Flocculation of Suspended Sediment in the Fly River Estuary, Papua New Guinea

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ABSTRACT


The suspended sediment of the Fly River is mostly fine silt with a mean particle size of 8 μm; the clay fraction makes up less than 20% of the suspended sediment by volume. On reaching brackish water in the estuary, the sediment flocculates. The floes are small (typical mean size of 30 μm) and are a mixture of fine silt and clay particles, with silt particles dominating. Because of the dominance of silt particles incorporated in the floes, the floes are structurally weak and are destroyed by tidal turbulence at spring tides. The clay particles are selectively trapped in the turbidity maximum zone of the estuary.

ADDITIONAL INDEX WORDS: Floe, turbulence, tidal flow, turbidity maximum zone.

INTRODUCTION

The Fly River drains the southwestern highlands of Papua New Guinea, which are among the wettest places on earth with rainfall reaching 10 m yr⁻¹; at the coast the rainfall is only 2 m yr⁻¹ (AITKEN et al., 1972; BROWN, 1983). The Fly River has a catchment of about 76,000 km². The mean discharges of freshwater and suspended sediment are about 6,500 m³ sec⁻¹ and 4 tonnes sec⁻¹ respectively (OK TEDI MINING LIMITED, 1988; SALOMONS and EAGLE, 1990).

It is located on a tectonically active collision margin which results in mountains of >4,000 m elevation being within a couple of 100 km of the estuary. To place the Fly River into perspective, Table 1 shows that the Amazon, Mississippi, and Ganges rivers have larger areas and sediment loads, but the Fly River has the highest yield, about 10 times higher than the Amazon and Mississippi rivers. Intrusion of sea water varies from about 20 to 45 km from the ocean, and its position is influenced by the strong tides (tidal range, MHWS – MLWS of 3.4 m). The work of WOLANSKI and EAGLE (1991) showed a turbidity maximum near the landward extent of the salinity intrusion. The Fly River estuary (Figure 1) was known to be turbid (PICKUP, 1984), but no quantitative data were available until recently when detailed field studies were undertaken on the hydrodynamics and the sediment transport (WOLANSKI and EAGLE, 1991). These authors identified a turbidity maximum zone near the landward limit of the salinity intrusion in the estuary. The purpose of this study is to demonstrate the importance of flocculation of silty sediments and its influence on sediment transport in an estuary.

METHODS

Vertical profiles of temperature, salinity and suspended sediment concentration were obtained at a number of stations using the CTD profiler cum backscatterance nephelometer of WOLANSKI et al. (1988).

Moorings were maintained at stations Alpha, Beta, Gamma and Delta in the estuary (Figure 1). Each mooring comprised a frame 2.5 m in height and pyramidal in shape constructed from 1” stainless steel tubing. Three self-logging, backscatterance nephelometers were attached at about 0.25 m, 1.25 and 2.25 m above the bottom on one side of the frame. Vector-averaging current meters were positioned along the axis of the frame at about 0.5 and 1.8 m above the bottom. The frames also had a sediment trap 1.5 m off the bottom.

The calibration of the backscatterance nephelometers was carried out using local suspended
sediment traps to minimise likely errors due to varying sediment grain size or floc size. For instance, the presence of sand particles modifies the calibration curve used to convert optical backscatterance data to suspend sediment concentration in a suspension of mud (LUDWIG and HANES, 1990). Sand size particles are common on the bottom but were never found in suspension in the Niskin bottles or in the sediment traps. By using suspended sediment for our calibration, this aliasing problem was avoided. Errors in converting optical backscatterance data to suspended sediment concentration may arise because of varying floc sizes modifying the calibration curve (GIBBS and WOLANSKI, 1992). For the typical range of mean floc size variation in the estuary, this error is in the order of 20%.

The floc size was planned to be measured using an in-situ camera. However, in-situ systems are not usable in the Fly River estuary because (1) the concentration was far to high, causing excessive floc overlap on the images, and (2) the strong tidal currents, up to 2 m sec⁻¹, caused floc breakage around windows. This is in agreement with the in-situ camera experience of EISMA et al. (1990). Based on experience with floc breakage by pipettes (GIBBS and KONWAR, 1982), by pumps (GIBBS, 1981), by analyzers (GIBBS, 1982a and b) and by Niskin sample bottles (GIBBS and KONWAR, 1983), a technique using Niskin bottles coupled with a slide with well was utilized. This technique has been tested next to an in-situ camera and it produced floc size distribution within 5% of the in-situ camera.

Table 1. Comparison of the area, load and yield for Amazon, Mississippi, Ganges and Fly Rivers (from MILLIMAN and SYVITSKI, 1992).

<table>
<thead>
<tr>
<th>River</th>
<th>Area 10⁶ km²</th>
<th>Load 10⁶ t year⁻¹</th>
<th>Yield t km⁻² year⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amazon</td>
<td>6.100</td>
<td>1200.</td>
<td>190.</td>
</tr>
<tr>
<td>Mississippi</td>
<td>3.300</td>
<td>210.</td>
<td>120.</td>
</tr>
<tr>
<td>Ganges</td>
<td>0.980</td>
<td>520.</td>
<td>530.</td>
</tr>
<tr>
<td>Fly</td>
<td>0.076</td>
<td>115.</td>
<td>1500.</td>
</tr>
</tbody>
</table>
images were used both to visually study the structure and components of the flocs and to calculate the floc size distribution using a special image analysis software package. Calibration of the system was accomplished using standard Coulter counter calibration samples of ragweed pollen (median size 17.5 μm) and latex particles (median size 40 μm).

The primary (not flocculated) particle size distributions were measured using a Horiba CAPA-300 gravitational/centrifugal particle size analyzer. For the majority of the samples, pre-processing was very important due to the regular occurrence of flocs, by treatment with an ultrasonic bath and Calgon-T dispersant. After this pre-processing and before running the sample through particle size analyzer, the samples were examined under the microscope system described above to ensure that no flocculation of the sediment would take place during the particle size analysis.

RESULTS

The distribution of suspended sediment concentration along the estuary (Figure 2B) shows a very high mean (depth- and tide-averaged) turbidity maximum with average concentration reaching 3 g L⁻¹ during spring tides and a much lower turbidity maximum during the neap tides. The position of this turbidity maximum corresponds to the first few ppt of salinity (Figure 2A).

The along-channel distribution of salinity, and the size of particles and flocs, both near the surface and near the bottom, are shown in Figure 3 for May 16–18, 1992. The estuary was well-mixed in salinity indicated by nearly vertical isohalines and the salinity intrusion limit was located near station Delta. Note that the salinity was only about 15 ppt at station Alpha at the mouth of the estuary.

The particle size distribution of the suspended sediment varied measurably along the estuary length (Figure 3). In freshwater, the median particle size, d₁₀, was about 5 μm both near the surface and near the bottom, i.e., fine silt prevailed. Fine grain sediment dominated the distribution as the particle d₁₀ and d₉₀ were about 1 and 18 μm respectively. Clay particles (particle size < 2 μm) accounted for about 20% of the suspended sediment in freshwater. However, the sediment was finer in the saline region of the estuary (Figure 3). For instance at station Gamma in the saline region, the median particle size was smaller, with a particle d₉₀ of about 2 μm (i.e., clay-size) near
the surface. The particle $d_{90}$ was less than 4 $\mu$m near the bottom. In coastal waters offshore from station Alpha, the particle size was similar to that in the freshwater region with a dominance of silt sized particles. The clay particles accounted for less than 20% of the sediment by volume.

In the freshwater region, at Lewada, the suspended sediment was not flocculated (Figure 4A). However, in the saline region of the estuary the sediment was flocculated (Figure 4B). This figure also shows that the floc size varied with depth, the largest flocs existing near the bottom and the smallest flocs near the surface. The largest flocs near the bottom were found at station Delta (Figure 3) where the median floc size, $d_{90}$, was 45 $\mu$m near the bottom and 31 $\mu$m near the surface. The flocs were largest in the estuary between stations Delta and Beta and were smaller at station Alpha and further offshore. The mean floc size at the surface was the largest at station Beta, i.e., downstream of station Delta which is where the maximum mean floc size at the bottom was found.

To ensure that the data from the longitudinal transects are not invalidated by the tidal transients, time series of data were also collected at a number of stations over one or two tidal periods. Figure 5 shows a time series plot of oceanographic data at station Alpha on May 16–17, 1992. The tidal velocity peaked at about 1.2 m sec$^{-1}$. The salinity varied with the tides in the range 6 to 22 ppt. Well-mixed conditions prevailed during peak tidal currents. A classical estuarine circulation prevailed the rest of the time when the currents were weaker and the waters were stratified in salinity. This is apparent near slack high tide at 24 hr when more saline water intruded near the bottom (Figure 5) and at the following ebb tide when fresher water was found at the surface flowing out of the estuary. The suspended sediment concentration (Figure 5) fluctuated with the tidal currents, with deposition occurring when the currents were weak ($< 0.5$ m sec$^{-1}$) and erosion during strong ($> 0.5$ m sec$^{-1}$) tidal currents. The bulk of the suspended sediment was located in the bottom 2 m. The moored nephelometers logged data at five minute intervals, while the CTD data were measured hourly and were collected from the ship.

Figure 3. Along-channel distribution in the Southern Channel of the salinity, and the near surface and near bottom particle size and floc size distributions, May 16–18, 1992.
Figure 4. Typical floc photographs in (a) the freshwater and (b) the saline region of the estuary. The bar represents 100 μm.
anchored 500 m away in a cross-channel direction. This distance was the minimum required for safety in order to avoid snagging the mooring with the anchor. This was of concern because it was not uncommon for the ship to drift on its anchor, being unable to hold on the soft sediment. An estimate can be made of the patchiness of the system by comparing suspended sediment concentration data from ship-borne and moored instruments 500 m apart (Figure 5). A very strong correlation is apparent (Figure 5). For instance, the two short-lived events of high concentration of suspended sediment near 19 and 23 hr and the prolonged period of high suspended sediment concentration close to the bottom between 26 and 30 hr, were observed both by the moored and the ship-borne nephelometers. However, there were also differences between the SSC data from the moorings and the ship-borne instruments; for instance, between 29 and 30 hr, an event of high suspended sediment concentration at the bottom sensor of the mooring was not observed from the ship.

The silt-dominant flocs of the Fly River estuary are structurally weak and are readily broken by tidal turbulence. The flocs go through a cycle of breakage and reformation through a tidal cycle as the current changes (Figure 6). In Figure 6, this cycle shows similar trends for both surface and bottom suspended flocs and the ebb and flood
currents, with little difference between increasing and decreasing current. This indicates fast (minutes) breakage and reformation of the flocs as the current changes. The median flocs in the bottom waters are about twice as large as the surface water flocs.

Through a tidal cycle, the particle size (Figure 7) near the surface showed only small fluctuations. The median particle size, $d_{50}$, varied little, averaging about 3–4 μm, except from 24 to 27 hr when the particle $d_{50}$ was slightly smaller. Near the bottom, the particle size showed a larger variation. The median particle size remained fairly constant at 3 to 4 μm (i.e., fine silt-size) up to about 20 hr. Thereafter, the median increased slightly to about 5 μm and from 24 hr to 28 hr remained fairly constant. During that time, over 60% of the sediment by volume was made of silt particles. After 28 hr, conditions similar to those before 20 hr prevailed.

At flood tide near the bottom, the clay-size (<2 μm) sediment accounted for about 30% of the distribution by volume, but only 10% at ebb tide. Particles of size between 3.9 and 7.8 μm preferentially left the estuary at ebb tide, and a mixture of particles of size between 1.95 and 7.8 μm entered the estuary at flood tide.

**DISCUSSION**

Processes operate in the Fly River estuary to selectively trap the clay particles in the turbidity maximum zone. This selective trapping of fine sediment was observed, not only in the southern channel as shown above, but also in the other two channels of the estuary in a number of transects carried out from May to July 1992 (not shown). The controlling mechanism appeared to be flocculation.

The floc size varies markedly with the tidal currents; it is smallest during strong (>0.8 m sec$^{-1}$) tidal currents and largest at neap tides and during small tidal currents. The flocs constantly are formed and are destroyed in phase with the tidal currents. The floc size also varied with the spring-neap tidal cycle. Indeed, the largest mean floc size (64 μm) was observed at neap tides in the turbidity maximum zone. A week later at spring tides, the flocs were smaller with a mean size of only 30 μm (not shown).

The situation in the Fly River estuary differs markedly from that in most other estuaries which are clay-dominant, such as the Amazon and Gironde River estuaries and Chesapeake Bay. In these estuaries, the flocs are robust and their size varies little with the tidal currents (Gibbs and Konwar, 1986; Gibbs et al., 1989; Schubel, 1971). To place the results into perspective of other estuaries, Table 2 shows that the Fly River system is in the high river concentration type as the Amazon and Mississippi rivers. The major difference is in the size of the flocs with the Fly River having floc diameters half the size of those in the Amazon. This difference is apparently caused by the much higher proportion of silt in the Fly River as compared to the Amazon and Mississippi rivers. The weak structure of the Fly River estuary flocs is apparent using a microscope. The flocs were easily destroyed by gentle mechanical stirring of the water in the slide. The weak structure of the flocs is also suggested from an examination of photographs at large magnification (Figure 4b). The flocs are seen to be comprised of clay and silt particles in an extremely porous and loose matrix. Apparently robust flocs, with a thick membrane of clay particles coagulated around silt particles, were only observed at neap tides (weak tidal currents) and in the turbidity maximum zone located typically between the 5 and 10 ppt isohalines. The
Table 2. Suspended material concentration (SMC, mg liter⁻¹), tidal range (T, m), turbidity maximum concentration (TMC, mg liter⁻¹) and maximum floc size (d<sub>max</sub>, μm) for various river/ocean systems (adapted from GUMS, 1987).

<table>
<thead>
<tr>
<th>River Types</th>
<th>SMC</th>
<th>T</th>
<th>TMC</th>
<th>d&lt;sub&gt;max&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low concentration</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delaware River</td>
<td>110</td>
<td>&lt;1</td>
<td>1100</td>
<td>150</td>
</tr>
<tr>
<td>Hudson River</td>
<td>110</td>
<td>1.5</td>
<td>150</td>
<td>180</td>
</tr>
<tr>
<td>Gironde River</td>
<td>110</td>
<td>6</td>
<td>3,000</td>
<td>190</td>
</tr>
<tr>
<td>High concentration</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amazon River</td>
<td>66</td>
<td>10</td>
<td>2,000</td>
<td>180</td>
</tr>
<tr>
<td>Fly River</td>
<td>400</td>
<td>3.4</td>
<td>3,000</td>
<td>90</td>
</tr>
<tr>
<td>Mississippi R.</td>
<td>180</td>
<td>1</td>
<td>1,000</td>
<td>150</td>
</tr>
</tbody>
</table>

Fly River estuary flocs are weak and readily disintegrate by collision and turbulent shearing.

In the freshwater region, the particles are not flocculated (Figure 4a), and the fine suspended sediment travels as a wash load (WOLANSKI and EAGLE, 1991). The Fly River estuary has a turbidity maximum zone, located about between the 5 and 10 ppt isohalines. This turbidity maximum is most apparent at spring tides when, at occasions, peak near-bottom suspended sediment exceeds 40 g l⁻¹ (WOLANSKI and EAGLE, 1991), and is least apparent at neap tides. The presence of a turbidity maximum zone can be explained by simultaneous baroclinic circulation and tidal pumping. Tidal pumping is created by tidal currents (DRONKERS, 1986; DYER and EVANS, 1989). In the Fly River, the asymmetry is pronounced at spring tides (WOLANSKI and EAGLE, 1991). The baroclinic circulation selectively transports upstream sediment in suspension near the bottom (WINANT and BRATKOVICH, 1977; GIBBS et al., 1989). Both mechanisms operate in the Fly River, but at different times. Tidal pumping is least efficient at trapping fine sediment at spring tides, when the floc size is smallest. The baroclinic circulation on the other hand is most efficient at trapping fine sediment in the estuary at spring tides when the near bottom suspended sediment concentration is typically a factor of 10 larger than at neap tides.

The selective trapping of clay particles in the estuary may be due to the continual processes of floc destruction and formation during a tidal cycle. The strongest flocs contain the most clay particles; they are least destroyed by strong tidal currents, have a large settling velocity and stay near the bottom. As a result, they are selectively advected upstream by the baroclinic circulation and the tidal pumping. The other flocs contain more silt particles; they are structurally weak and readily destroyed by strong turbulence. When the flocs are destroyed, the floc size decreases. Having a smaller fall velocity, the small flocs and the individual silt particles are more evenly distributed in the water column and less affected by baroclinic circulation and tidal pumping.

The largest flocs are found near the bottom in the upper reaches of the saline region of the estuary; at the surface the largest flocs are found downstream (Figure 8). This is because the small flocs and the unflocculated particles are not restricted to the bottom layer. They progressively flocculate as they move further downstream with the net currents. This transport brings them near the bottom where they are advected upstream by tidal pumping and the baroclinic circulation. This process is inhibited by the regular destruction and formation of the flocs at tidal frequency. Floc destruction may affect the silt particles the most because they have less charge per unit weight. Hence, silt particles are less able to remain trapped in the estuary and can be flushed to sea. Clay particles are preferentially retained in the estuary (Figure 8).

**CONCLUSIONS**

The fate of fine sediment in the Fly River estuary is controlled by flocculation dynamics, tidal pumping and the baroclinic circulation. The flocs
are composed mainly of silt particles and are destroyed by strong tidal currents, but they form again at slack tide and during weak tidal currents. These processes result in the selective trapping of clay particles in the turbidity maximum zone of the estuary.

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LITERATURE CITED


