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TRANSFER OF WATER AND SEDIMENT FROM THE YANGTZE RIVER
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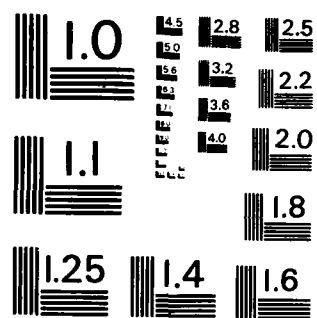
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Transfer of Water and Sediment from the Yangtze River to the East China Sea, June 1980^{1,2}

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The Yangtze River, fourth largest in the world in terms of sediment discharge, contributes about 500×10^6 t annually to the East China Sea. A disproportionate part of the load is carried after peak summer discharge, presumably the result of draining the rice fields. During a week-long study of the estuary, greatest water discharge was observed in the North Passage. Suspended sediment concentrations were highest in the South Channel of the South Passage, although in contrast to the North Passage little of the suspended sediment was coarse. The high sediment concentrations in the South Channel appear to be the result of oscillatory (net transport upstream) movement of material, in contrast to the marked seaward transport measured in the North Passage.

Key words: Yangtze River, sedimentation, discharge, transport, estuary

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Le fleuve Yang-Tseu, le quatrième en importance dans le monde en terme de transport de sédiment, contribue environ 500×10^6 t annuellement à la mer de Chine orientale. Une partie disproportionnée de la charge est transportée après le maximum estival de débit, résultant probablement du drainage des rizières. Au cours d'une étude d'une semaine de l'estuaire, le débit d'eau le plus important a été observé dans le passage Nord. Les concentrations de sédiment en suspension étaient les plus élevées dans le chenal Sud du passage Sud, bien que, contrairement à ce que l'on a observé dans le passage Nord, il y avait très peu de particules grossières en suspension. Les hautes concentrations de sédiment dans le chenal Sud semblent résulter du mouvement oscillatoire (transport net vers l'amont) du matériel, contrairement au transport nettement vers la mer observé dans le passage Nord.

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In terms of sediment discharge, the large rivers of the world drain Asia and, to a lesser extent, South America (Table 1). Combined, the rivers of southern and eastern Asia and neighboring oceanic islands contribute nearly 70% of the estimated

13.5×10^9 t of suspended fluvial sediment reaching the ocean annually, while South America rivers account for an additional 13% (Milliman and Meade 1982). With the exception of the Chinese rivers, however, none of the great Asian rivers have been studied in detail. The largest river, the Ganges/Brahmaputra, for example, has not been measured during flood conditions, and the estimated 1.1×10^9 t annual figure could be in error by 50%. Even more extreme is the Irrawaddy, whose reported sediment discharge (265×10^6 t·yr⁻¹) is based on 19th century data. The lack of gauging data from these big rivers is matched by our ignorance concerning the transfer of their solid and dissolved loads to the ocean. The best estuarine studies come from North America and Europe, which generally have small rivers.

To help rectify this problem, we are studying the sediment

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TABLE 1. Ranking of the largest world rivers, with particular reference to the Yangtze River. Data compiled by Milliman and Meade (1982).

Drainage area ($\times 10^6 \text{ km}^2$)		Water discharge ($\text{km}^3 \cdot \text{yr}^{-1}$)		Sediment load ($\times 10^6 \text{ t} \cdot \text{yr}^{-1}$)	
Amazon	— 6.15	Amazon	5519	Ganges/Brahmaputra	1170
Zaire	— 3.82	Zaire	1250	Huangho	1140
Mississippi	— 3.27	Orinoco	1007	Amazon	900
Nile	— 2.96	Ganges/Brahmaputra	971	YANGTZE	500
La Plata	— 2.83	YANGTZE	900	Irrawaddy	265
Yenisei	— 2.58				
Lena	— 2.50				
Ob	— 2.50				
YANGTZE	— 1.94				

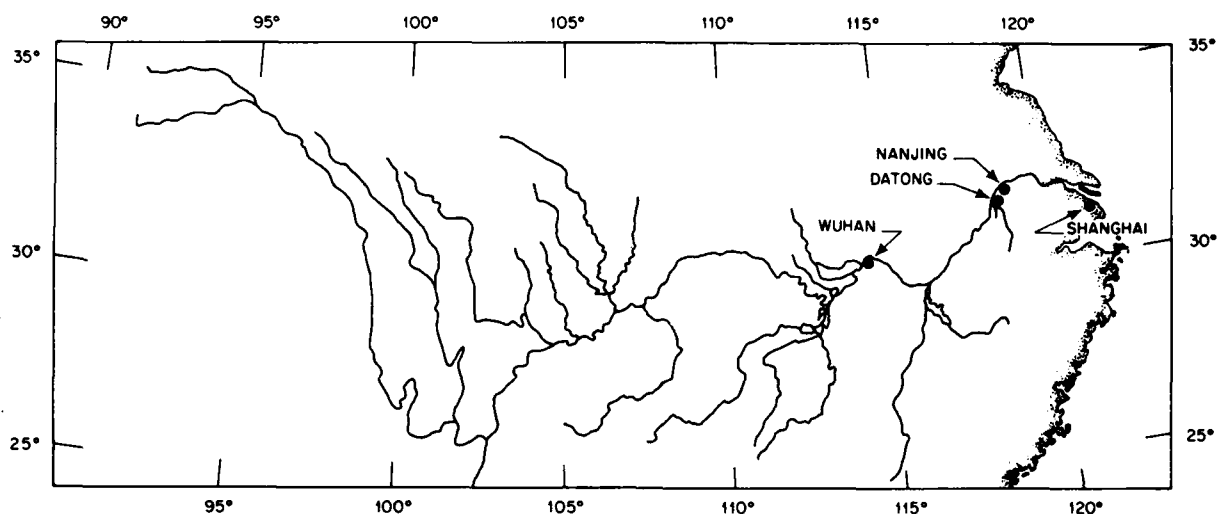


FIG. 1. Drainage Basin of Yangtze River.

transfer from the Yangtze River (Chang Jiang) to the East China Sea. This river is ranked fourth in terms of sediment discharge ($500 \times 10^6 \text{ t} \cdot \text{yr}^{-1}$) and, together with the Huangho (ranked second in the world), has been studied carefully by the Chinese since 1951. These rivers are unquestionably the best documented in Asia, with a fluvial data base that allows a more efficient and thorough study of their estuaries.

The Yangtze River and Estuary

The Yangtze is more than 6000 km long, and its 1.94 million km^2 drainage basin is the home for nearly half of China's billion inhabitants. The river is the major source of irrigation for agriculture (particularly rice), serves as a principal means of transportation to the interior, and yet also is a frequent source of disaster during devastating floods. The large basin area contains a wide diversity of terrain, geology, and climate; its headwaters are located in the Tibetan high plateaus, while its southern tributaries are subtropical and its northern tributaries are temperate (Fig. 1). The river discharges an average of 23 000 m^3 of water per second, with relatively little year-to-year variation (generally less than 30%). The period of main runoff occurs from late June

through early August, when rainfall is highest (Hayami 1938), but the diversity of the terrain and climate within the basin modulates the runoff so that no one month averages more than 15% of the runoff (Fig. 2).

The annual suspended load, averaging about $500 \times 10^6 \text{ t}$ at the head of the estuary (Huang et al. 1980), shows relatively little fluctuation from year to year. At Hangkow, 400 km upstream from the mouth, for instance, sediment discharge between 1954 and 1972 ranged from 267 and $579 \times 10^6 \text{ t}$; 15 of the 19 yearly values fall between 372 and $515 \times 10^6 \text{ t}$. Suspended matter concentrations generally range from 100 to 1000 mg/L with only about 30% or less being coarser than $10 \mu\text{m}$ (Hayami 1938). Peak sediment loads occur during and just after peak discharge (Fig. 2), nearly 60% of the annual load being carried in July, August, and September. Concentrations of suspended solids during the 6 mo after peak discharge are about twice as high as those during the months preceding or during the peak, resulting in a hysteresis loop running counter to that for most other rivers (Fig. 3). In most rivers, early season flow removes the easily entrained material, resulting in higher sediment concentrations during these months but lower values later (e.g. Milliman 1979). The higher concentrations in the Yangtze after peak runoff may be related to the draining of the rice fields in August, prior to

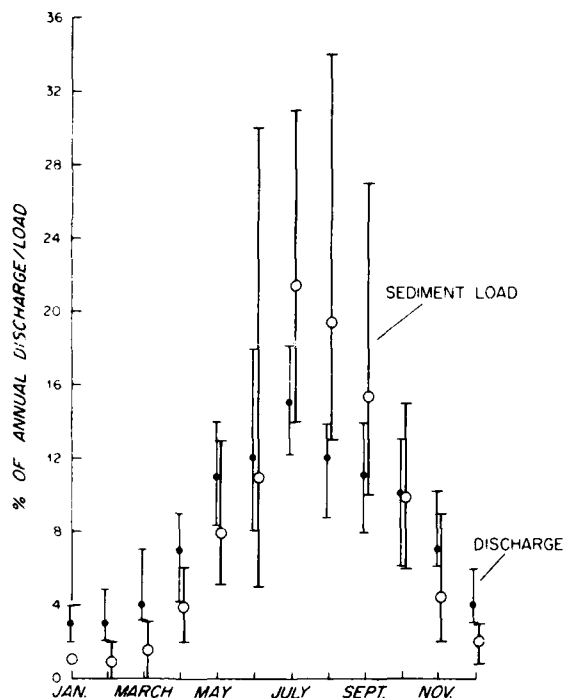


FIG. 2. Annual distribution of water discharge and sediment load for the Yangtze River, based on unpublished Chinese data (at Hangkew, 400 km upstream from the mouth) for the years 1958-72.

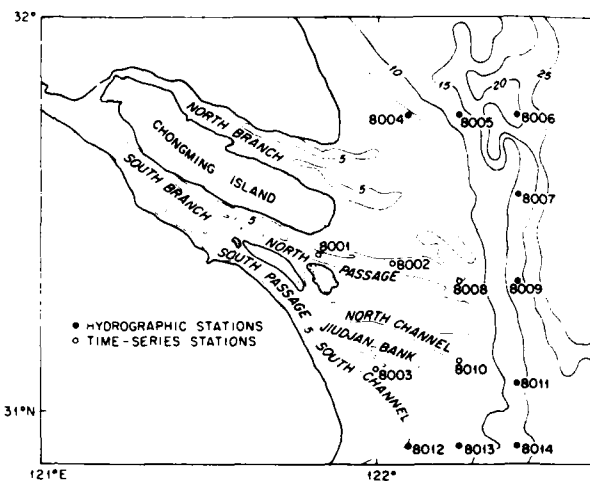


FIG. 4. Yangtze River Estuary, together with stations occupied during this study. Depth contours, based on Chinese charts, are in metres (mean low water).

harvest. These muddy waters continue to empty into the Yangtze and its tributaries until the beginning of rice planting the following February. Since the post-flood runoff carries an average of 53% of the annual sediment load (Fig. 2) and since post-flood concentrations should be smaller than pre-flood values, we suspect that at least 20-30% of the 500×10^6 t carried yearly by the Yangtze must be directly related to the draining of the rice fields.

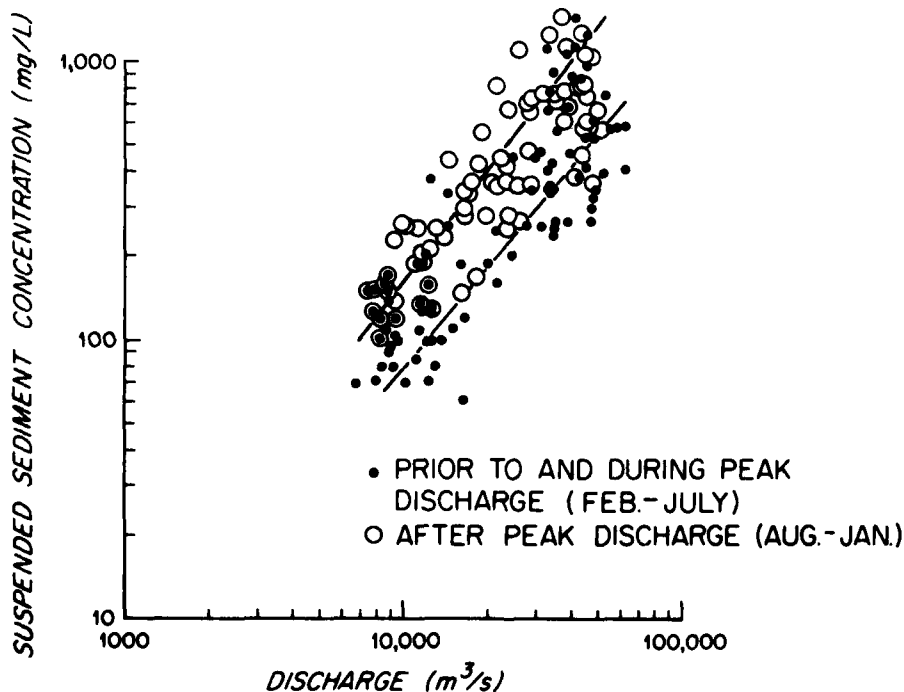


FIG. 3. Rating curve for the Yangtze, showing the comparison of pre- and post-flood sediment concentrations. Based on monthly averages of sediment data from the Hangkew station, 1958-72.

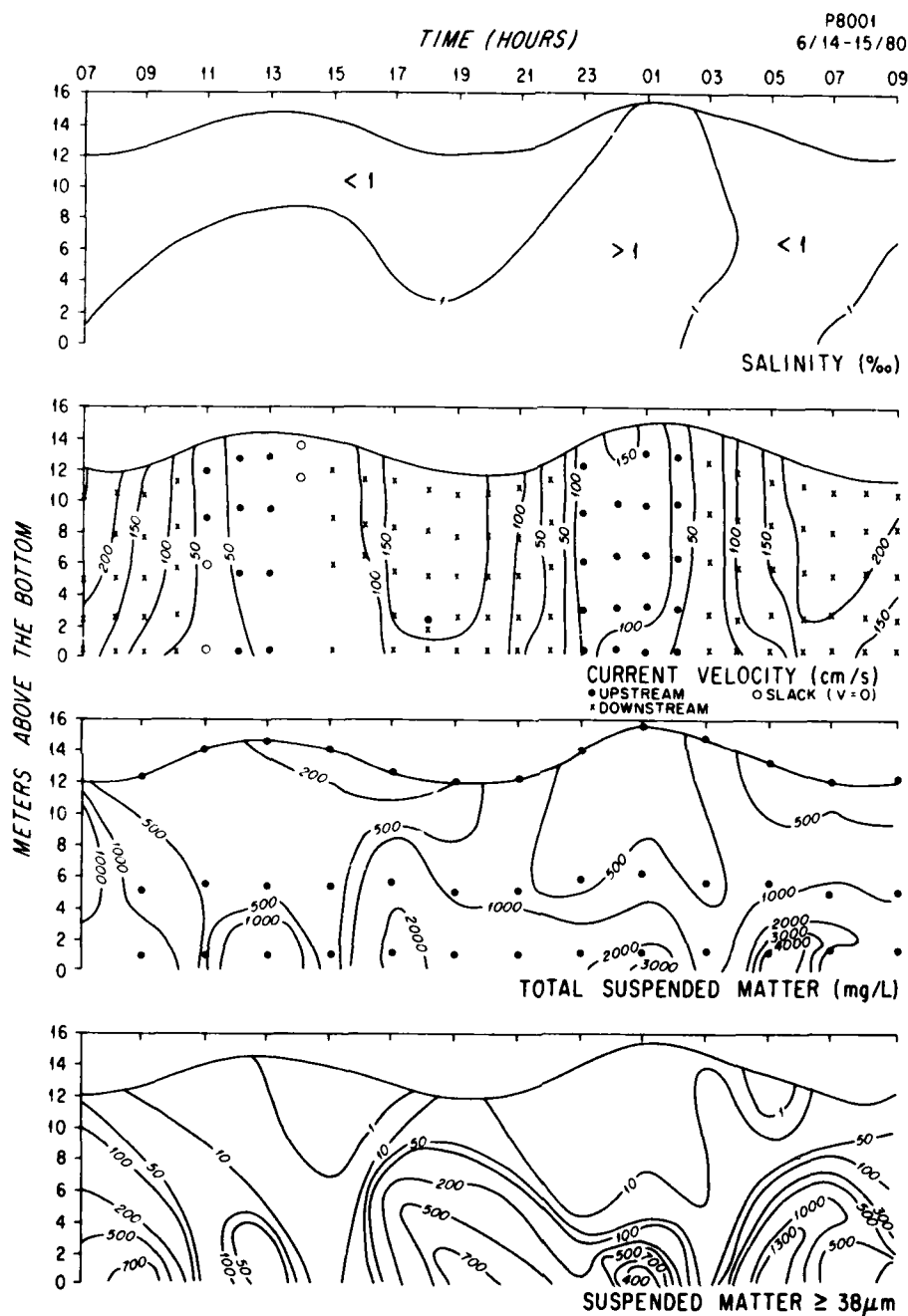


FIG. 5. Time-series plot of salinity, current velocity, total suspended matter, and suspended material coarser than $38 \mu\text{m}$ at station 8001, June 14–15, 1980.

The Yangtze Estuary bifurcates into North and South branches around Chongming Island (Fig. 4). In turn, the South Branch divides into the North and South passages at Changxin Island, and the South Passage is split into North and South channels by Jiudjan Bank. At present, the North Branch of the river has no net discharge of freshwater; in fact, according to our Chinese colleagues, it experiences a net landward

influx of salt water, resulting in slightly saline river water ($0.5\text{--}1\text{‰}$) in the South Branch (Huang et al. 1980). It is a mark of the rapid evolution of this estuary that less than 1000 years ago, the North Branch was the major distributary of the Yangtze, and within the past 3000 years, the mouth was considerably to the north (Ren and Tseng 1980). At present, best estimates are that the North Passage has discharged more

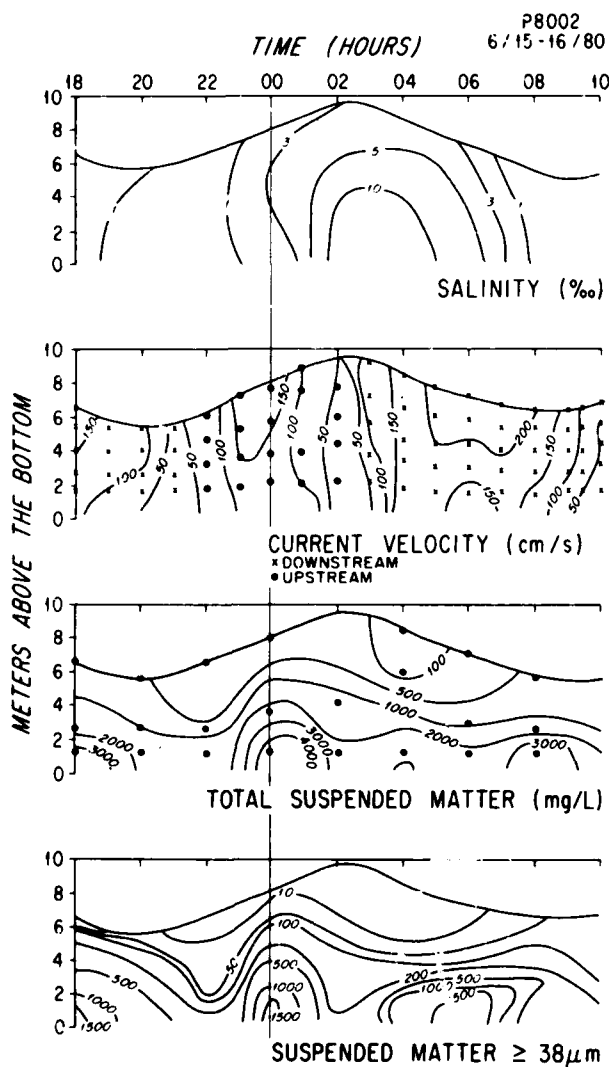


FIG. 6. Time-series plot of salinity, current velocity, total suspended matter, and suspended material coarser than $38 \mu\text{m}$ at station 8002, June 15–16, 1980.

water than the South Passage since 1966; in the South Passage, the South Channel has discharged more than the North Channel. The South Channel around Jiudjan Bank, exhibits considerable shoaling (Huang et al. 1980), a point of concern for ship navigation into Shanghai Harbor.

Another important feature of the Yangtze is the great range of tides (mixed with a strong semidiurnal component). In the North Passage, tidal range can exceed 4.5 m (Huang et al. 1980), and the tidal component of the current locally can exceed $2 \text{ m} \cdot \text{s}^{-1}$ (Shen et al. 1980). Even during peak runoff, tidal reversals in the current occur during flooding tide. Results presented in this paper plus preliminary data from 1981 cruises suggest, in fact, that the tidal range (spring versus neap) may play as important a role in sediment discharge as the river stage.

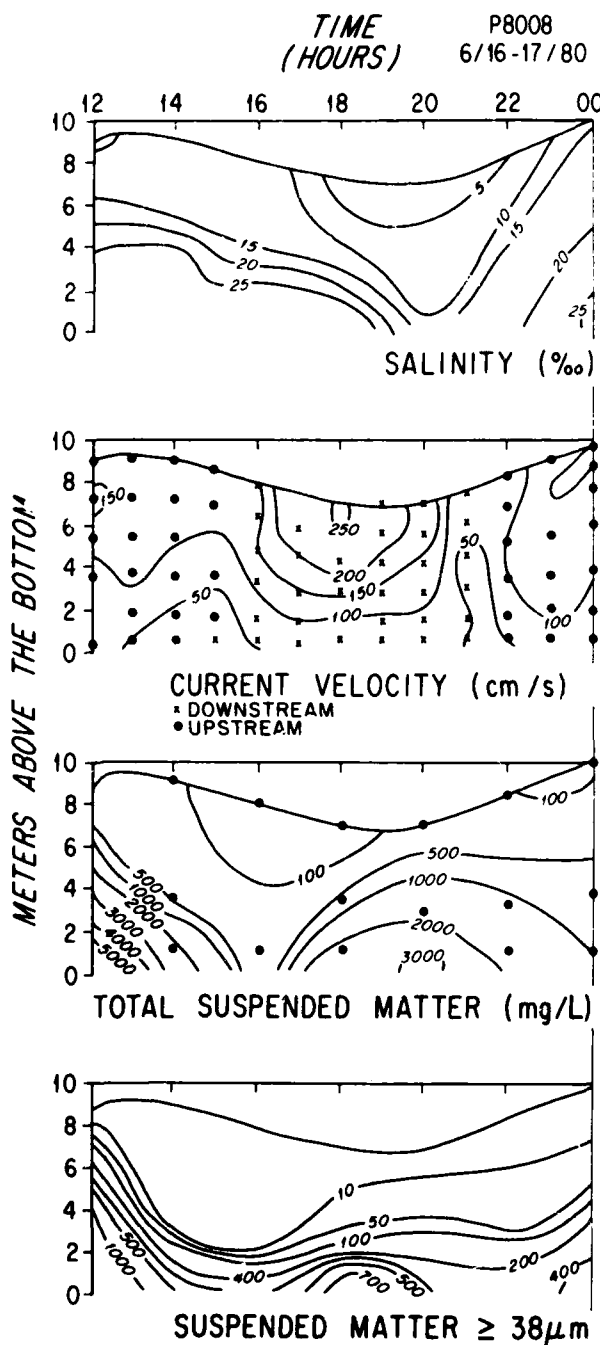


FIG. 7. Time-series plot of salinity, current velocity, total suspended matter, and suspended material coarser than $38 \mu\text{m}$ at station 8008, June 16–17, 1980.

Methods

Data were collected from the Chinese oceanographic vessel Shuguang No. 6 during mid-June 1980 at five anchor stations within the estuary and nine hydrographic/suspended matter

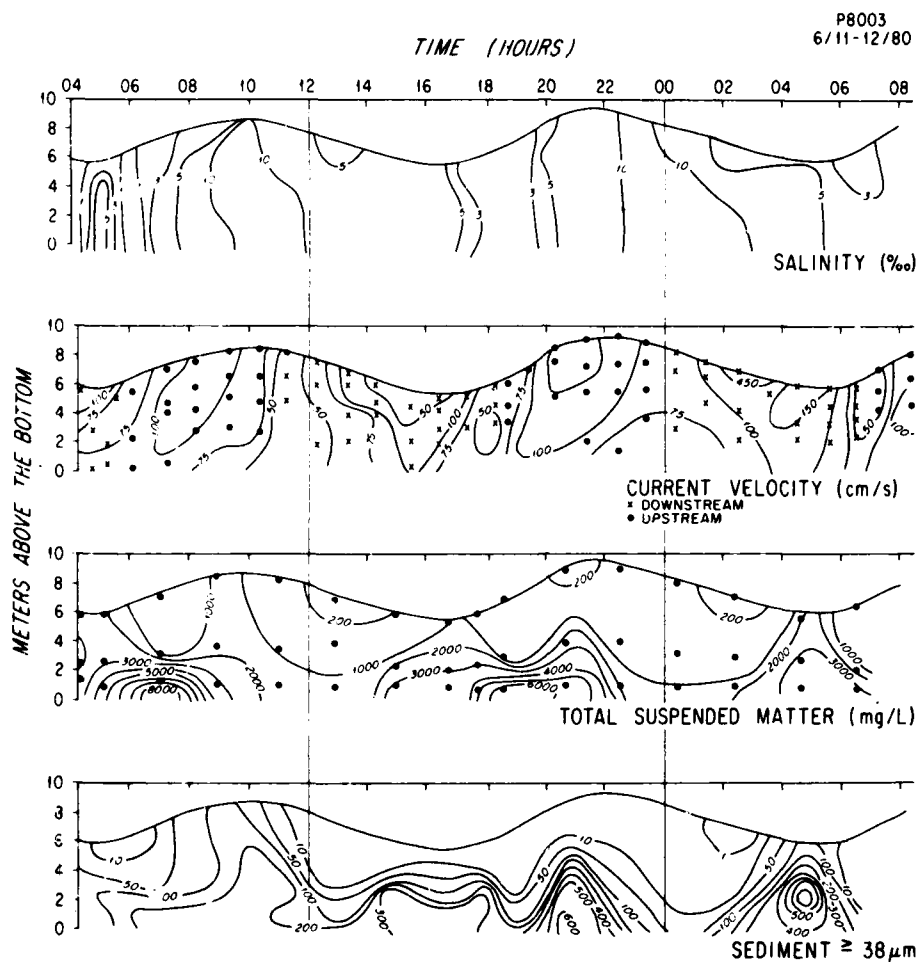


FIG. 8. Time-series plot of salinity, current velocity, total suspended matter, and suspended material coarser than $38 \mu\text{m}$ at station 8003, June 11–12, 1980.

stations around the northern, southern and eastern boundaries of the estuary (Fig. 4). Each anchor station was occupied for at least 13 h and three for the full tidal cycle (25 h). Hydrographic stations were taken before (June 10) and after (June 17) the anchor stations. Although daily data are not available for the study period, discharge for the month of June averaged $32\,000 \text{ m}^3/\text{s}$, about normal for that month and about 80% the value of normally high discharge in July–August. Predicted spring tides occurred on June 14, inferring increased discharge and upstream flow during the time of the anchor stations. Measured tidal range at station 8002 (North Passage) was 4 m.

At each of the time-series stations (three in the North Passage and two in the South Passage), temperature, salinity, suspended solids, and current speed and direction were measured, as well as dissolved solids (J. Edmond et al., Earth and Planetary Science, Massachusetts Institute of Technology, Cambridge, MA, unpublished data). Current measurements were made hourly using a Chinese-made meter at the surface and bottom as well as 0.8, 0.6, 0.4, and 0.2 the water depth;

measured velocities agreed closely with those made by an Endeco current meter used by U.S. scientists, although at high velocities, the latter meters tended to be erroneously low (G. Cannon, Pacific Marine Environmental Laboratory, Seattle, WA, personal communication).

The suspended matter samples were collected every other hour in 1-L horizontal water bottles (to prevent the loss of sand when sampling) at three levels within the water column — surface, mid-depth, and 1 m above the bottom. Salinities were measured from the water samples using an optical refractometer. The samples were emptied through two sieves (62 and $38 \mu\text{m}$) to remove the coarse fraction, and the filtrate passed through micro-filters, either Millipore or Gelman filters, with nominal pore diameters of $0.45 \mu\text{m}$. No control filters were needed, since the weight change of the filters was small compared to the quantity of material collected on the filters. Both the filters and the coarse fraction were rinsed with distilled water and stored until return to the laboratory, where they were air dried and weighed. The concentrations of both the coarse and fine fraction were computed subsequently.

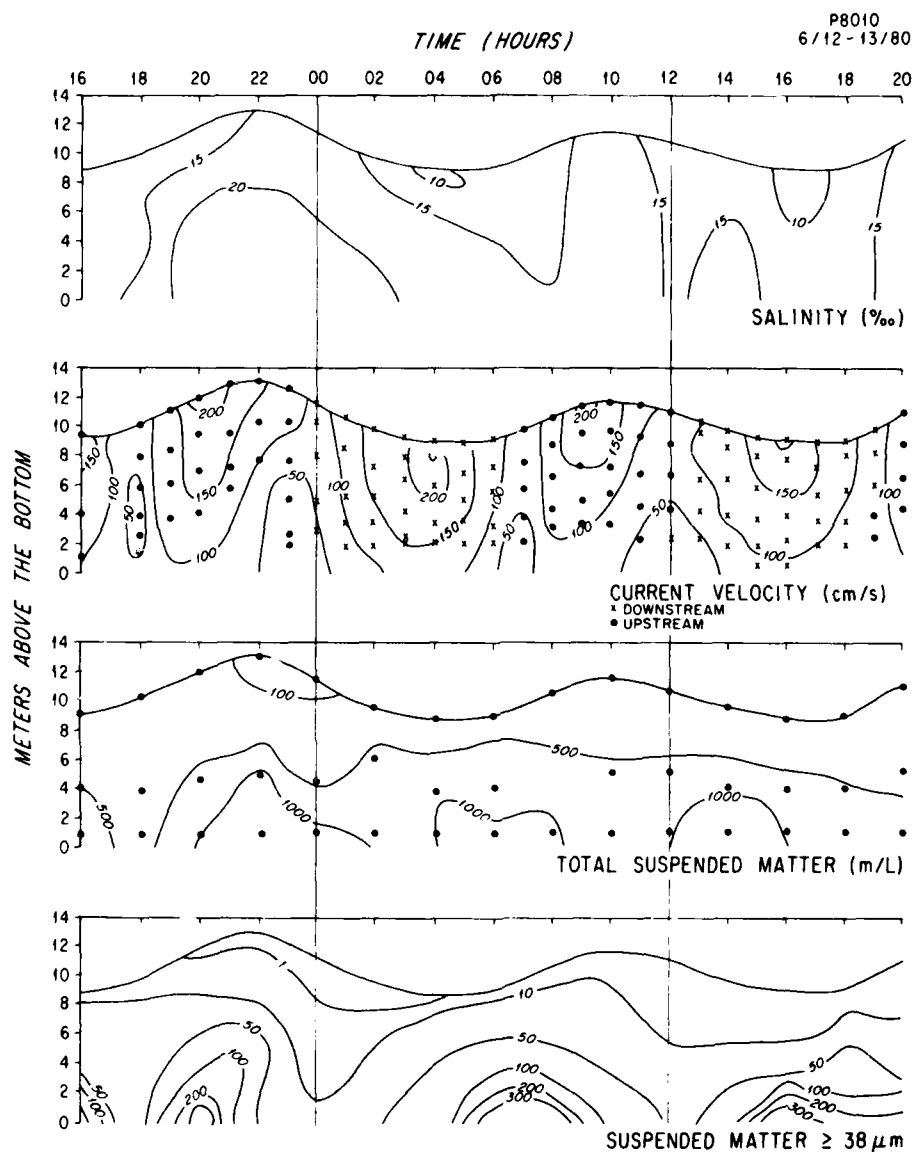


FIG. 9. Time-series plot of salinity, current velocity, total suspended matter, and suspended material coarser than $38 \mu\text{m}$ at station 8010, June 12–13, 1980.

Some filters were ashed (at 500°C) to determine the organic content. Most filters were mounted on glass slides with optical oils for visual inspection under transmitted light. Those samples that proved particularly interesting were then examined under the scanning electron microscope.

Results

Because of the great tidal range in the Yangtze, both hydrographic and suspended material character changed markedly with time. In the North Passage, the innermost station (8001) experienced essentially fresh water during the entire 26 h of measurement (Fig. 5), while downstream at

station 8002, subsurface values exceeded 10‰ during high tide (Fig. 6). At both North Channel stations currents were predominantly offshore (peak velocity exceeding 200 cm/s), but landward during part of the flood tide (generally $50\text{--}100 \text{ cm/s}$). Surface and mid-depth suspended matter concentrations at both stations ranged from 200 to 500 mg/L , values consistent with predicted river concentrations during this season (Fig. 3). Near-bottom values, in contrast, generally exceeded 1000 mg/L (occasionally greater than 4000 mg/L), of which more than 40% was coarse ($\geq 38 \mu\text{m}$) (Fig. 5, 6).

Salinities in the south channel of South Passage (just south of Jiudjan Bank) generally were less than 5‰ except during

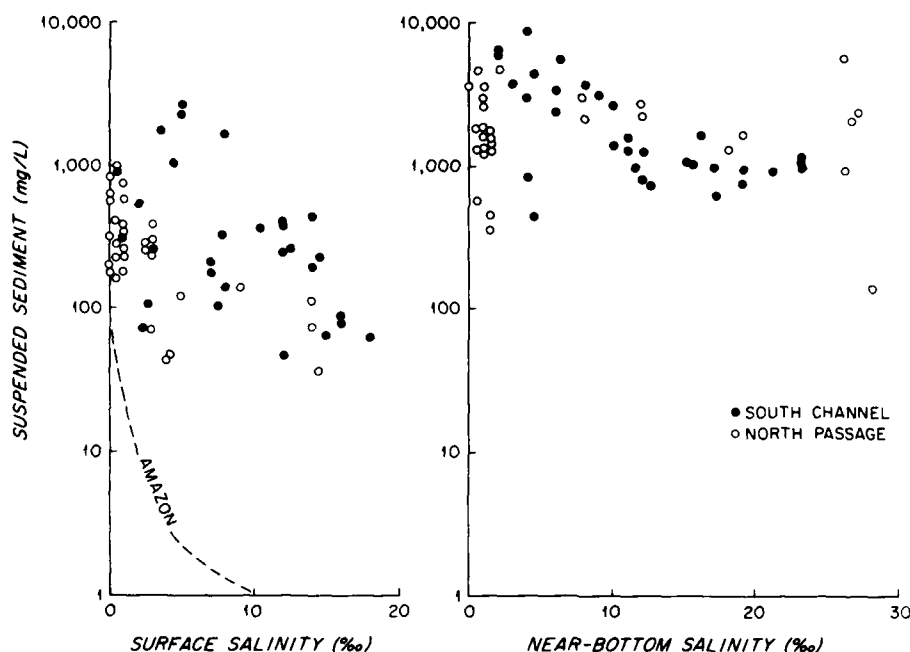


FIG. 10. Variation of suspended sediment and water salinity in surface (left) and near-bottom waters (right) of the Yangtze Estuary. Note the higher relative concentration of suspended solids in the south channel surface waters. Comparison with the trend for surface waters in the Amazon River (after Milliman et al. 1975) illustrates the turbulent (resuspended sediment) nature of the water column.

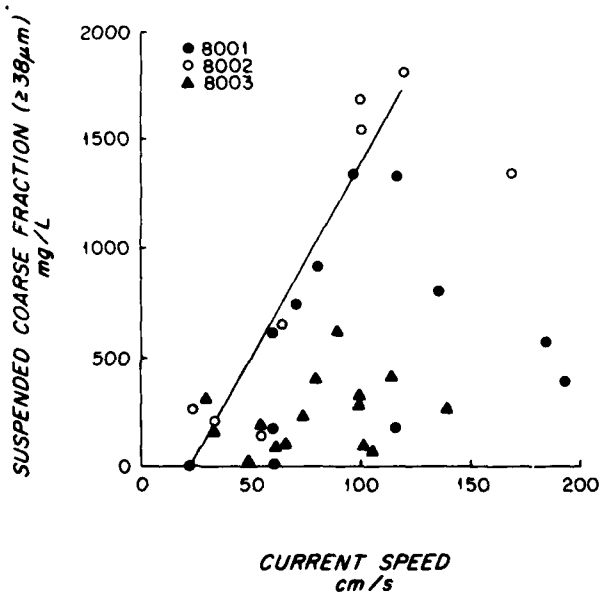


FIG. 11. Comparison of the coarse fraction in suspension and the current speed 1 m above the bottom at stations 8001, 8002, and 8003.

high tides (Fig. 7). Ebb currents exceeded 150 cm/s, but bottom currents during rising tides reached 100 cm/s (upstream). Near-bottom suspended solid concentrations were much higher (6000–8000 mg/L) than in the North Passage, but sand and coarse silt contents were small (Fig. 8).

Salinities at stations 8008 and 8010, the seaward ends of the North and South Passages, were far more marine, with near-bottom values exceeding 20‰ during high tide (Fig. 8 and 9). Surface velocities were as high as those at the landward stations but near-bottom currents never exceeded 100 cm/s, probably the result of density stratification. In contrast to the shoreward stations, peak currents were during high and low tides, not at flood and ebb, and thus were out of phase with tidal stage. Highest concentrations of suspended matter occurred during flooding tide (Fig. 8 and 9).

The high concentrations of suspended sediment at various salinities (as compared to a drastic decrease with increased salinity in the Amazon) (Fig. 10) indicates that a large portion of the surface water sediment was resuspended or maintained in suspension by turbulence. Although peak velocities in the South Channel (station 8003) were lower than in the North Passage, the concentration of suspended matter was higher (compare Fig. 5, 6, and 7). Interestingly, the amount of suspended coarse material in the South Channel was far lower than in the North Passage, the concentrations apparently unrelated to current speed (Fig. 11).

Time-averaged surface currents at all five time-series stations flowed offshore, but the average speeds were greater in the north than the south (Table 2). This agrees with Chinese observations, and explains the lower average salinities in the North Passage. Current speed decreased with water depth at all stations, but net water transport generally remained offshore.

Integrating the sediment concentration and current speed over one or more tidal cycles allows calculation of the

TABLE 2. Calculation of net water and sediment discharge for five anchor stations in the Yangtze Estuary. Mid-June 1980. The "On" and "Off" after the sediment discharge numbers refer to onshore or offshore transport.

Sta.	Tidal cycles	Water discharge (cm/s) (direction)		Sediment discharge (t/m of river width) (on or off shore)	
		Surface	Near-bottom	Total sediment	$\geq 38 \mu\text{m}$
8001	1	110 (110°)	75 (115°)	180 on	30 on
				480 off	190 off
8002	<1	105 (70°)	70 (72°)	660 off	220 off
				190 on	40 on
8008	<1	55 (60°)	35 (275°)	250 off	120 off
				440 off	160 off
8003	1	30 (68°)	35 (95°)	112 on	30 on
				3 off	20 on
8010	1	45 (132°)	35 (112°)	115 off	10 off
				660 on	50 on
				180 on	0
				480 off	50 off
				220 on	10 on
				170 off	10 off
				390 off	20 off

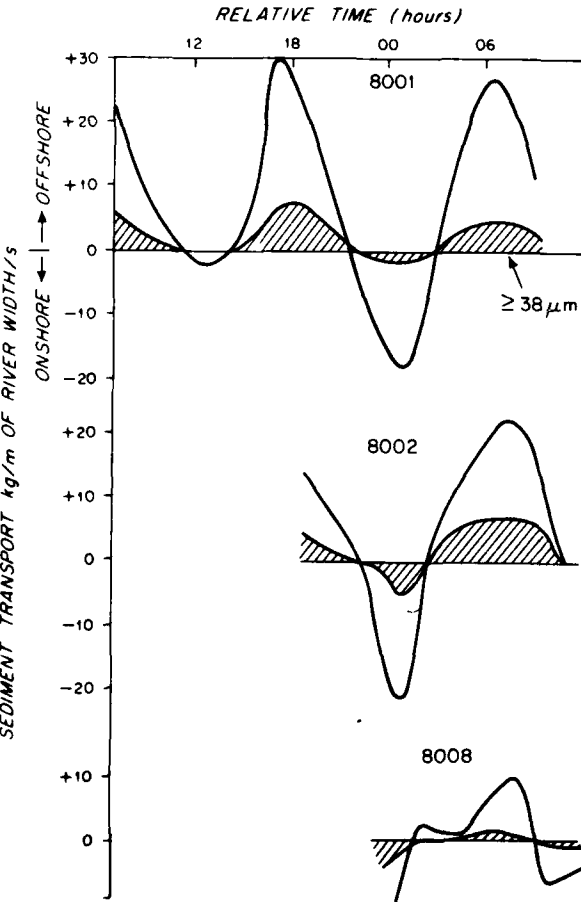


FIG. 12. Calculated sediment transport in the North Passage. Current speeds and suspended sediment concentrations were integrated over depth and time to yield this curve. Sand flux is shown hatched pattern.

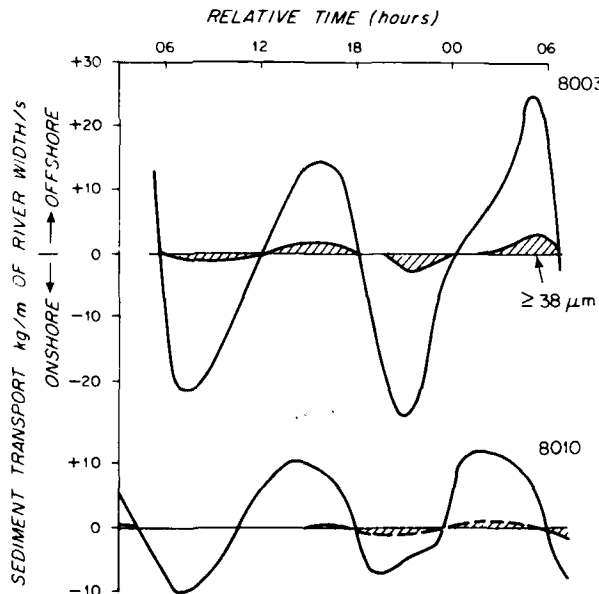


FIG. 13. Calculated sediment transport in the South Passage. Current speeds and suspended sediment concentrations were integrated over depth and time to yield this curve. Sand flux is shown the hatched pattern.

sediment discharge at each station. The North Passage during the study period displayed a marked offshore transport; landward transport at station 8001 occurred only during low low-tide (LLT). Although station 8002 was not occupied for a full 25-h tidal cycle, the measured flux was similar (Fig. 12). Sand transport accounted for 40% of the net sediment flux at 8001 and nearly 50% at 8002, with little landward transport during flooding tide (Fig. 12; Table 2).

In contrast, calculations for the south channel of the South

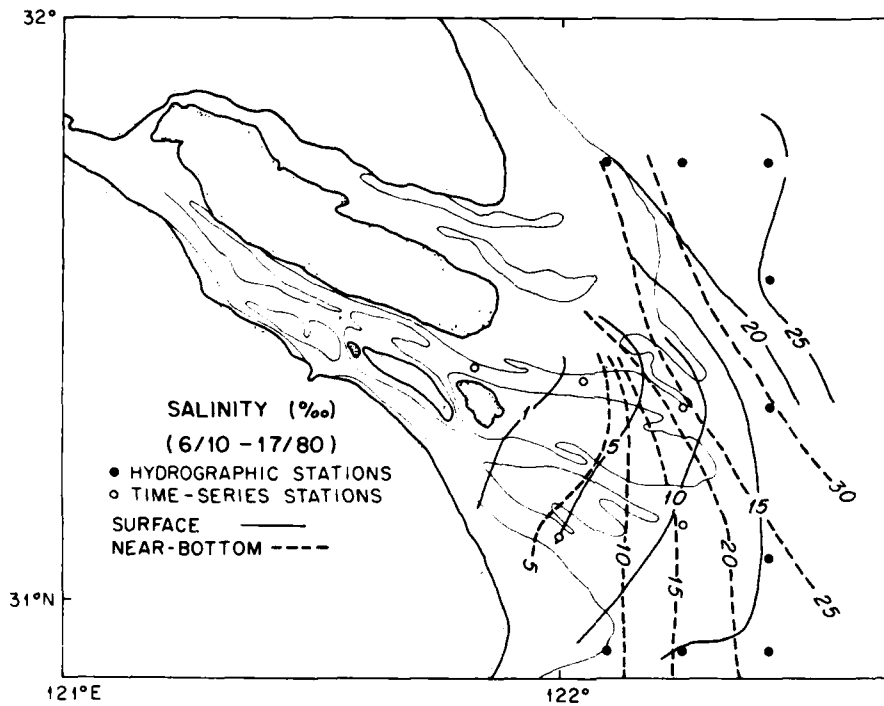


FIG. 14. Average salinity distribution in the surface waters of the Yangtze Estuary during the period June 10–17, 1980. The values for the time-series stations represent tidally averaged values, while the hydrographic stations were measured at the beginning and end of the survey period.

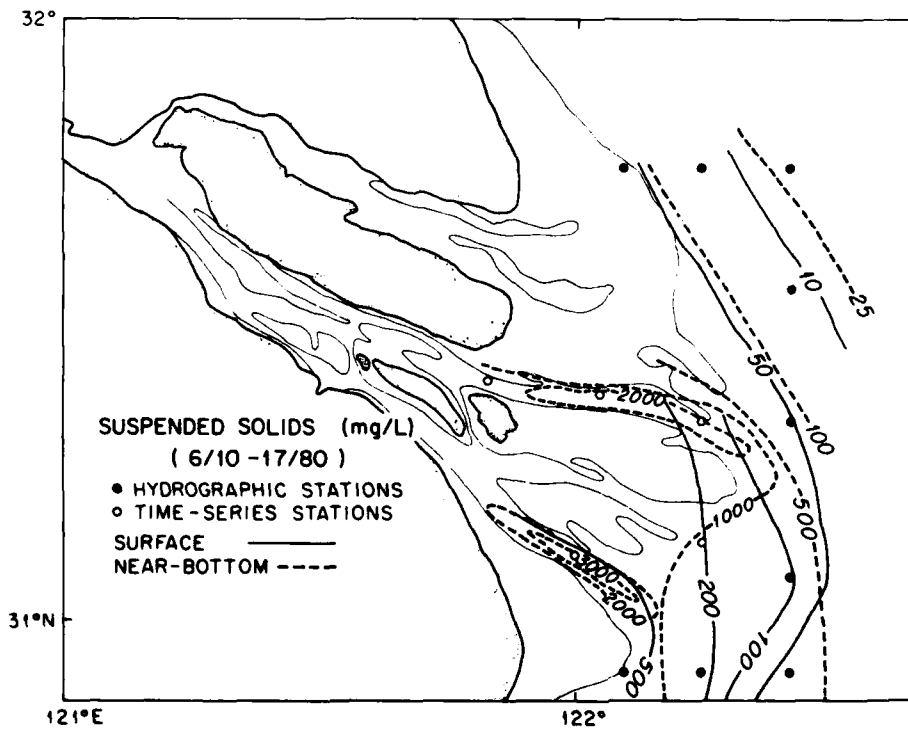


FIG. 15. Distribution of suspended solids in the surface waters of the Yangtze Estuary, June 10–17, 1980.

Passage showed landward sediment transport, but with large upstream and downstream components (Fig. 13). The strong oscillatory nature of transport with net landward flux would explain the high concentrations of sediment within the water column and the shoaling around the bank.

While the time-series results give transport vectors, the hydrographic stations taken around the periphery of the area do not take into account tidal variations or fluxes. Still, plotting these latter values with the mean values from the time-series stations shows that the fresh/brackish water plume escaped to the southeast from the Yangtze mouth; values off the North Branch, as predicted, were far more saline, indicative of the lack of freshwater discharge. Similarly, near-bottom waters were significantly more saline off the North Branch than the South Branch (Fig. 14). In terms of concentration, the suspended solids in both surface and near-bottom waters were greatest in the south, decreasing markedly both north and east of the South Branch (Fig. 15). These hydrographic data represent only distributions of concentrations and not fluxes, since offshore transport occurred primarily in the North Passage. Highest near-bottom concentrations were confined to the channels, but much of the study area had concentrations in excess of 100 mg/L. Although the suspended coarse fraction on the outer parts of the study area tended to be greater in the south, highest sand concentrations, as mentioned above, were confined to the North Passage.

Discussion

The Yangtze River, carrying 500×10^6 t of suspended sediment annually, is one of the major rivers of the world and the biggest river emptying into the East China Sea. Our data, based on observations taken during the week of June 10–17, 1980, describe a complete hydrographic regime: waters within the estuary are well mixed with nearly vertical salinity gradients. In contrast, waters seaward of the distributary channels are more stratified both in terms of salinity and suspended solid concentrations. Tidal variations play an important role in the discharge of both water and sediment from the river, upstream transport occurring during flood tides.

Calculated net current speeds in the North Passage exceeded 100 cm/s, resulting in a major offshore transport of suspended sediment, 40–50% sand and coarse silt. Although

sediment concentrations are much higher in the South Channel than in the North Passage, tidally integrated calculations show large oscillatory excursions of material, with a net upstream sediment transport. The oscillatory sediment transport with a net upstream flux may explain the highly turbid waters in the South Channel as well as the relatively low concentrations of sand and the shoaling nature of the channel near Jiudjan Bank.

Acknowledgments

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The Yangtze River, fourth largest in the world in terms of sediment discharge, contributes about 500×10^6 t annually to the East China Sea. A disproportionate part of the load is carried after peak summer discharge, presumably the result of draining the rice fields. During a week-long study of the estuary, greatest water discharge was observed in the North Passage. Suspended sediment concentrations were highest in the South Channel of the South Passage, although in contrast to the North Passage little of the suspended sediment was coarse. The high sediment concentrations in the South Channel appear to be the result of oscillatory (net transport upstream) movement of material, in contrast to the marked seaward transport measured in the North Passage.

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