculated by considering the drag on the edge of a thin disc at the equator. This yields

$$\tau = \frac{1}{8} \mu G \qquad (2)$$

where $\mu =$ dynamic viscosity of the fluid. As an example, considering $G = 34$ sec$^{-1}$ at a relative elevation $z/h = 0.1$ at station 4 would correspond to $\tau = 0.0046$ N/m2, given $= \mu$ $1.0 \times 10^{-3}$ kg/m-sec. Assuming the kaolinitic canal sediment to have properties similar to those of the Brunswick Harbor sediment, aggregates of all four orders could easily exist over most of the water column, since the aggregate shear strengths for all the orders, as noted previously, would be higher than 0.0046 N/m2. This of course will be the case provided that a sufficient quantity of suspended sediment were available for the inter-particle collision frequency (and consequently the rate of aggregation) to be high. However, because of low sediment concentrations, higher order aggregates (e.g. second or third order) probably do not form to any significant extent in the canal. This would explain the low settling velocities of the sediment as noted below.

*Settling velocity and diameter*: The assumption of a steady state condition for transport under a fully developed turbulent flow results in the following expression for the vertical distribution of the suspended sediment concentration, C (Vanoni, 1975)

$$\frac{C(z)}{C_a} = \left[\frac{a(h-z)}{z(h-a)}\right]^{w/ku_*} \tag{3}$$

where $C_a =$ concentration at a reference elevation, a, above the bed and $u_* =$ friction velocity which can be estimated at a given location in the flow cross-section from

$$u_* = (fh/8R)^{\frac{1}{2}}\,\bar{\bar{u}} \tag{4}$$

where $h =$ instantaneous flow depth at the site of the measurement, $R =$ instantaneous hydraulic radius of the cross-section and $\bar{\bar{u}} =$ cross-sectional average instantaneous flow velocity.

Application of eqn. 3 to the present case can be justified on the grounds that temporal variations induced by the tide are of a comparatively very low frequency, and that the suspended sediment concentration in the canal was too low for mutual particle interference to be significant. In the latter case, the settling velocity tends to vary measurably with the suspended sediment concentration and therefore cannot be assumed to be constant, as in the present case (Mehta and Hayter, 1982).

Suspended sediment concentration measurements (Fig. 8) at station 1 at 0845 hr, 1230 hr and 1330 hr were of a nature where C(z) increased monotonically from surface to bottom, and were considered to be suitable for the determination of w using eqn. 3. The surface values correspond to C at a depth of 0.3 m below the instantaneous water surface and bottom values 0.3 m above the bed. Vertical concentration profiles are plotted in Fig. 9. These are normalized according to eqn. 3, using data given in Tables II and III together with eqn. 4. The reference elevation, a, was considered to be

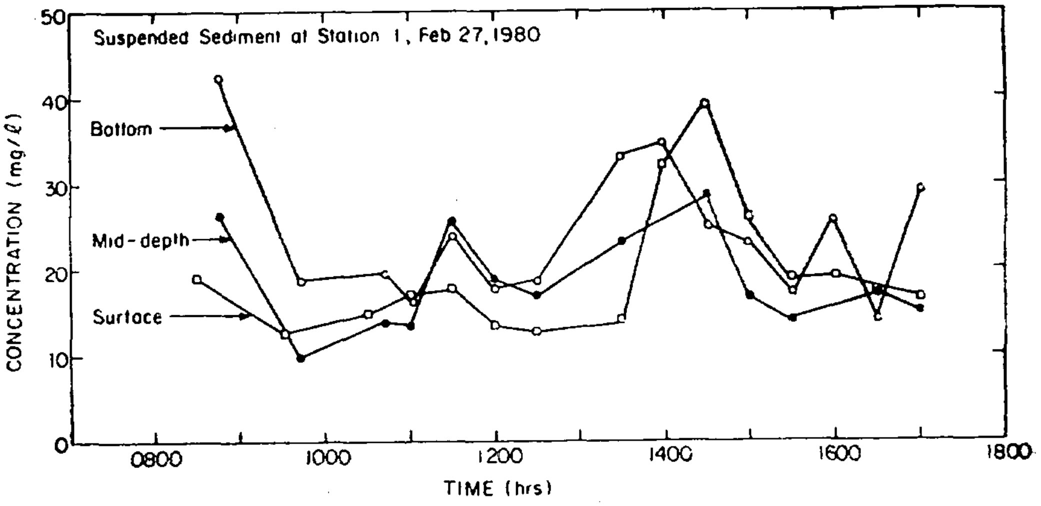

Fig. 8. Suspended sediment concentration variation with time at three relative elevations, station 1.

Table II. Computation of $u_*$ using eq. 4.

| Time (hr) | $\bar{u}$ (m/sec) | f | R (m) | h (m) | $u_*$ (m/sec) |
|---|---|---|---|---|---|
| 0845 | 0.03 | 0.042 | 3.0 | 6.7 | 0.027 |
| 1230 | 0.27 | 0.049 | 2.2 | 6.2 | 0.035 |
| 1330 | 0.15 | 0.049 | 2.1 | 5.8 | 0.020 |

Table III. Parameters for eq. 3 and computed values of w.

| Time (hr) | h (m) | a (m) | $C_a$ (mg/liter) | w (m/sec) |
|---|---|---|---|---|
| 0845 | 6.7 | 0.3 | 42.5 | $1.1\times10^{-4}$ |
| 1230 | 6.2 | 0.3 | 18.5 | $4.6\times10^{-4}$ |
| 1330 | 5.8 | 0.3 | 33.0 | $6.4\times10^{-4}$ |

0.3 m, which means that the corresponding concentration, $C_a$, was taken to be the measured bottom concentration. The ratio a/h was 0.045, 0.048 and 0.052 for the profiles at 0845 hr, 1230 hr and 1330 hr, respectively, which is reasonably close to the usually recommended value of 0.05 (Vanoni, 1975). The slopes of the lines of Fig. 9 yield values of w which ranged from $1.1 \times 10^{-4}$ to $6.4 \times 10^{-4}$ m/sec and are reported in Table III. When analyzing data from Savannah Harbour in a similar manner, Krone (1972) obtained w ranging from 0.0037 to 0.046 m/sec which indicates that the settling velocities of the canal sediment were an order of magnitude lower. The mean settling velocity based on values given in Table III was $4.1 \times 10^{-4}$ m/sec.

The settling diameter, d, for the sediment is obtained from Stokes' law according to

$$d = \left[\frac{18\,\mu w}{(\gamma_s - \gamma)}\right]^{1/2} \tag{5}$$

where $\gamma_s$ = unit weight of the aggregates and $\gamma$ = unit weight of the fluid. Equation 5 yields $d = 0.07$ mm corresponding to $w = 4.1 \times 10^{-4}$ m/sec. This is an order of magnitude lower than the value of 0.6 mm (for first order aggregates) determined for Savannah Harbour (Krone, 1972), and corroborates the earlier observation that small and probably low order aggregates occur in the canal. This conclusion also appears to be in agreement with the nature of the suspended sediment data of Fig. 8. During periods close to slack water (0910 hr and 1510 hr) at station 1, clarification of the waters (resulting from a rapid deposition of the suspended sediment) was not nearly as pronounced as was observed at Savannah Harbor, where the majority of the suspended load deposited at slack water (Krone, 1972). In fact, the data collected in this study (at stations 2, 3 and 4 indicated comparatively minor concentration changes produced by deposition and resuspension. Aggregates with low settling velocities together with suspended organic matter contributed to the observed turbidity of the canal even during slack water.

*Sediment transport rate:* The instantaneous value of the rate of suspended sediment transport, $Q_s$ is obtained from

$$Q_s = \int_0^b \int_a^h C(z)\, u(z)\, dz dy \tag{6}$$

where $a = 0.05$ h, y = lateral coordinate and b = instantaneous canal width. Utilizing C(z) distributions from Fig. 9 and measured u(z) profiles (Mehta and Hayter, 1981), $Q_s$ = 0.73, 5.92 and 5.38 kg/sec can be calculated at 0845 hr, 1230 hr and 1330 hr, respectively, at station 1. These rates are relatively low, and tend to corroborate the general observation that under typical fair weather conditions, suspended sediment transport in the canal is not very significant. However, the presence of a longitudinal salinity gradient in the canal (Rao, Cherian, Varma and Varadachari, 1976) suggests that, on a long-term basis, there is likely to be a small net upstream transport of sediment (associated with a density-induced bottom current) which enters from Zuari and proceeds towards Banastarim.

*Wind effect:* Wind influences the flow distribution by generating a surface current together with gravity-controlled waves as well as surface tension-controlled waves, both of which can cause a significant amount of turbulent mixing near the water surface. Furthermore, when the waves break on the banks, additional sediment can be brought into suspension. Settling of the finer portion of this material could be hindered by the surficial turbulence. If during this time resuspension of the bottom sediment were limited by the magnitude of the prevailing current, a situation could arise wherein the surficial suspended sediment concentration would be greater than that near the bottom.

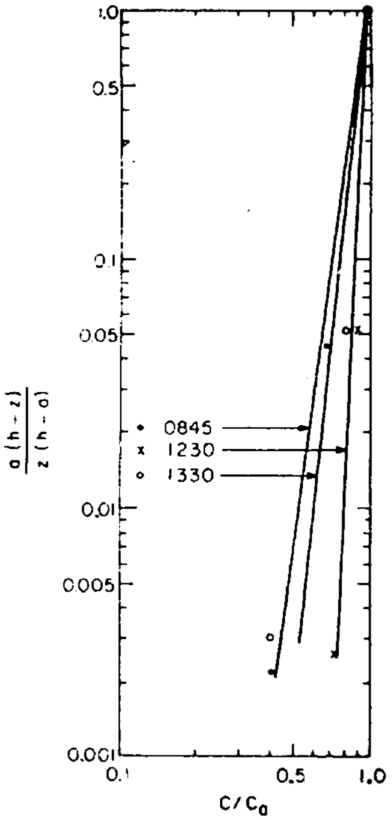

Fig. 1. Normalized suspended sediment concentration profiles based on measurements at station 1.

Waves of approximately 0.15 m breaking height were observed to suspend significant quantities of bank sediment at station 1 (Mehta and Hayter, 1981). At this station the influence of wind was relatively more significant in comparison with the other three stations. Fig. 10 schematically depicts the contribution to the suspended sediment load due to bank erosion. It is shown how the bank-derived material might be transported horizontally near the water surface, under the combined action of the main flow and the secondary flow towards the middle of the channel. The resulting situation may be examined with reference to the concentration data at station 1, between 1330 hr and 1500 hr (Fig. 8). In Fig. 11, the normalized concentration, C/Ca, is plotted against normalized elevation, z/h. The corresponding wind velocities (in m/sec and measured at 1.5 m elevation) are also given. It is observed that the surficial concentration relative to that at the bottom increased with the wind speed, and as the speed increased, the surficial sediment load became greater than that at the bottom or at mid-depth, or both.

*Monsoon regime*: Although no measurements were made during the south-west monsoon season (June–October) under the present investigation, some general observations can be made based upon data obtained under two previous studies (Das, Murty and Varadachari, 1972; Rao, Cherian, Varma and Varadachari, 1976).

The canal regime during monsoon is more severe as a result of high freshwater flow, wind and direct precipitation. The flow is known to become vertically startified, and during July–August the salinity drops to near-zero levels. During the same period, the suspended sediment load ranges from 20 to 120 mg/l. It is likely that sediment is trapped in the relatively more saline lower layer, and that the material entrained in the upper layers is carried by

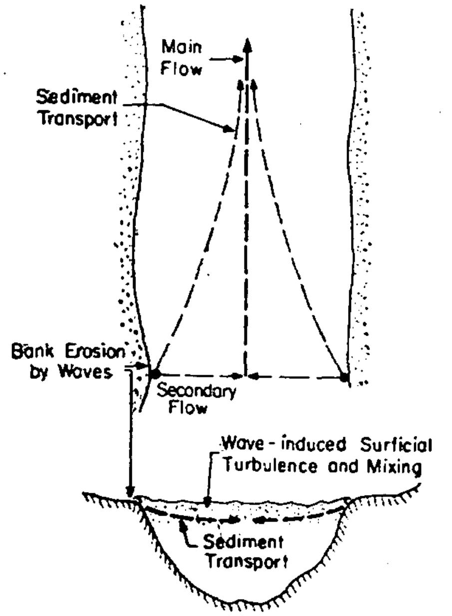

Fig. 10. Transport of bank-derived suspended sediment in the presence of wind-generated waves.

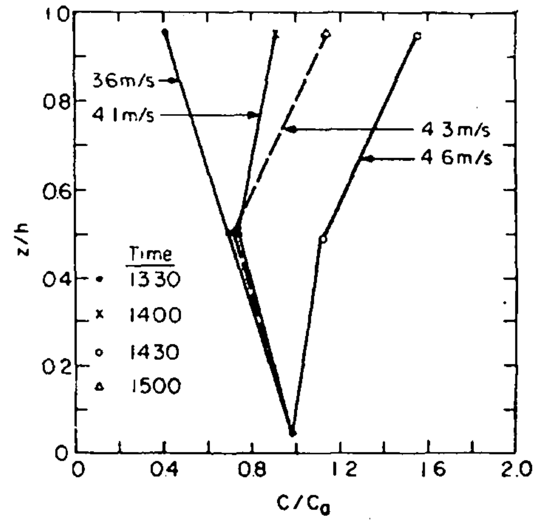

Fig. 11. Normalized suspended sediment concentration, C/C$_a$ , against relative elevation, z/h, at four wind speeds (measured at 1.5 m elevation above the water surface).

the freshwater flow to the Zuari River. There probably is some depletion of the bottom sediment from the canal. However, the amount depleted is likely to be less than the net amount transported into the canal during fair weather, as the canal bed is fairly resistant to erosion. Accurate bathymetric surveys for evaluating a long-term sediment budget for the canal are presently unavailable.

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