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CHINA-U.S. JOINT MUDDY COAST RESEARCH, PART 1, A REVIEW OF HYDROLOGICAL AND SEDIMENTARY PROCESSES IN HANGZHOU BAY, CHINA

by

Hsiang Wang
and
Hong-Chao Xue

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The final report consists of three parts. In this Part I report, the Hydrological and Sedimentary Processes in Hangzhou Bay, China was reviewed based upon historical information and available data.

Hangzhou Bay has evolved from a river mouth in ancient time to its present form under the combined influence of sea-level rise, strong tidal flow and the large influx of sediment from the sea. It is a sea-factor dominated bay. The sediment is very active. The Bay is gradually losing surface area owing to combined effect of shoreline hardening on the north and land reclaimation activities on the south shore. Field data are abundant in the Qidong river estuary. However, the knowledge on the dynamic process of sediment movement in the bay proper is very limited. Data are scarce, particularly simultaneous measurements of currents, waves and sediment concentrations whether in-situ or synoptic.

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Preface

This is Part I of three reports documenting a joint research project between the People's Republic of China and the United States to study the muddy coast environment. They are:

Part I: A Review of Hydrological and Sedimentary Processes, Hangzhong Bay, China.

Part II: In–Situ Wave, Current and Tide Measurement in Hangzhou Bay, China, Data Summary, 1985–89.

Part III: In–Situ Suspended Sediment Measurement, Hangzhou Bay, China.

The project was jointly sponsored by the Ministry of Water Conservancy and Electric Power of China and the Army Corps of Engineers of the United States, Coastal Engineering Research Center, Contract No. DACW 39–86–K–009. The aim of the project was to achieve a better understanding of muddy coast sedimentary process under the influence of strong tidal current and waves.

Originally, the project was to be a three–year effort to review available information, implement in–situ measurements and, finally, conduct synoptic current–wave–sediment measurements over nine tidal cycles. The project was terminated in two–years upon mutual agreement. The final phase of the project was not carried out.

The following persons were participants at various stages of the projects:

From Coastal Engineering Research Center, U. S. Army Corps of Engineers:

Andrew Garcia (Project monitor in the first phase).

James Huston (First instrument deployment).

David McGehee (Project monitor in the second phase).

From Hohai University, People's Republic of China:

Guo Da (Project Manager)

Wu Jian–Guo (Data Collection)

Xue Hong-Chao (Historical Review)

Yan, Yi–Xin (Data Collection and Analysis)

Zhong, Hu-Sui (Data Collection)

From the University of Florida, Coastal & Oceanographic Engineering Department:

Sidney L. Schofield (Instrumentation and Field Deployment)

Ashish J. Mehta (Suspended Sediment Measurement)

Harley Winer (Field Deployment)

Hsiang Wang (Project Manager)

The team also received strong technical and logistic support from the local government of CiXi Prefecture Zhejiang Province and Zhejiang Provincial Institute of Estuarine and Coastal Engineering Research. Li–Hwa Lin, R.C.F.G. Costa and Jingzhi Feng, of Coastal and Oceanographic Engineering Department performed data analysis.

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A Review of Hydrological and Sedimentary Processes in Hangzhou Bay, China

by

Hsiang Wang and Hong–Chao Xue

1 INTRODUCTION

Muddy coast accounts for about 70 percent of the world coastline including practically all the major estuarine and bay systems around the world. In the United States, the Narragansatt Bay in the north, the Chesapeake Bay and Delaware Bay in the mid-Atlantic and the Kings Bay, Pensacola Bay and Mobile Bay in the south are all in muddy estuarine environment. They are invariably the magnets that attract population and settlement owing to the fertile land surrounding them, the rich and productive marine environment, and the all important ability to serve as the centers of water- borne commerce. They all serve as important waterways for the nation and contain many major commercial and/or military ports and harbors. Understanding such an environment has always been of keen interest to the nation. This is evidenced by the numerous studies carried out in recent years. During Reagan's administration, for instance, cleaning and managing the Chesapeake Bay was designated as a national priority.

In China, the coastal belt has one of the highest population concentration in the world. Here, practically all the important coastal commerce centers, harbors and waterways are located in muddy environment. Numerous high sediment-laden rivers empty into the coast creating difficult conditions for navigation and coastal flooding. Therefore, coastal plain management and waterway maintenance have been a preoccupation since ancient time. Consequently, a wealth of knowledge and experience has been accumulated.

In 1986, a joint research program was developed between China through the Ministry of Water Conservancy and Electric Power and the United States through the Coastal Engineering Research Center of the Army Corps of Engineers to study the muddy coast dynamics with the overall objective of advance the state-of-the-art in understanding and solving problems at coastlines, harbors and estuaries where capital and maintenance costs for alleviating mud- related problems including siltation are extremely high. The intent is to pool the expertise together, in particular, the long historical experience from China and the contemporary instrumentation and measurement techniques from the United States to conduct a concerted research.

A specific research plan was developed that falls within the protocol between the Corps of Engineers of the Department of the Army of the United States of America and the Department of the Foreign Affairs of the Ministry of Water Conservancy and Electric Power of the People's Republic of China on Cooperation in Scientific and Technological Research and Laboratory Activities in the Field of Water Resources Engineering and Related Studies Concerning Muddy Coast and Related Subjects. The tasks to be performed were:

1. Conduct field experiments for measurement of waves, water levels, currents and sediment in a representative muddy bay environment.
2. To examine and analyze available historical data on the hydrography and hydraulics of the bay in order to ascertain historical long-term trend.

It is hoped that the information acquired will enable us to develop and verify predictive capabilities and to facilitate comparisons of bay environment between China and the United States.

A total of six possible field experimental sites were examined before Hangzhou Bay was selected. This site is highly desirable for the following reasons:

1. It represents a typical muddy environment with rather uniform bottom material of fine grains and a high percentage of clay.
2. The range of sediment concentration, on a spatial and/or temporal basis is rather wide but measurable within the capability of modern instrument.
3. The environment is sufficiently dynamic that detectable changes can be measured within reasonable experimental time frame.
4. It has a definable boundary of manageable size.
5. Finally, or perhaps most importantly, good historical documentation of hydraulic and morphological changes is available.

In this Part I report, the characteristics of the hydrological and sedimentary processes are summarized.

2 GEOMORPHOLOGICAL CHARACTERISTICS AND HISTORICAL DEVELOPMENT

Hangzhou Bay is situated in the populous southeast region of China immediately south of Changjiang (Yangtze River) delta (see location map in Figure 1). It is the largest estuarine system along the coast of East China Sea. Land flanking the Bay is most fertile and this region is often referred to as one of the rice and fishing factories

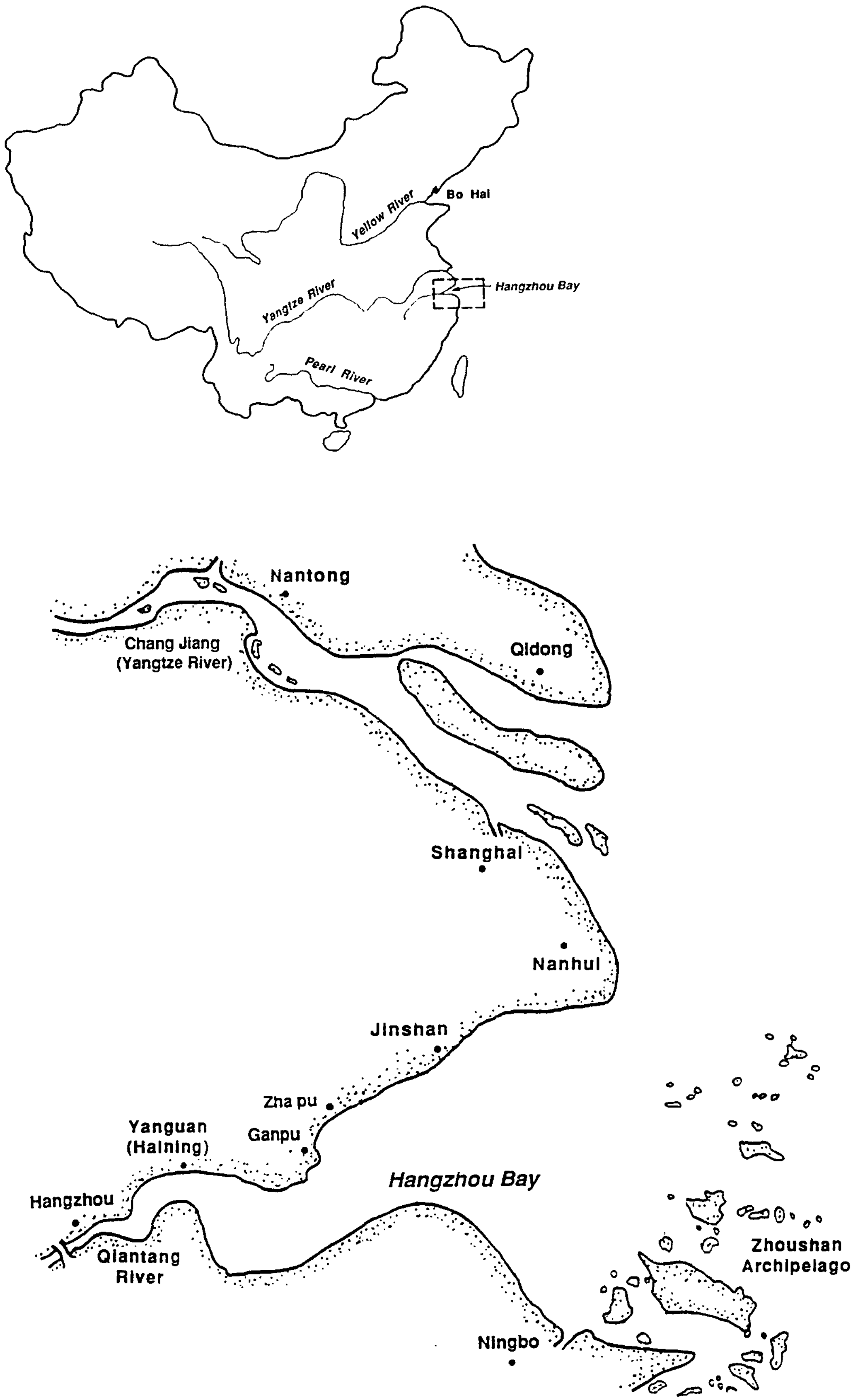


Figure 1: Location Map of Hangzhou Bay

for the nation. Major commerce centers including Shanghai, Hangzhou and Ningbo are all within 80 km from the Bay. The city of Hangzhou, which has the same name as the Bay, also served as the Capital of the South Sung Dynasty (1127–1279 AD) and numerous regional kingdoms. Owing to its historical and economical significance, Chinese government always maintains a high level of activities along the bay shore, the bay proper and the upper estuaries. Such activities include flood and erosion control, land reclamation, waterway maintenance and training of upper estuaries.

The bay proper as shown in Figure 2 is funnel-shaped with its major axis oriented in east-west direction. The center is approximately located at 30° 15'N and 120° 10'E. The east end opens to the East China Sea and has a width of about 100 km at the mouth. Towards west, it gradually narrows to approximately 20 km near Zhapu which is about 80 km from the bay mouth. The region in between is considered as the bay proper and the hydraulics is tidal dominated. By and large, the bay proper is shallow and flat with water depths average less than 10 m. Along the northern shore, however, owing to the influence of strong tidal currents, scouring holes up to 50 m deep were developed. Land locations adjacent to these deep holes are the natural choice for deepwater port sites.

West of Zhapu, the Bay rapidly narrows to merge with the lower reach of Qiantang River. From Zhapu to Hangzhou (Figure 1), the width decreases from 20 km to 1 km over a length of 120 km. In this reach, the hydraulics is under the mixed influence of ocean tide and river flow. It is designated as the estuarine reach. In this reach, the incoming ocean tide progressively amplifies owing to the combined effect of rapid bank convergence and the shallow bottom. At the throat of the bay near Ganpu, for instance, the tidal amplitude nearly doubles that at the bay mouth, reaching a mean tidal amplitude of 5.45 m and a maximum value of

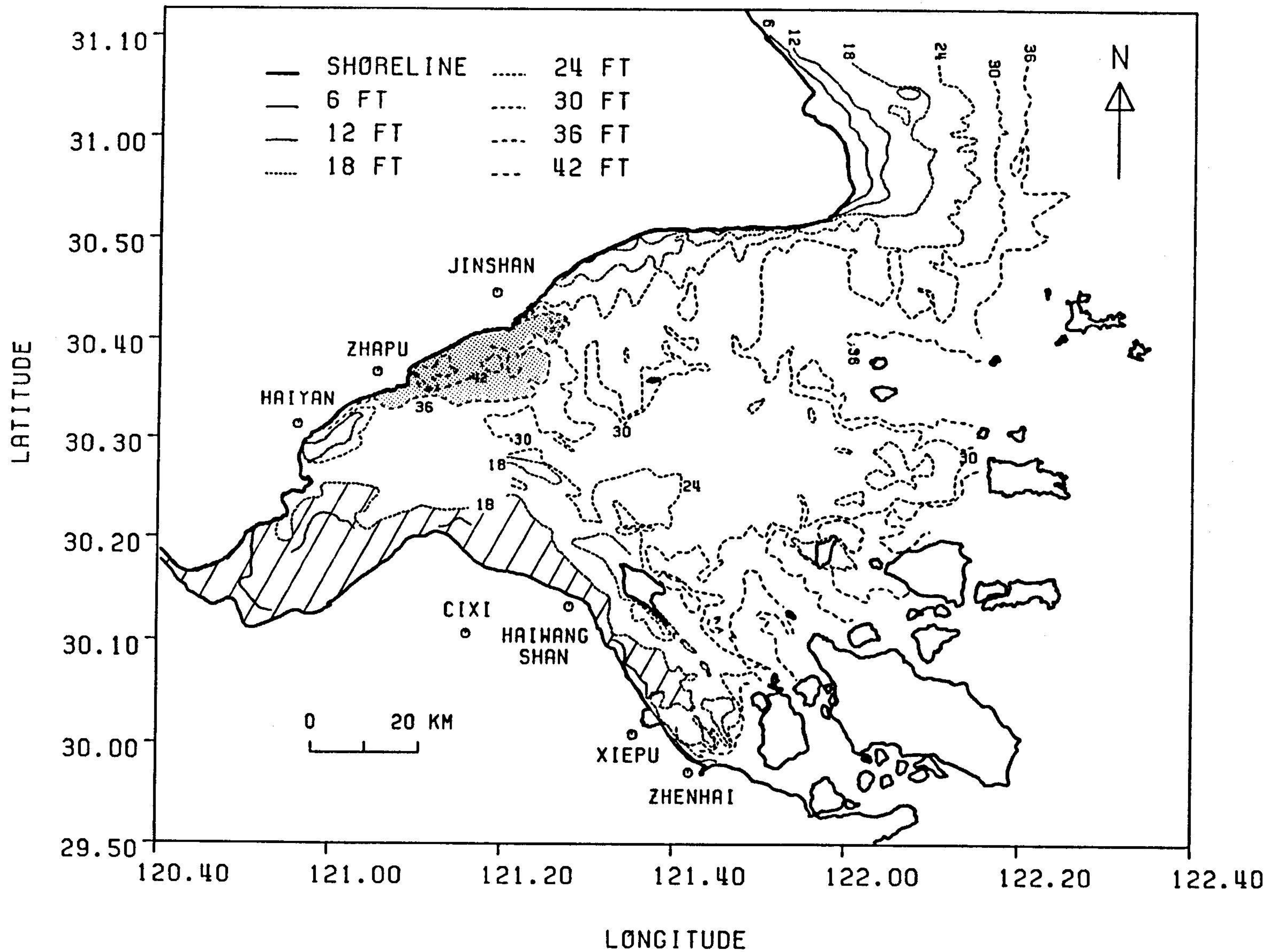


Figure 2: Hangzhou Bay Proper

8.93 m (Dai and Lee, 1978). The associated strong tidal current coupled with the shallowness of the bay bottom causes large quantity of sediment to be carried into this reach, forming a huge sand bar. Figure 3 shows the longitudinal bottom profile along this reach. This amplified tide when enters the reach of converging bank and shoaling bottom produces the world renowned spectacular tidal bore phenomenon. This tidal bore initiates in the vicinity of Jinshan when the water depth can no longer sustain a sub-critical flow. This tidal bore, climbing over the rapidly assenting sand bar, reaches its peak height near Yanguan (Haining). Figure 4 shows the tidal curve at Yanguan. The bore heights under normal condition are about 1 to 2 m but can reach as high as 3 m during spring tides in Autumn. Further upstream from Yanguan, the bottom becomes so shallow that the tidal bore is being dissipated rapidly. When it reaches Qibao (about 30 km upstream from Yanguan), the tidal bore is practically diminished.

Upstream from Hangzhou, the tidal effect is much weakened but can still be felt during dry seasons. Beyond Wenjiayan some 10 km west of Hangzhou, the tidal influence is considered to be minimal and the hydraulics is dominated by the river flow.

Hangzhou Bay originally was an integral part of Qiantang River with a much narrower width. The shoreline on the north side was also considerably southward with respect to its present position. The abundant sediment supply from Changjiang led to the eastward growth of the northern bank and the filling in at the bay mouth. The strong flood tide hugging the northern bank due to Coriolis force constantly eroded away the bank material in the inner section of the bay proper, causing this part of the bank to retreat northward. Massive bank stabilization projects were implemented in the last few centuries. Now, the northern bank is largely hardened. Figure 5 shows the hardened shoreline and the great tidal bore near Yanquan.

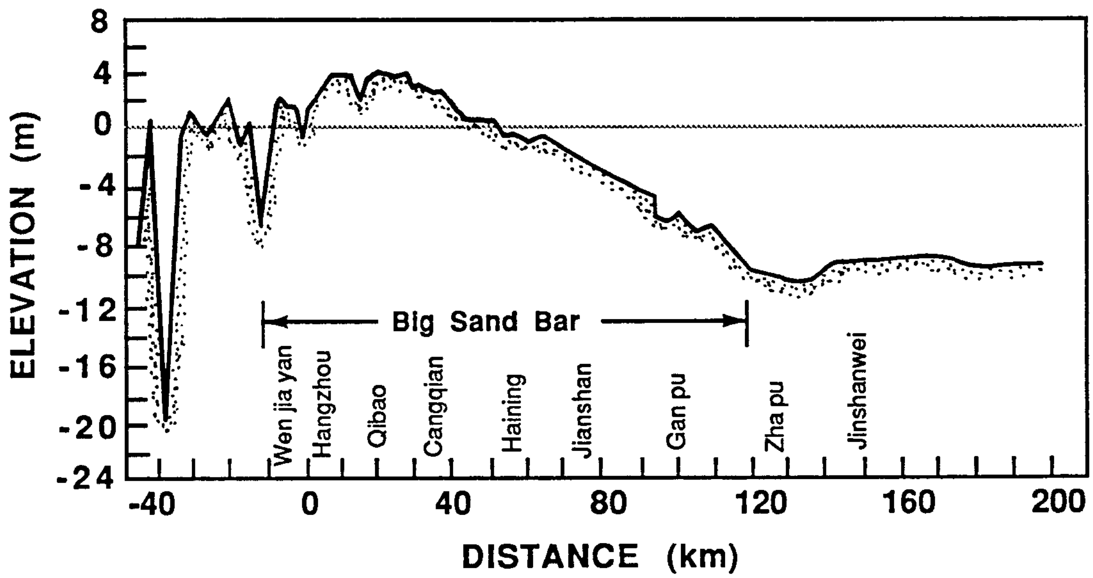
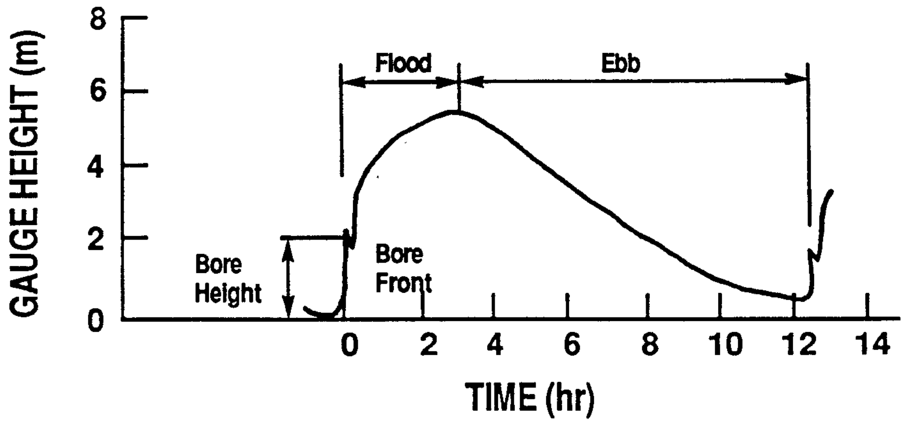
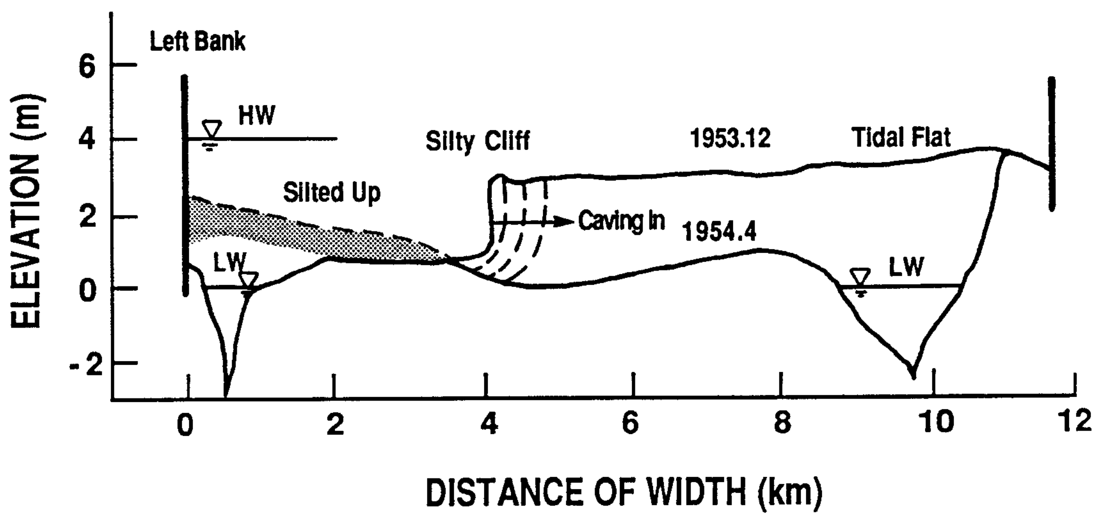


Figure 3: Longitudinal Bottom Profile Along the Estuarine Reach



TIDAL CURVE AT YANGUAN



SHIFTING OF MAIN CHANNEL

Figure 4: Tidal Curve at Yanguan

Figure 5 Hardened Northern Shoreline and Great Qiantang Tidal Bore

The morphology on the southern part of the Bay is more complicated. The Bay mouth on this side is flanked by the Zhoushan Archipelago which wraps around a semicircle from the southern tip of the Bay to the east. It is part of a submergent coast, thus, numerous deep channels exist between the inlands. Among the important ones are the Jin Tang Channel, the Blackwall Channel and the Tower Hill Channel. They are natural candidate sites for deep water ports. Sediment from the continental shelf brought in through these channels tend to deposit on the southern portion of the Bay. This coupled with the sediment brought from upstream rivers by ebb tides created a depository environment conducive to land reclamation. Large and systematic land reclamation projects were carried out here. Tens of thousands of hectares of land were reclaimed along the southern bank from the city of Zhenhai on the east extending into the Qiantang River as far west as Shaoxing.

Hangzhou Bay has evolved from a river mouth in ancient time to its present form under the combined influence of sea level rise, strong tidal flow and a large influx of sediment from Changjiang and the continental Shelf. The most significant sea level rise occurred approximately 7,000 years ago. An ancient gulf was formed which became the origin of the present Hangzhou Bay. The sea level remained relatively stable afterward and sediment gradually filled the gulf to form a submerged plain. Shoreline changes were active with the northern bank progressively retreating and the southern bank progressively advancing. The northern shore was finally stabilized with hardened protective structures and the Bay eventually developed into the present funnel shape.

Based upon archaeological evidence and ancient notes, the historical shoreline changes since 3000 B.C. were re-constructed as shown in Figure 6. As can be seen from this figure, prior to the 8th century, the main body of the present Hangzhou Bay is still part of the East China Sea. The north shore advanced eastward ap-

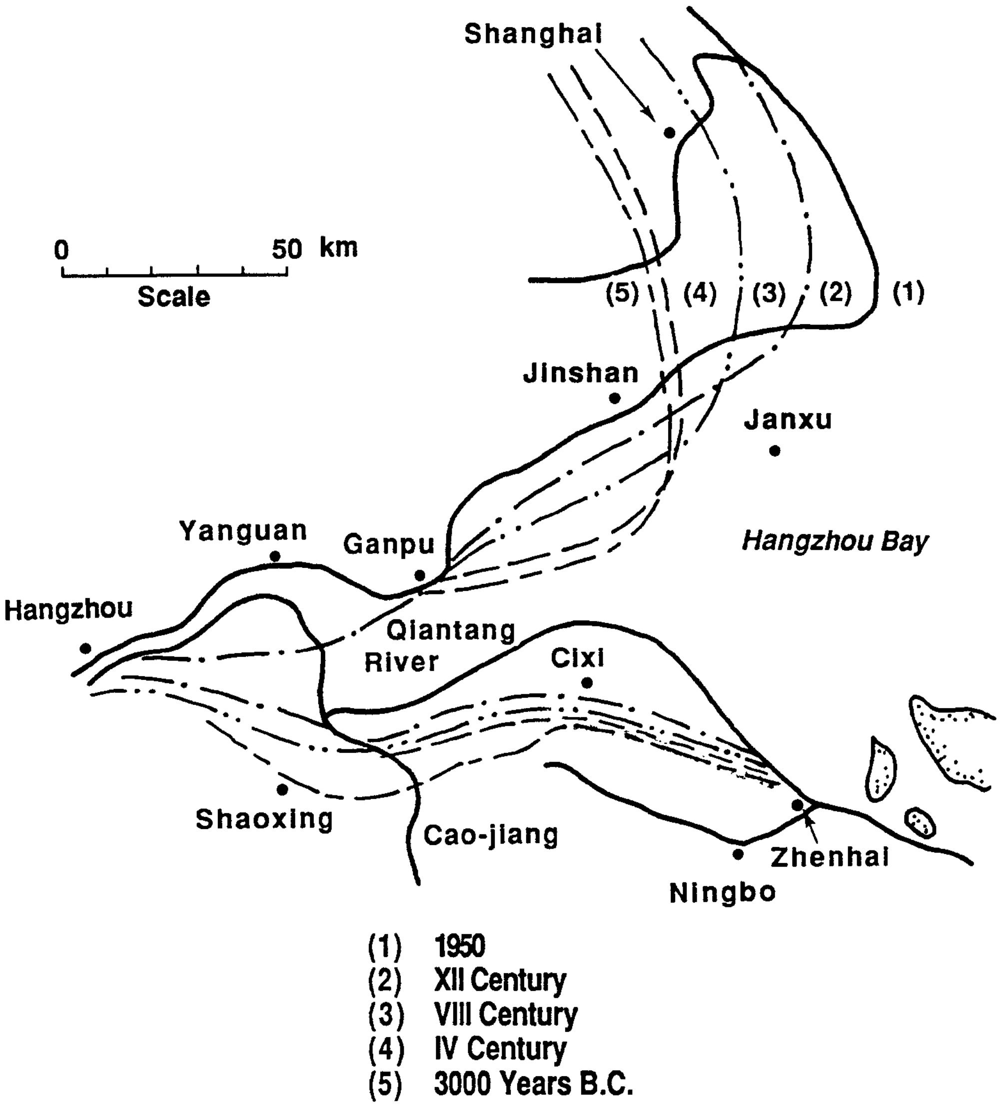
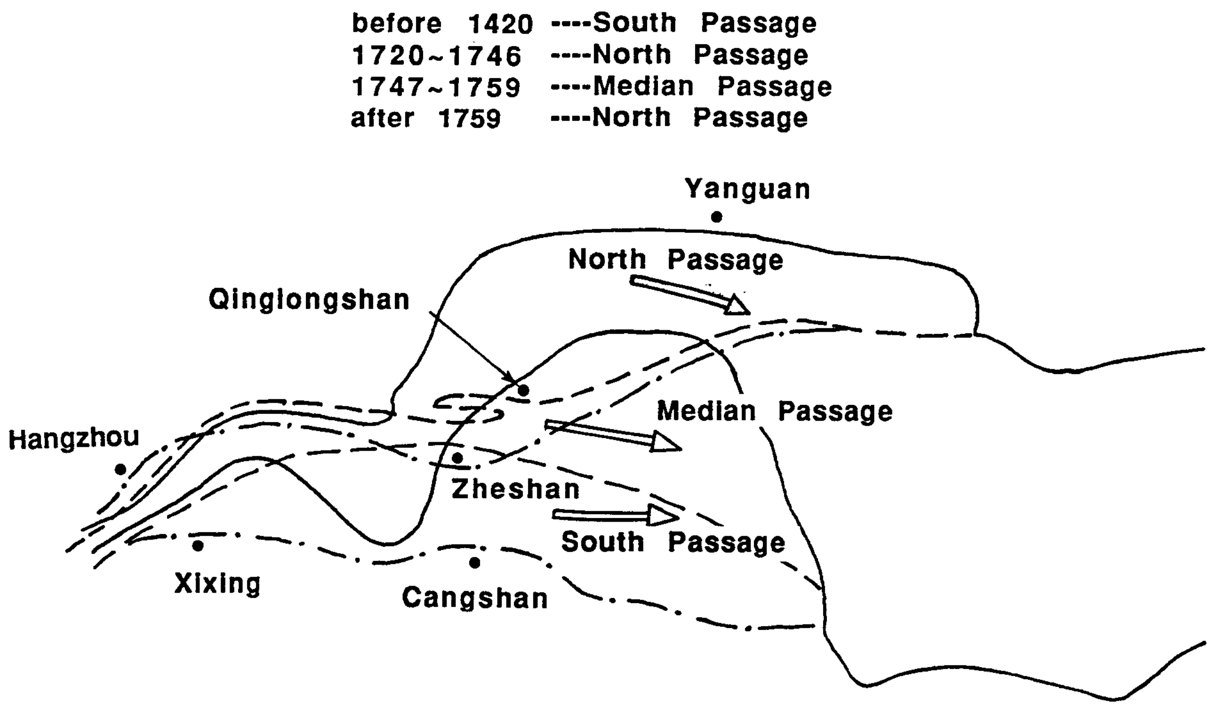


Figure 6: Historical Shoreline Changes in Hangzhou Bay

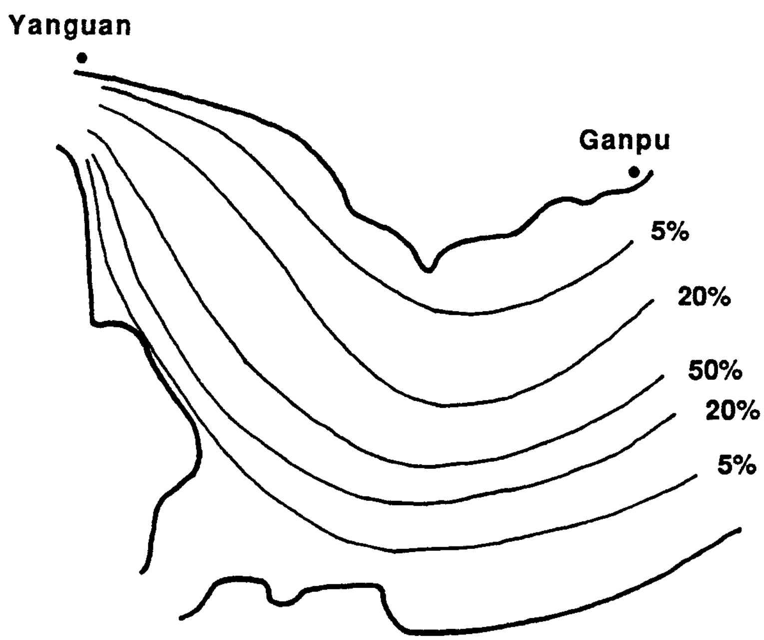
proximately 50 km in 1500 years, or about 30 meters per year. The erosion and the associated shoreline retreat of the north shore are equally evident. The south shore was accretional but at a much slower rate. The significant accretion after the 12th century was partially due to land reclamation effort and the attempt to stabilize the upstream Qiantang River.

Historically, the main flow path in the lower reach of the Qiantang River swung widely between the hardened river banks. In this reach (Figure 7), the average width was more than 20 km but the mean water depth sometimes was less than 1.5 to 2 m at low tide. The effect of such a wide and shallow river bed was that the strong flood and ebb flows tended to carve their own flow path in the loose bed material. This coupled with different river stages governs the location of the main flow path. When the river stage was low and the river discharge was small, the main flow path was dictated by the flood channel. On the other hand, when the stage was high and discharge was large, the main flow path tended to follow the ebb channel. Since the river stage is cyclic annually and sometimes on a multi-year scale owing to large scale meteological events, the main flow path will respond with minor adjustments or major changes. In the past centuries, major swings occurred among three passages as shown in Figure 7. Associated with each major change of river course was the destruction of vast productive tidal flats and reclaimed land. It also altered sediment process resulting in unexpected erosion and accretion along the banks of the bay proper.

In an effort to control and train the river path major reclamation efforts were launched since the 1950's. Figure 8 shows the various stages of land reclamation project in this reach. The purpose was to channelize the river, to maintain adequate energy dissipation and, at the same time, to reclaim land for agriculture purposes. In a 30–year period, the river from Cangqian to Yanguan was narrowed to less than

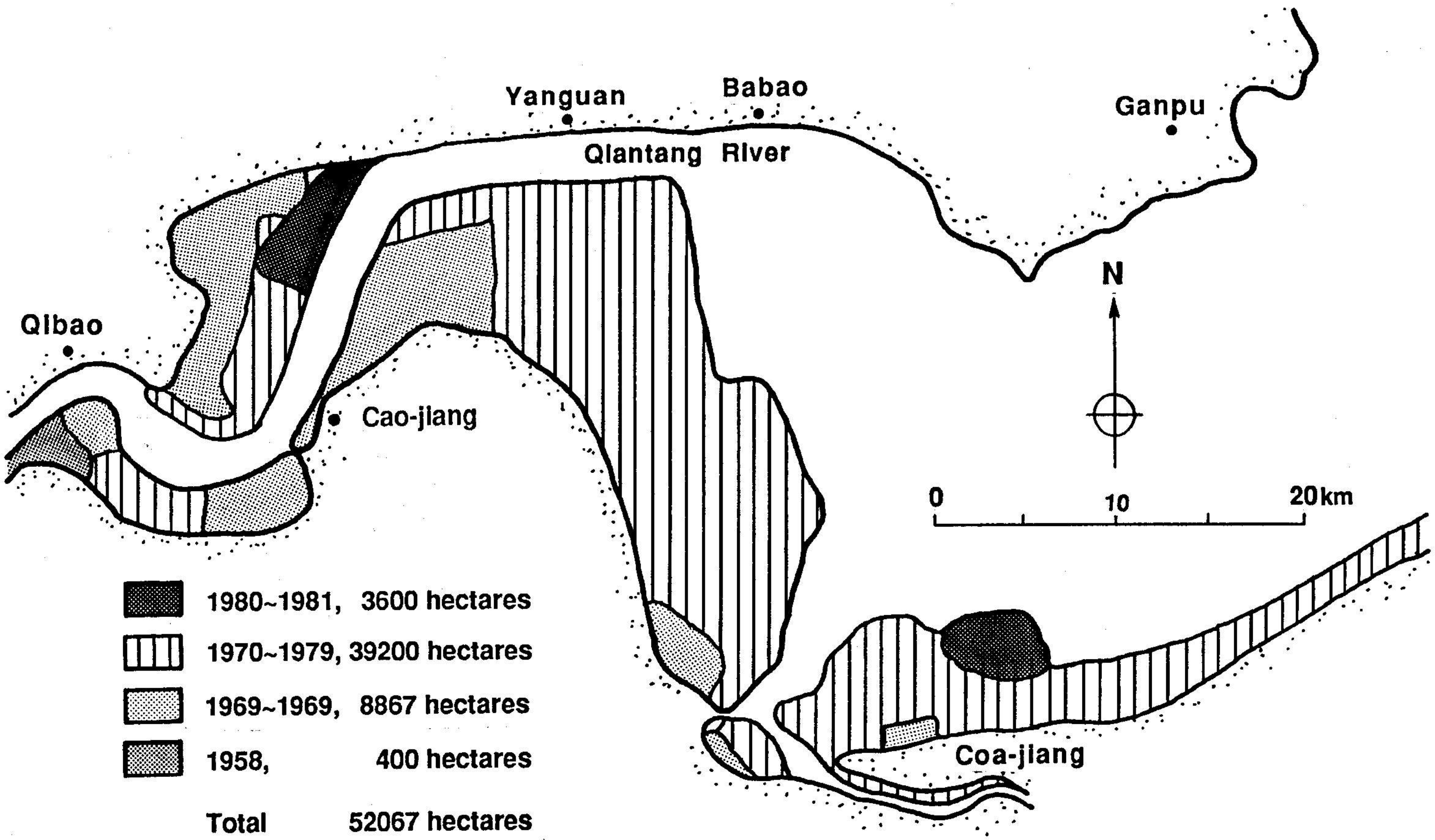


Main Passage Of Qiantang River Mouth



Probablity Of Main Flow Path

Figure 7: Historical Changes of Qiantang River's Main Channel



Land Reclamation In Qiantang River Mouth

Figure 8: Land Reclamation Stages Along Qiantang River Since 1950

3 km and confined to the north passage. The flow, however, did not stop changing course; only that the changes now occurred further downstream. Figure 9 shows the course changes since 1954.

Bank protection work began as early as in the 14th century, first along the river bank on the north shore, then gradually extending to the bay shore to prevent shoreline retreat. By the 18th century, the north shore was largely hardened. The south shore, however, continued to encroach into the bay. Figure 10 chronicles the shoreline advances and the associated reclamation works along the south shore.

3 HYDROMETEOROLOGICAL CONDITIONS

3.1 WINDS

Hangzhou Bay is situated in a zone of transition between temperate and subtropical conditions. Wind variations are seasonal. In the Spring time, easterly winds prevail. Wind direction gradually shifts to southeasterly in the Summer. Then, the wind becomes light and unstable during the Fall. In the Winter time, the formation of high pressure systems over the continent produces steady northwesters. The statistical distributions of wind directions along the north shore are, however, quite different from that of the south shore owing to opposite relationships of sea and land.

Along the north shore, the most prevalent winds are from SSE, SE and ESE. Their cumulative distributions are 11%, 11% and 10%, respectively (Chou, 1984). Therefore, a total of 32% is distributed within the sector centered around SE. The next most frequent wind directions are NW, NNW and N. Their cumulative frequencies are 10%, 10% and 7%, respectively, or, a total of 27% centered around NNW.

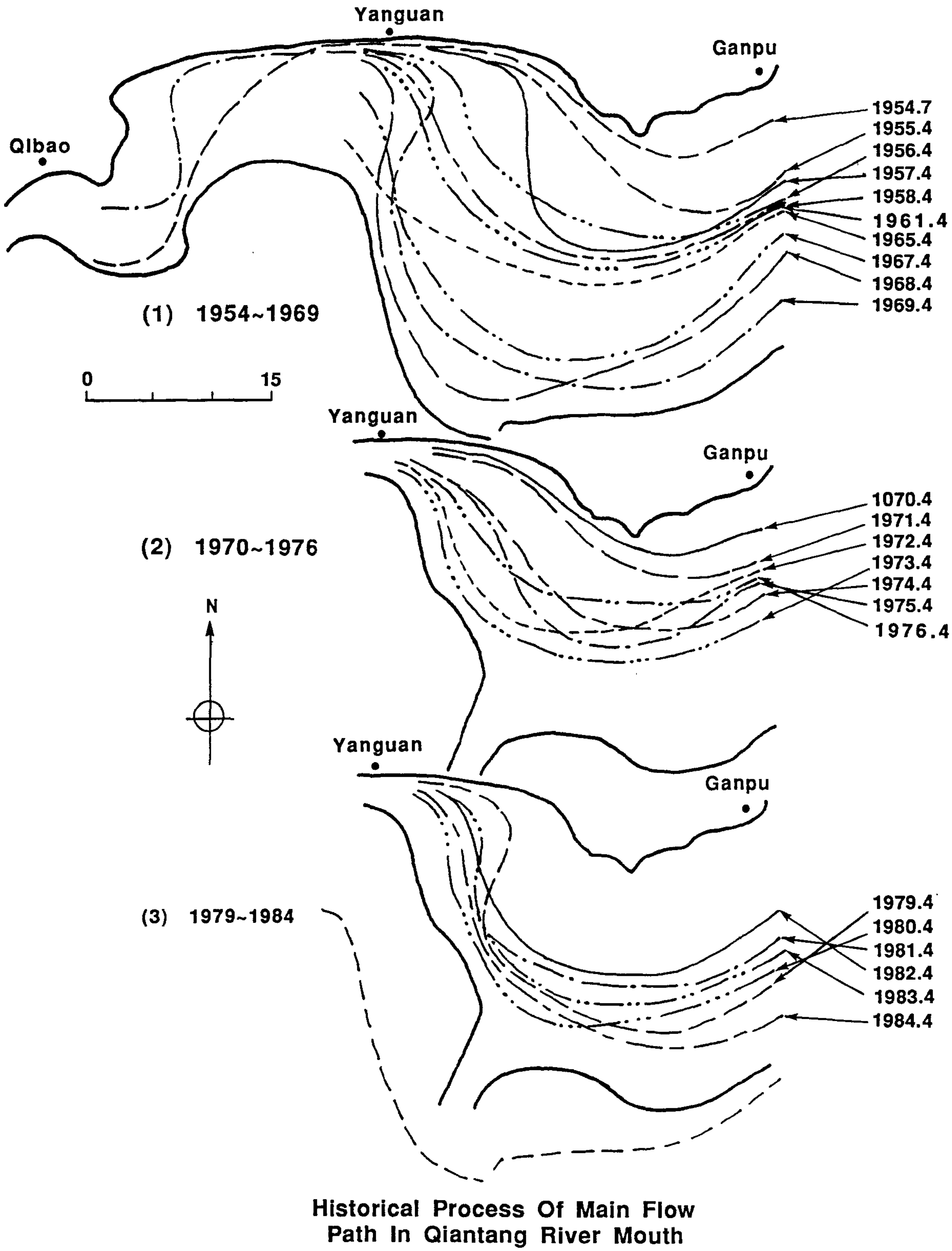


Figure 9: Qiantang River Course Changes Since 1954

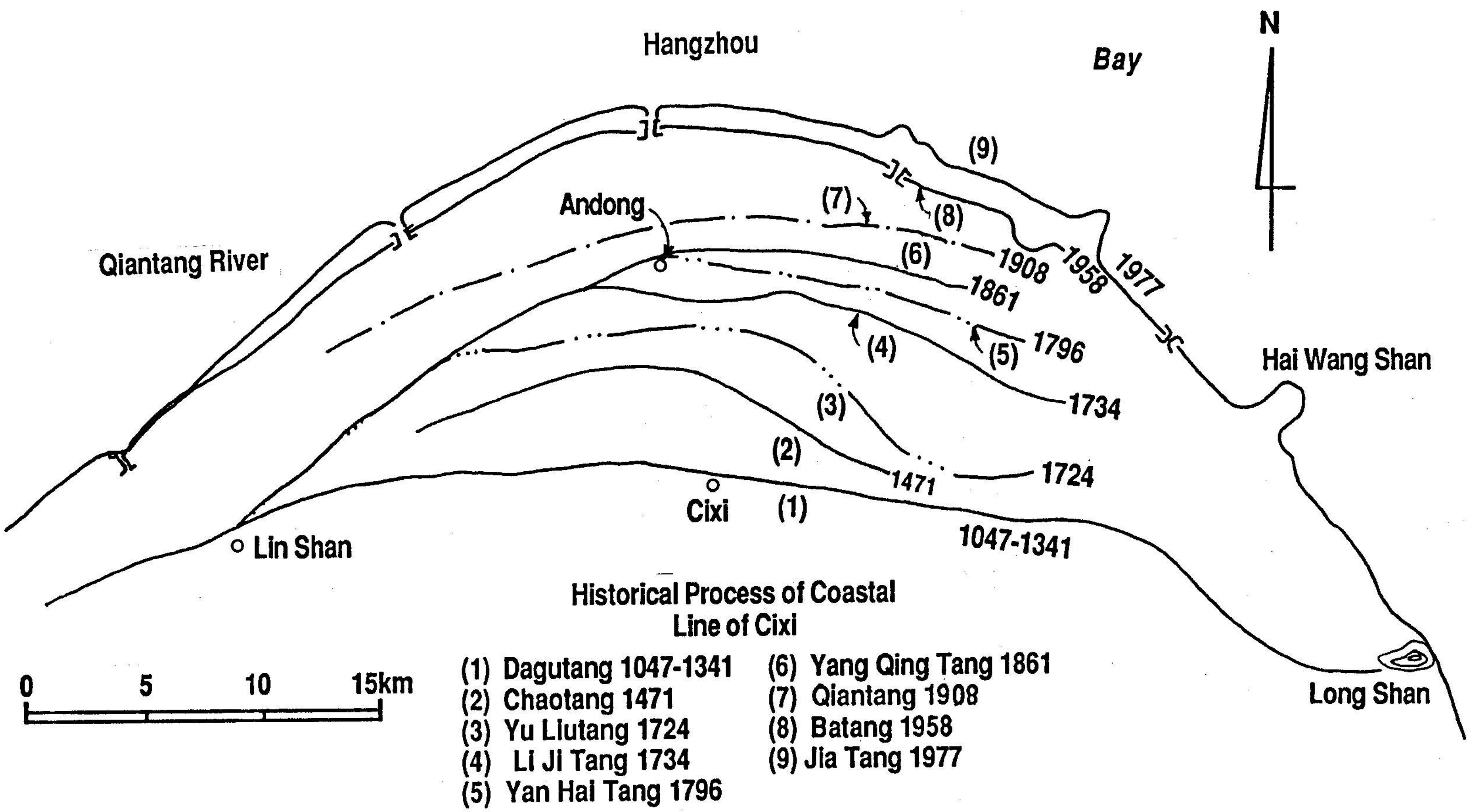


Figure 10: Shoreline Advances Along South Bank of Qiantang River

The south shore is shielded by the land mass from the southerly and southeasterly winds. The most frequent wind directions are from NW, NNW and N with a combined total of approximately 41%. Winds from ESE actually account for 12%, the highest frequency from one direction. But, the combined winds from ESE, SE and SSE, the second highest frequency group, only account for a total of 26% because of the aforementioned shielding effect.

In terms of wind strength, the south shore, in general, experiences stronger wind because of its northerly exposure. Strong breezes with strength over Beaufurt force scale above 6 (10.8-13.8 m/sec) contributes about 10 to 11%, of which about 9% of the strong breezes are from the NW to NE guadrangle (based on statistics provided by CiXi prefecture, 1985). On the north shore, on the other hand, strong breeze is less than 1% and is mainly due to gale winds associated with low pressure systems in the Summer with southeasterly direction.

The extreme winds are usually associated with typhoons; wind direction varies with the path of the storm. Within the last century, extreme winds were observed mainly from NE, henceforth, affected the south shore more than the north shore. Maximum wind speed with 50-year return period was estimated to be 34 m/sec and extreme gales reached 42 m/sec.

3.2 WAVES

Reliable wave information in the bay proper is scarce. Most of the wave observation stations were located near the shoreline. The so-called Ivonov wave gages were the most common instrument employed in the past for wave measurement. They were essentially wave staffs installed at a distance and measurements were made through remote visual observations. Therefore, only simple wave statistics such as significant wave height, wave period and the like could be deduced. Also, most stations were set up for specific purposes of a limited duration. Long term uninterrupted data did not exist. Simultaneous records at two or more stations were also hard to find.

Along the north shore, wave statistics near Jinshan (Goldon Mountain) were compiled by Chou (1984) and the results were given in Table 1. The dominant wave directions are ESE, SE and SSE, with a total of 32%. High waves are also from these directions. The mean wave height is less than 0.4 m.

Along the south shore, there was one wave station at Haiwagshan of CiXi prefecture for a duration of a number of years. The wave statistics at that location is given in Table 2.

Table 1: Wave Statistics at Jinshan (North Shore)

Wave Height/ Direction	0-0.5 M	0.6-1.0 M	1.1-1.5 M	1.6-2.0 M	2.1-30 M	>3.0 M	Total (%)
N	6.70						6.70
NNE	5.30	0.01					5.31
NE	4.90	0.01	0.02				4.93
ENE	2.50	1.30	0.50	0.10	0.04		4.44
E	3.70	2.10	0.80	0.10	0.02	0.03	6.75
ESE	4.60	3.20	2.00	0.30	0.06	0.01	10.17
SE	4.50	2.70	2.70	0.60	0.10	0.01	10.61
SSE	4.20	2.80	2.90	0.80	0.10	0.01	10.81
S	3.70	1.00	0.70	0.10	0.03		5.53
SSW	2.40	0.30	0.10				2.80
SW	1.90	0.20	0.04	0.01		0.01	2.16
WSW	1.30						1.30
W	1.70	0.01					1.71
WNW	4.20						4.20
NW	10.20						10.20
NNW	9.80						9.80
Calm	2.90						2.90
Total (%)	74.50	13.63	9.76	2.01	0.35	0.07	

*Source: Chou, 1984

Table 2: Wave Statistics at Haiwangshan (South Shore)

Wave Height/ Direction	<0.7m	0.8–1.3m	1.3 T 2.0m	>2.0	Total (%)
N	13	1	0.2		14.2
NNE	9	1.2	0.2		10.4
NE	8	0.3	0.2		8.5
ENE	9	0.2			9.2
ES	11				11.0
ESE	12				12.0
SE	6				6.0
SSE	3				3.0
S	1				1.0
SSW	1				1.0
SW	0				0.0
WSW	1				1.0
W	1				1.0
WNW	2	0.2	0.2		2.4
NW	5	0.2	0.2		5.4
NNW	7	0.6	0.4	0.2	8.2
Total (%)	89	3.7	1.4	0.2	

*Source: CiXi Prefecture

The prevailing wave directions are N, ESE and E. Large waves are from NNW. The average annual wave height is about 0.3 m, slightly smaller than the north shore waves.

Along the south shore, Hangzhou Bay extends into a series of deep water channels, with Jin Tang Channel being the closest one to the mainland. Because of its natural depth the Beilun deep water iron ore transshipment terminal is located here. Of the three deep water berths, one is capable of handling 100,000 DWT ships. It is the deepest shore facility in the east China region. During the period of the 1970's to early 1980's, wave data were collected at four locations along the Channel at four stations as shown in Figure 11, they were located at Yusan, Laozhusan, Beilunsan and Maoqioshan, respectively, from the west end to the east end of the Channel. Yusan is located at the eastern tip of the Bay along the south shore.

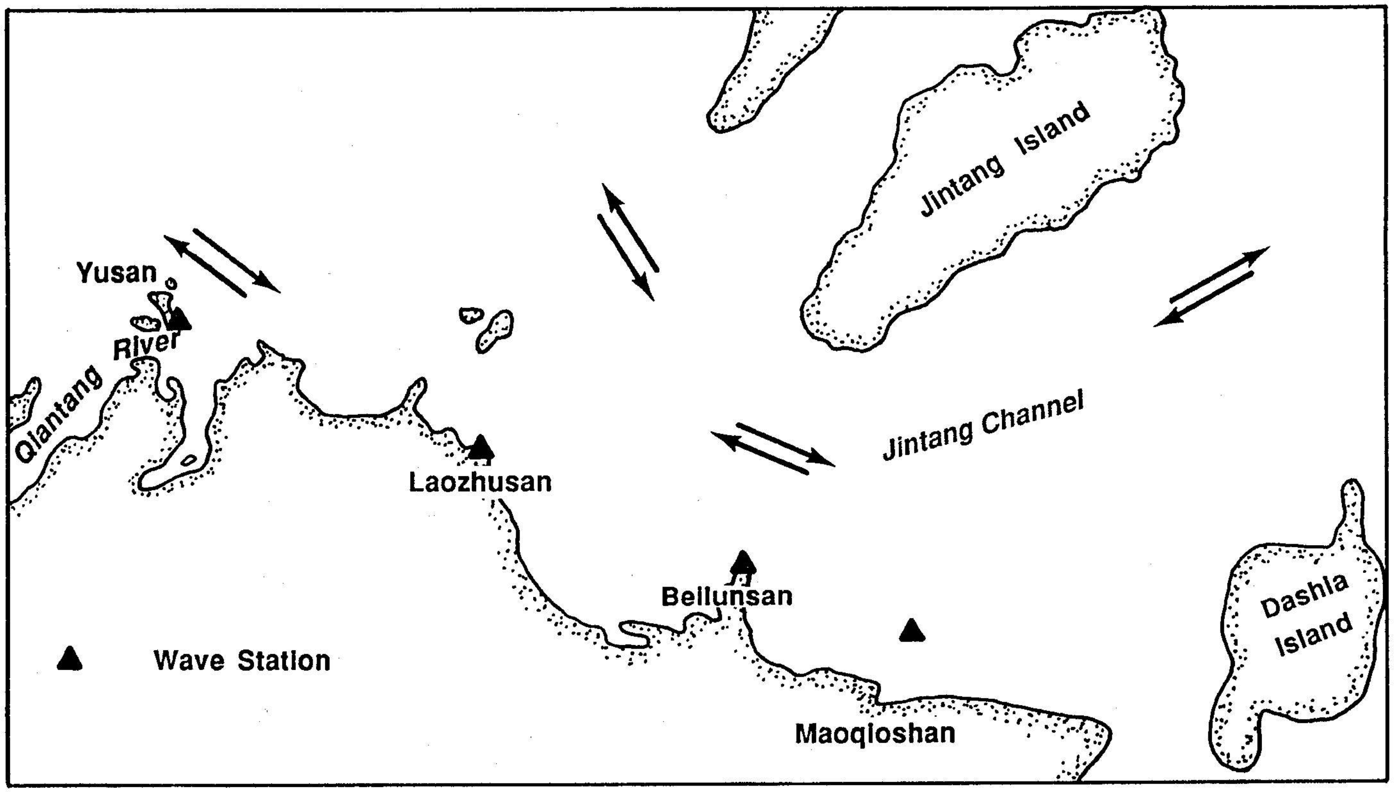


Figure 11: Wave Stations in South Hangzhou Bay

Data were compiled and analyzed by Chou (1984b) and Sun (1984). Comparisons of wave characteristics from the four stations given in Tables 3 to 5 revealed the clear tendency that wind waves and swell gradually lost their strength from the west end towards the east end. Figure 12 shows the seasonal and annual wind and wave roses at Yusan and Laozhusan Stations. It can be seen that the wave and swell are higher at Yusan Station, which is at the west end, than that at the Laozhusan Station which is at the middle of the channel. Basically, wind and wave directions are consistent. In the winter months, both wind and wave are persistently from NW, whereas in the summer months, the prevailing wind and waves are from the SE. These conditions are further accentuated by the channelization effect. For example, in the month of December, the cumulative frequency of waves from NW was about 12% at the west end of the channel (Yusan) but increased to 19% at mid channel (Laozhusan).

As discussed earlier, during the last century, the strong winds associated with typhoons were mostly from the NW to NE quartant. The waves due to typhoon winds were also from the same directions. They were usually in the order of 2 to 2.5 m. The south shore is more susceptible to typhoon waves, owing to the counterclockwise wind field associated with the typhoons and the typical track from the low altitude towards the high altitude as the storm swept across the Bay.

3.3 TIDE AND TIDAL CURRENT

Hangzhou Bay is noted for its strong astronomical tides. The dynamic process of the Bay is dominated by the tidal force. Owing to the prominence of this natural phenomenon, significant amount of tide and tidal current information have been accumulated over centuries. Tidal stations have been abundant along the entire bank of the Bay and the upper estuary. Figure 13 shows the existing locations of

Table 3 Wave Statistics in South Hangzhou Bay

Yusan

Direction	Average Wave Height (M)	Max. Wave Height (M)	Average Period (SEC)	Percentage %
N	0.3	1.6		5.1
NNE	0.2	1.2		6.5
NE	0.2	0.9		8.9
ENE	0.1	0.8		6.5
E	0.1	0.4		8.8
ESE	0.1	0.3		12.2
SE	0.1	0.3		8.0
SSE	0.1	0.2		3.8
S	---	---		---
SSW	---	---		---
SW	---	---		---
WSW	---	---		---
W	---	---		---
WNW	0.3	1.6		6.0
NW	0.4	1.4		9.4
NNW	0.4	2.0		11.3
Average	0.21			
Maximum		2.0		

Source: Sun, 1984

Table 4 Wave Statistics in South Hangzhou Bay

Laozhusan

Direction	Average Wave Height	Max. Wave Height	Average Period	Percentage %
N	0.2	0.9		4.6
NNE	0.2	0.7		2.0
NE	0.1	0.7		2.0
ENE	0.2	0.7		1.0
E	0.1	0.6		2.2
ESE	0.2	1.0		8.0
SE	0.2	0.8		16.0
SSE	0.2	0.7		13.2
S				
SSW				
SW				
WSW				
W				
WNW	0.3	1.5		5.8
NW	0.4	1.4		26.0
NNW	0.3	0.7		9.0
Average	0.24			
Maximum		1.5		

Source: Sun, 1984

Table 5 Wave Statistics in South Hangzhou Bay

Bailun San Station

Direction	Average Wave Height (M)	Max. Wave Height (M)	Average Period (sec)	Percentage %
N	0.29	1.6	2.5	11.16
NNE	0.26	1.0	2.6	3.70
NE	0.16	0.8	2.1	1.46
ENE	0.16	0.6	2.1	1.88
E	0.15	0.5	2.0	1.19
ESE	0.13	0.6	2.1	0.52
SE	0.12	0.4	1.9	0.52
SSE	0.12	0.4	2.0	0.93
S	0.13	0.5	2.2	0.91
SSW	0.09	0.2	1.6	0.05
SW	0.05	0.2	1.6	0.02
WSW	0.07	0.3	2.0	0.05
W	0.15	1.8	2.2	0.41
WNW	0.37	1.2	2.9	7.31
NW	0.39	1.6	2.9	42.72
NNW	0.34	1.7	2.7	27.34
Average	0.20		2.6	
Maximum	0.20	1.8	2.6	

Source: Sun, 1984

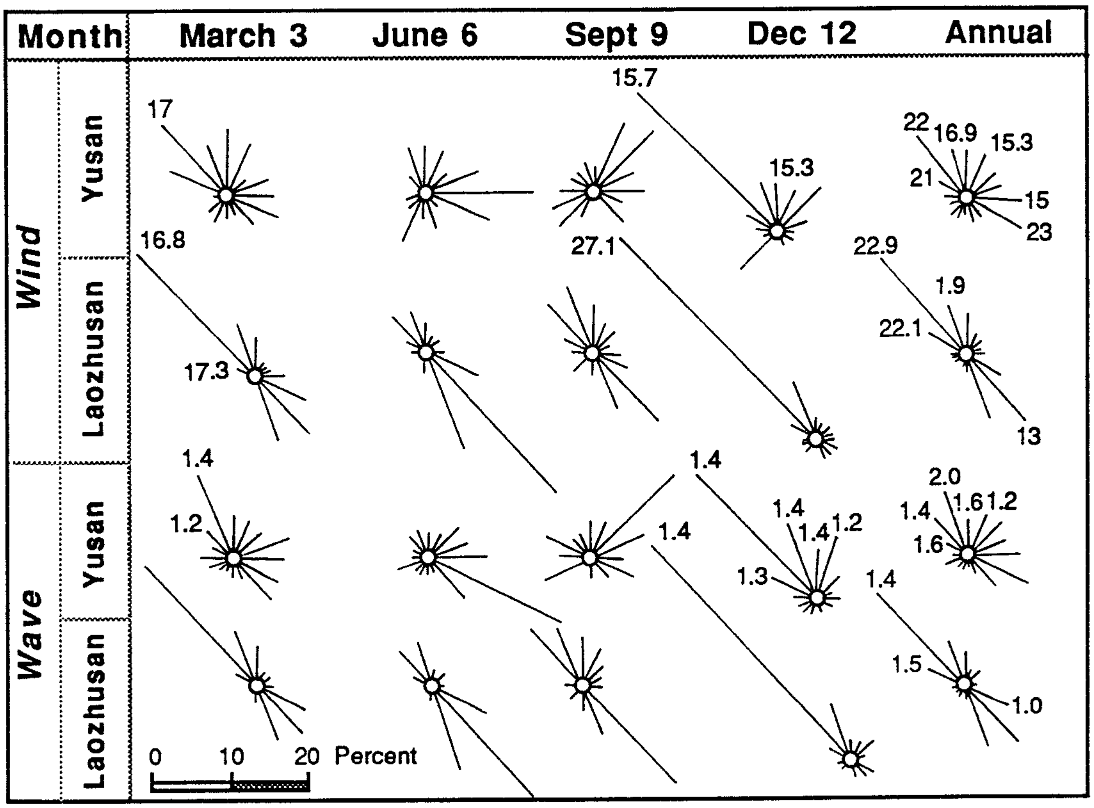


Figure 12: Seasonal and Annual Wind Roses at Yusan and Laozhusan Stations (From Sun, 1984)

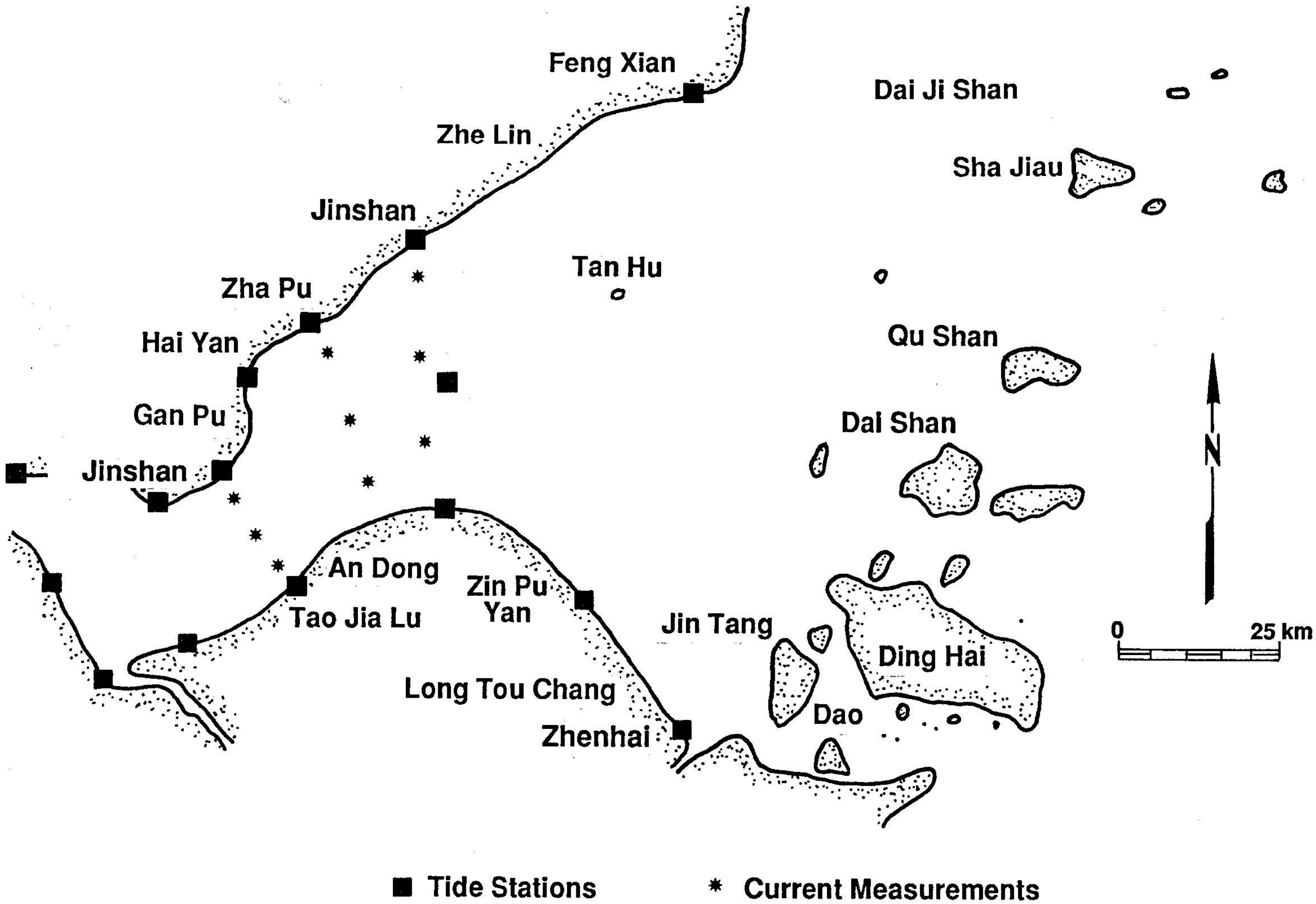


Figure 13: Tidal Stations in Hangzhou Bay

the primary tidal stations. Synoptic tidal current measurements were also carried out systematically since the 1950's.

Hangzhou Bay is situated in a meso-tidal environment. The nature of the tide belongs to irregular mixed semidiurnal, with two highs and two lows in each solar day. The neighboring highs and the neighboring lows are generally unequal owing to the influence of diurnal components. The high-high tide usually follows the low- low tide. Therefore, on the average the flood range is always larger than the ebb range (see Figure 14 for illustration). In the shallow portion of the Bay, the influence of quarter diurnal (M4 tide) is manifested to a varying degree. Also owing to the combined effect of Coriolis force and bottom topography, tidal range is considerably higher along the north shore than along the south shore. However, the most pronounced effect is the funnel- shaped geometry. Tidal range increases rapidly from the entrance of the mouth toward the head of the bay, almost doubling its value in 80 km. Figure 15 shows the change of tidal range in Hangzhou Bay along the north and the south shore and into the Qiantang River estuary. The change of width along the Bay as well as the change in bottom elevation is also shown in the same Figure. Table 6 summarizes the values of tidal range at various tidal stations along both shores. Along the north shore, the "average" tidal range at the mouth of the bay is 3.12 m (Luchaogang) and increases towards the west, reaching a peak value of 5.54 m at Ganpu, approximately 80 km from the mouth. The corresponding "maximum" tidal ranges at bay mouth and at Ganpu are 5.06 m and 8.87 m, respectively. Beyond Ganpu, the influence of river flow becomes increasingly important, the bottom elevation increases rapidly owing to the river sediment being deposited there by the balance of stream and tidal forces. The tidal range also begins to decrease as the energy dissipation becomes more and more important. The tidal range variations along the south behaves in a similar manner except the magnitude is smaller.

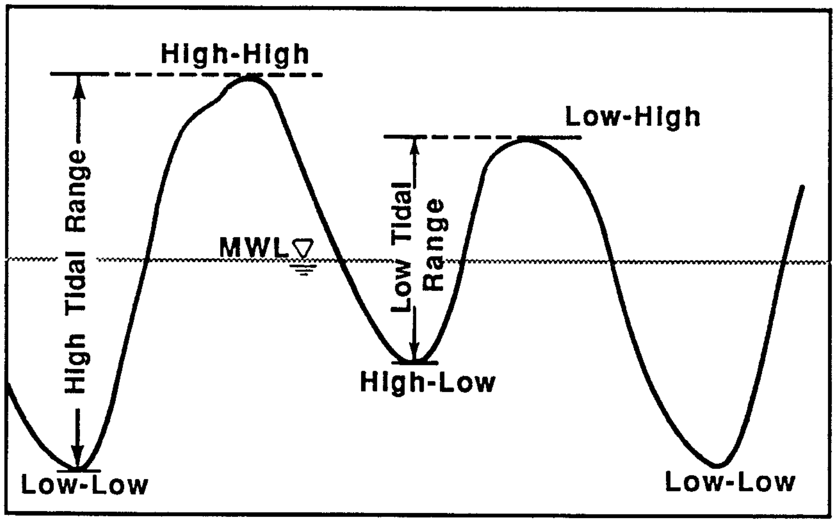


Figure 14: Illustration of Typical Tidal Curve in Hangzhou Bay

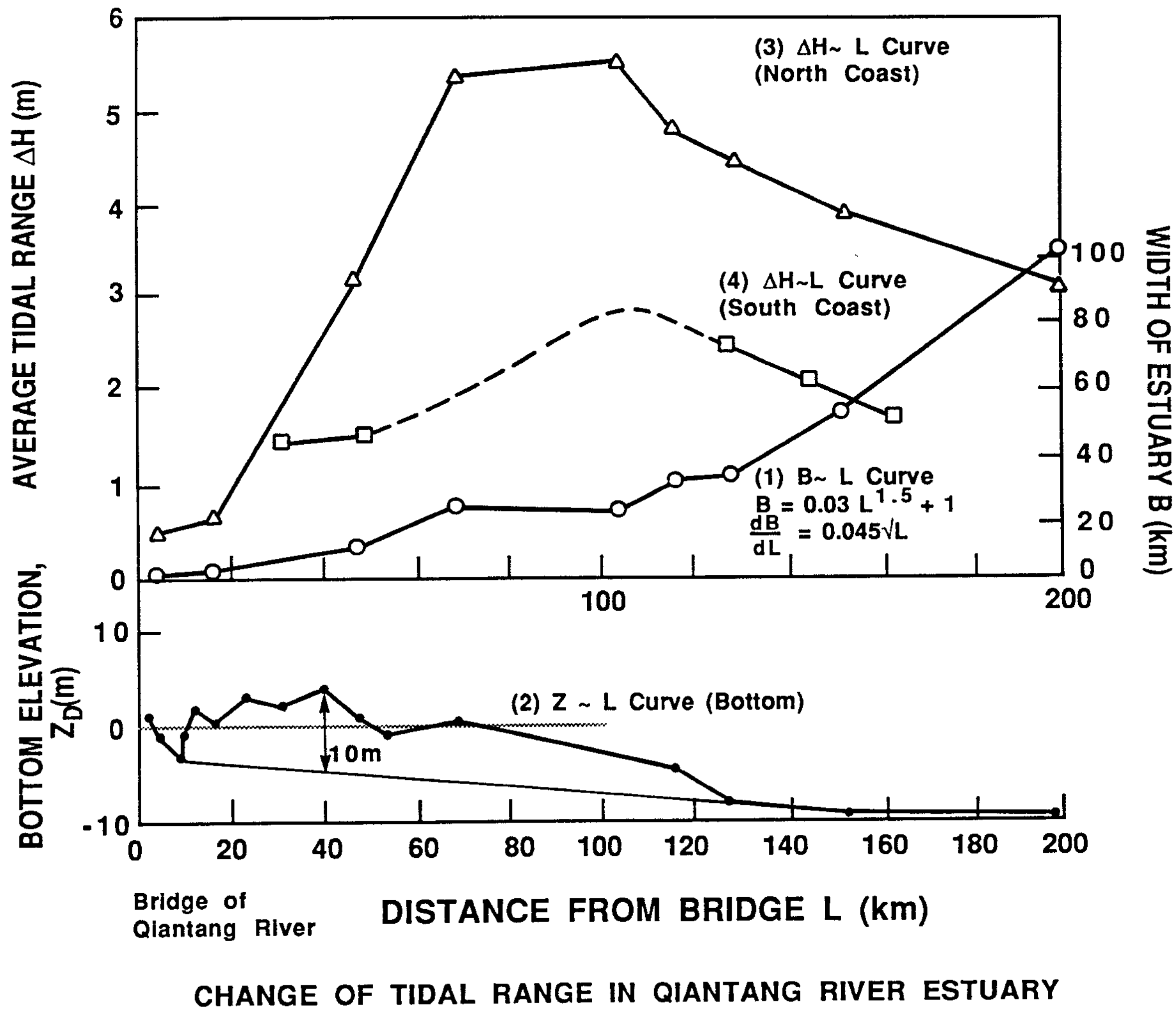


Figure 15: Tidal Ranges North and South Shore and in the Qiantang River

Table 6: Tidal Range at Tidal Stations along Bay Shore

Width of Estuary (km)	1	2	9.5	23	21	30	32	50	100
North Shore	Zhakou	Qibao	Yanguan	Jiajshan	Ganpu	Haiyan	Zhapu	Jinshan	Luchaogang
Distance* from Bridge (km)	2	18	48	71	105	118	130	155	200
Average Tidal Range (m)	0.50	0.70	3.21	5.40	5.54	4.81	4.56	3.91	3.12
Maximum Tidal Range (m)	3.57	3.49	7.24	8.13	8.87	7.85	7.57	6.24	5.06
South Shore		Cangqian	Lihai				Haiwang-Shan	Longshan	Zhenhai
Distance* from Bridge (km)		33	51				129	147	165
Average Tidal Range (m)		1.52	1.57				2.52	2.16	1.75
Maximum Tidal Range (m)		4.90	3.63				4.26	3.62	3.30

*Measured from Qiantang Bridge in Hangzhou.

The distribution of equi-tidal-hour is shown in Figure 16. The equi-tidal-hour lines, at the bay mouth are slightly inclined to the NE-SW direction. Influenced by the presence of Zhoushan Archipelago, the lines tend to bulge in the middle toward the east. Once entering the Bay, tides travel faster on the north side due to deeper depth. The equi-hour lines become almost straight lines in N-S orientation in the vicinity of Jinshan. Further upstream from Jinshan, the shallow water effect on the south side further retards the tidal propagation, the equi-tidal-hour lines start to bend and eventually become bulged in the middle toward the west.

Near Jinshan, a tidal bore begins to form. The bore becomes fully developed when it reached Yanguan. Figure 17 illustrates a fully developed tidal bore near Yanguan. The bores are influenced by the shifting of the river channel. When the channel is straight and deep, higher bores are formed and they reache further upstream. Therefore, in some years, bores reached as far as 40 km upstream of Hangzhou (located at 200 km from the Bay mouth). In other times, bores were completely dissipated way before reaching Hangzhou.

The nature of the tidal current is also governed by the geometry of the bay. The flood and ebb current pattern is shown in Figure 18. The tidal elliptics are very much elongated, dominated by the major axis which almost coincides with the flood-ebb direction. Thus, the tidal current direction is dictated by the bay geometry. Table 7 illustrates the magnitudes of the tidal current in the bay proper. The average tidal current velocity is in the order of 1 m/sec. It can reach as high as 3.5 m/sec at certain locations.

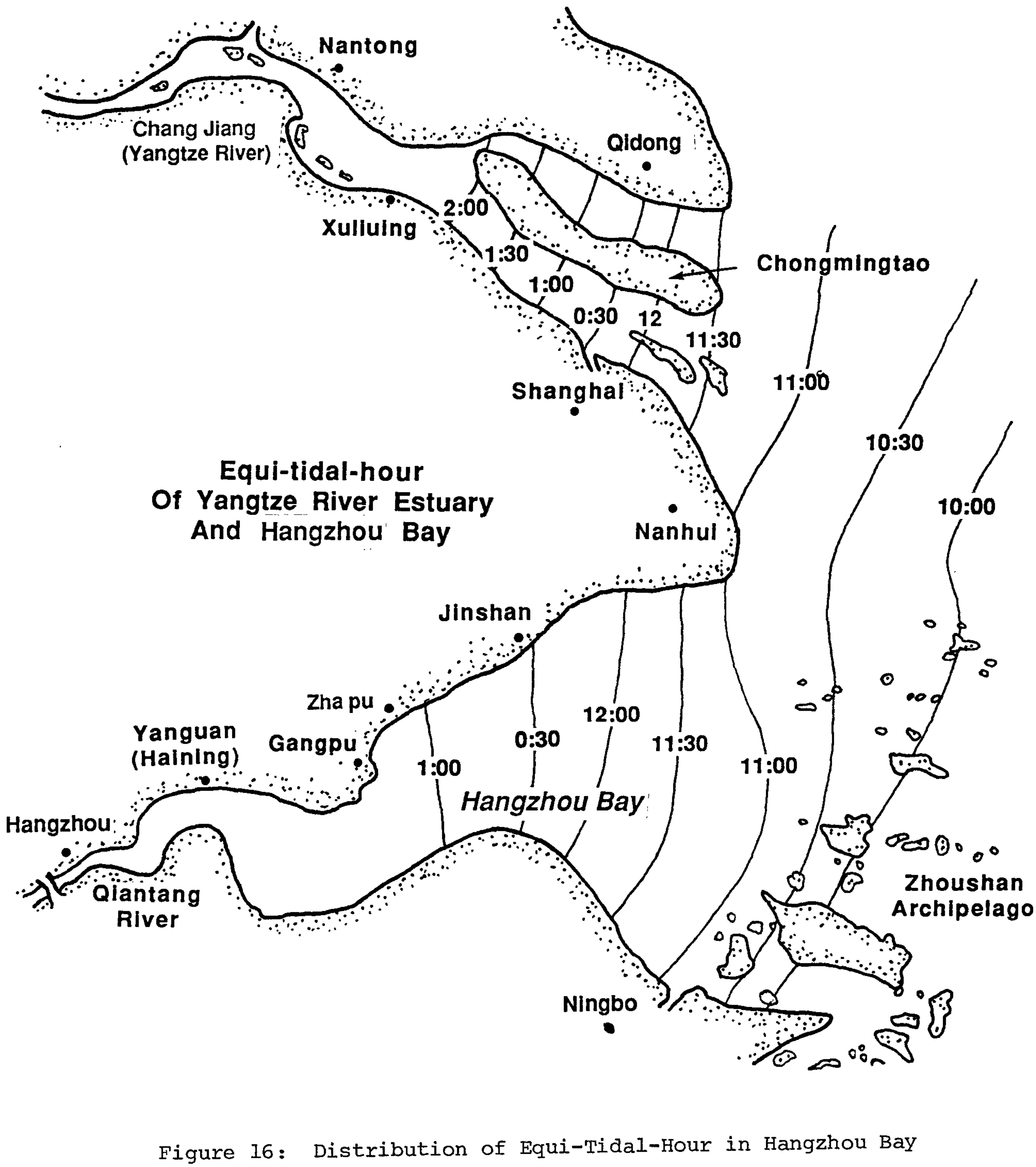


Figure 16: Distribution of Equi-Tidal-Hour in Hangzhou Bay

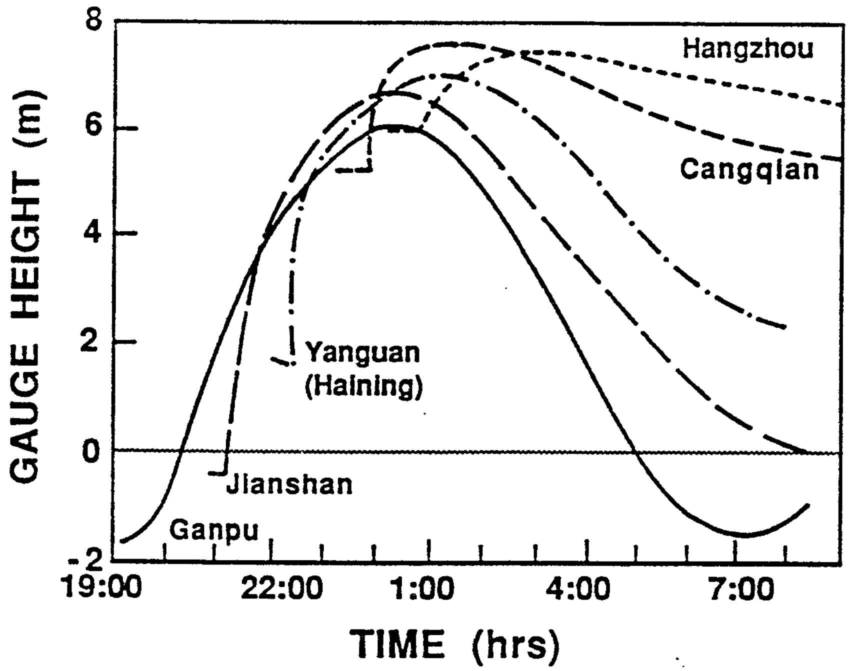


Figure 17: Fully Developed Tidal Bore near Yanguan (Haining)

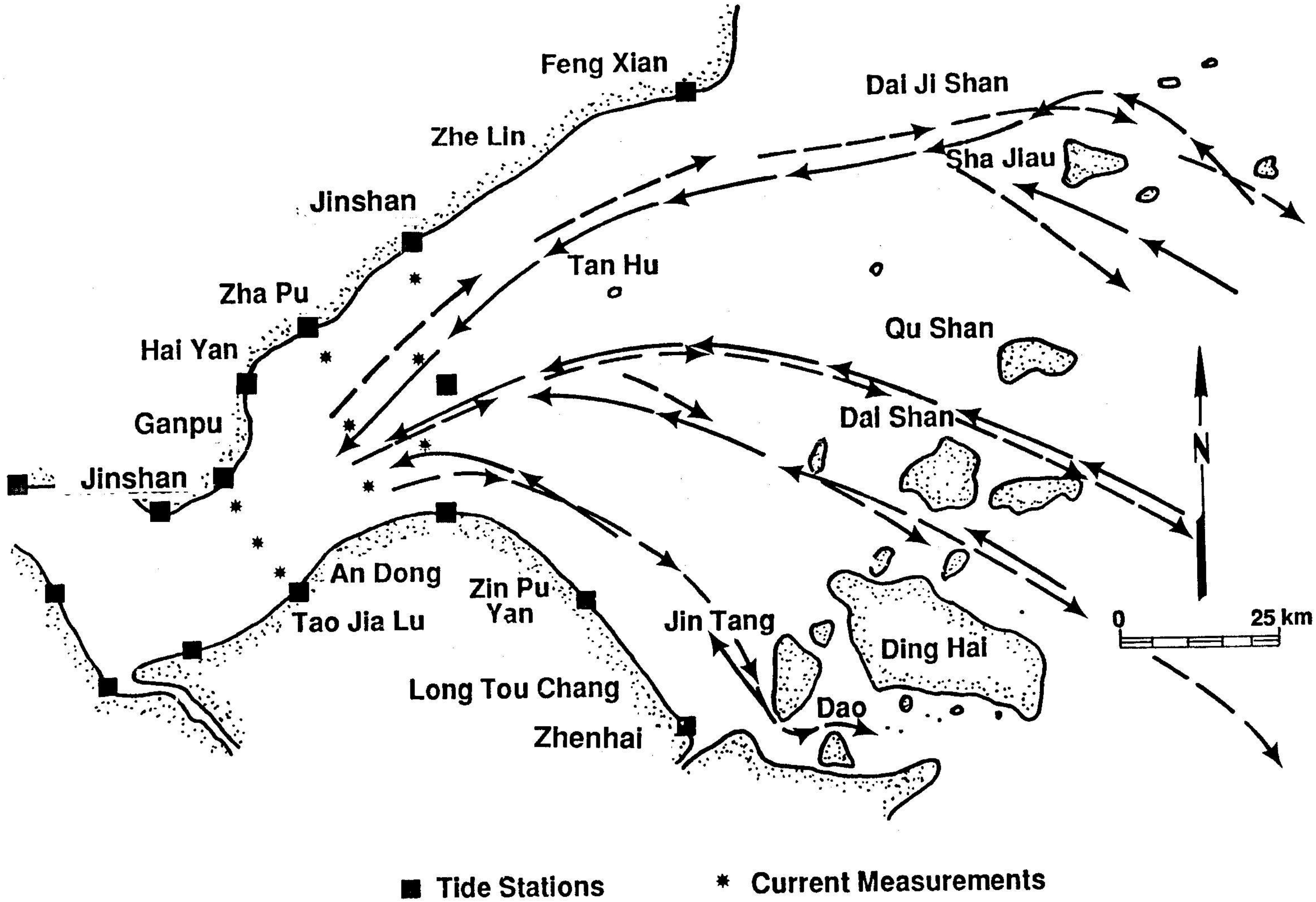


Figure 18: Flood and Ebb Current Pattern in Hangzhou Bay

Table 7 Tidal Current Velocity in Hangzhou Bay

Summer

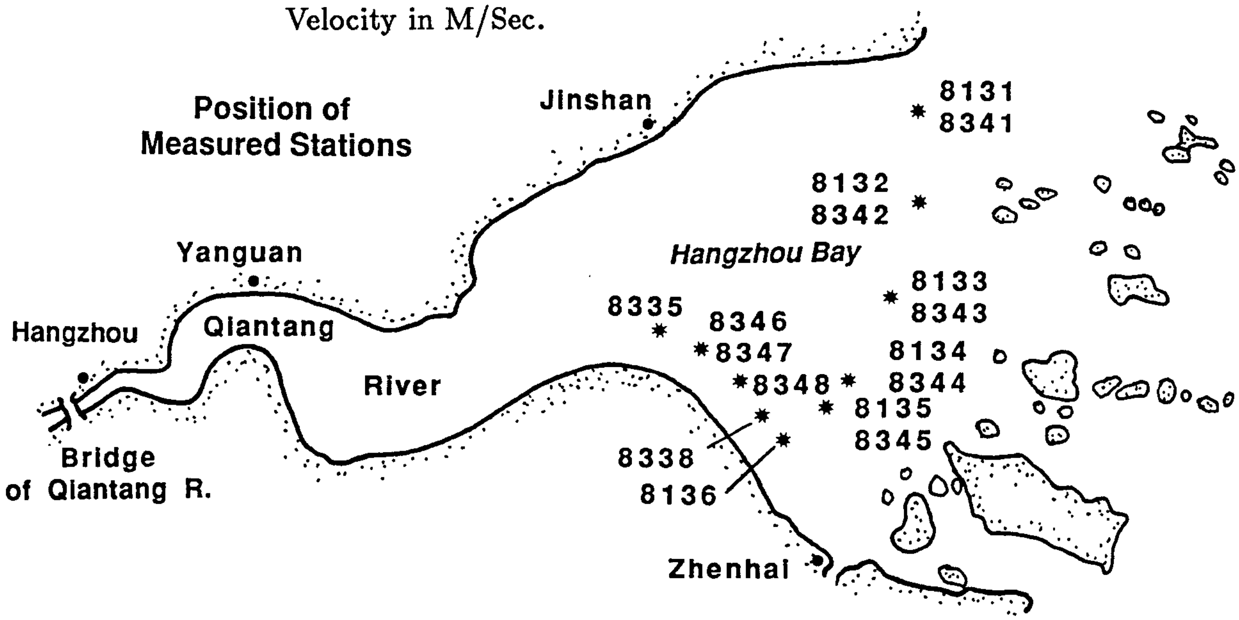
Station		8131	8132	8133	3134	8135	8136
V_{max}	Flood	2.18	1.92	2.04	1.88	1.27	1.29
	Ebb	2.85	3.63	1.76	1.99	1.50	1.55
V_{ave}		1.13	1.10	1.03	1.14	0.85	0.86

Winter

Station		8341	8342	8343	8344	8345
V_{max}	Flood	1.76	1.72	1.36	1.35	0.98
	Ebb	1.96	2.07	1.52	1.54	1.45
V_{ave}		1.09	0.99	0.83	0.985	0.79

Station		8335	8346	8347	8348	8338
V_{max}	Flood	1.80	1.69	1.83	2.72	3.44
V_{ave}		1.24	0.87	1.02	1.56	1.88
V_{max}	Ebb	1.82	1.69	1.58	1.40	1.99
V_{ave}		1.13	1.01	0.87	0.84	1.17

Velocity in M/Sec.



4 SEDIMENT ENVIRONMENT

4.1 GENERAL DESCRIPTION

The northern coast of Zhejiang Province has experienced three sea transgressions during the late Quaternary period. Based upon the evidence of the boring material, it was determined that they occurred, respectively, about 100,000 - 70,000 years, 37,000 - 29,000 years and less than 10,000 years ago (Wang, 1984). The region, in general, experienced a gradual land subsidence since late Pleistocene as illustrated in Figure 19.

The modern Hangzhou Bay was formed during the latest sea transgression in Holocene Epoch occurred between 7,000 - 10,000 years ago. Therefore, the bottom material of the bay is primarily of marine origin. The first layer of approximately 40 m deep is almost completely marine deposit of saturated grey clayey silt or silty clay. They are the deposit of 3rd phase sea transgression. The material is soft and fluidic, with fine but distinct horizontal layers. Beneath this layer are the marine deposits of 2nd and 1st phases of sea transgression, separated by veneers of land deposit. The material of the 2nd and the 1st phase of marine deposit is similar to the 3rd phase. They are, however, much denser than that of the 3rd phase, more hardened but not completely solidified. The land material that forms the veneers between the marine deposit are much coarser ranging from coarse sand, gravel and solidified carbonized organic soil of land origin. In the bay proper, the land layers are usually less than 6 m. The total depth of the deposit extends to approximately 100 m below the bay bottom. Bed rock appears beyond this depth.

The modern sedimentary process of Hangzhou Bay is governed by two groups of environmental factors that are related to land and sea respectively. The bay proper

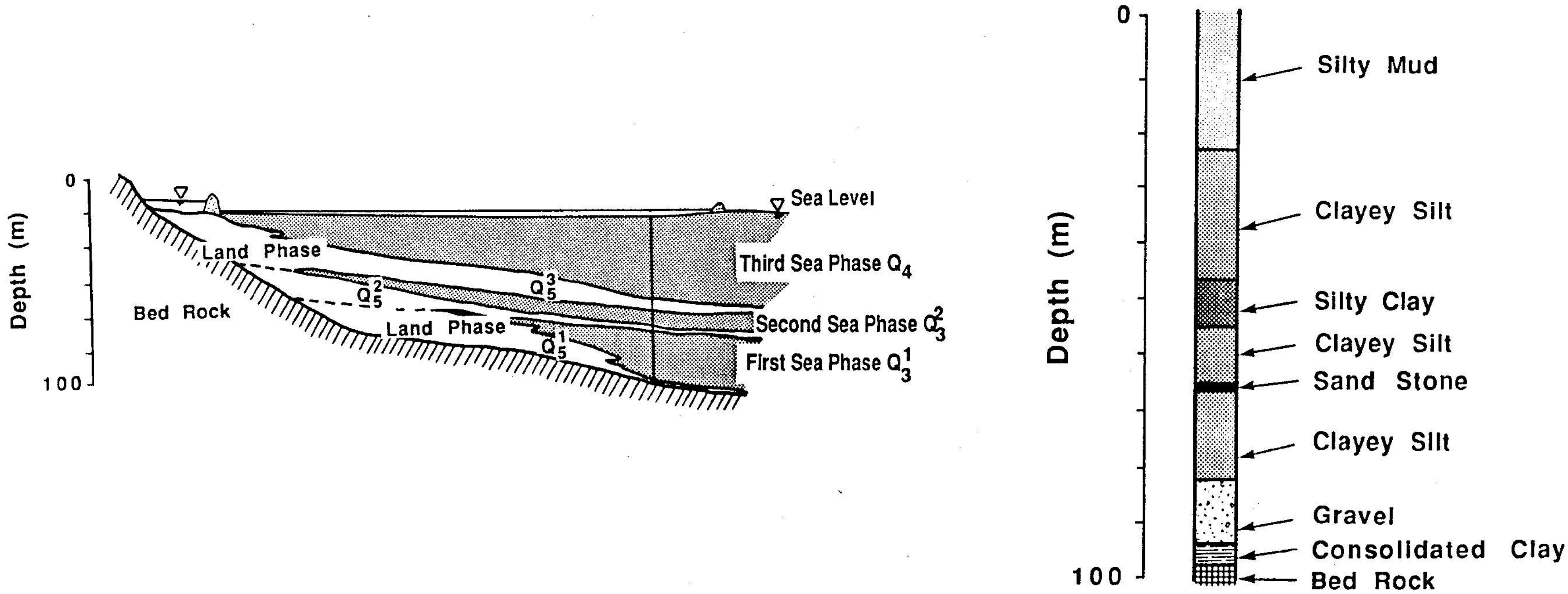


Figure 19: Historical Land Subsidence in Hangzhou Bay

is predominantly sea-governed both in terms of dynamic process and in terms of sediment source. The dominant force is undoubtedly the tidal generated current which brings in large quantity of shelf sediment. The southerly longshore current along the northern coast below Changjiang delta is another sea force which transports the sediment discharged from the adjacent Changjiang (Yangtze) estuary into the bay. The warm Taiwan Strait currents which enter the bay from south through deep channels bring in sediment from the Zhoushan sea region and eroded materials from the continental shelf and the channel. The only land significant source is the sediment carried into the bay by the Qiantang River. The aforementioned sediment sources are depicted in Figure 20.

4.2 SEDIMENT PROCESS

In the bay proper, the bottom material is primarily of marine origin consisting of grey clayey silt, silty clay and fine silt. Other than along the bay fringe and in the upper reach near the mouth of Qiantang River, the water depth in the bay is rather uniform of about 10m and the depth variation has been slight over the years. This is because the sediment moving into the bay, mainly in suspended mode, remains suspended and moves with the current. This new sediment even, at times, settled on the bottom temporarily is easily resuspended. However, this fine material, if given time to consolidate, becomes exceedingly erosion resistant. The motion threshold velocity of the consolidated fine silt in this region is estimated to be in excess of 2m/sec. This partially explains why the bay bottom is rather stable.

The suspended sediments in Hangzhou Bay are predominantly fine silt with less than 10% clay content. The size distributions during a tidal cycle is given in Table 8. The sediment is finer in the northern region of the bay than the southern region. This is because the flood-dominated northern region is diluted by the intru-

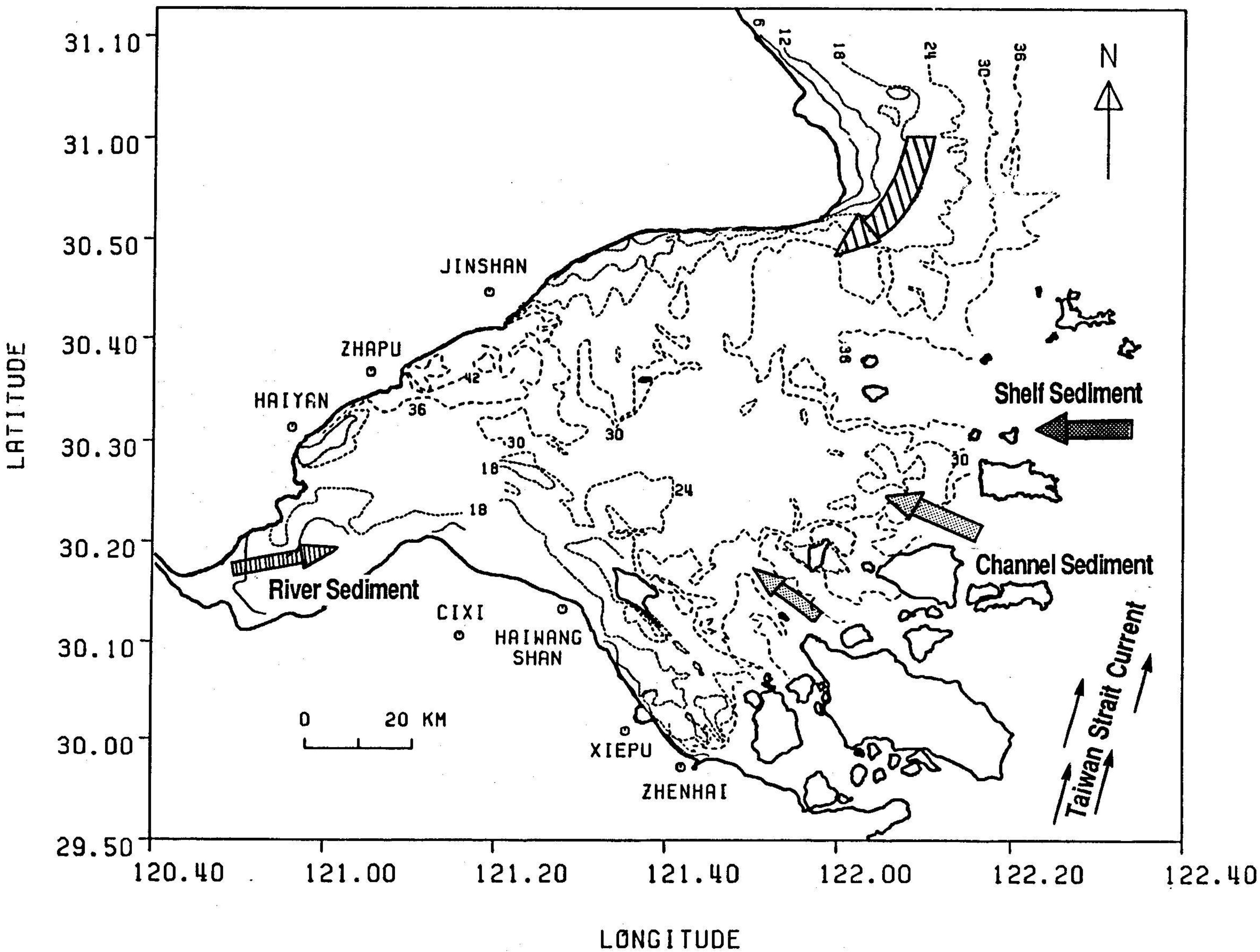


Figure 20: Sediment Sources Entering Hangzhou Bay

Table 8 Sediment Size Distribution Averaged Over A Tidal Cycle

Location	<4	Grading (μm)					Average medium grain size (μm)
	4-8	8-16	16-32	61-32	32-63	>63	
North	7.11	30.18	32.03	22.28	6.60	1.68	10.88
Bay head	7.77	27.68	31.08	26.93	6.53	1.02	11.71
South	5.96	22.03	29.00	30.87	10.36	1.6	14.61
Average	6.95	26.63	30.70	26.73	7.50	1.44	12.61

Table 9 The Grain Size Components of the Sediment in the Hangzhou Bay During Ebb and Flood Cycles

Location	Station	Tide	Grading (μm)						Medium size (μm)
			<4	4-8	8-16	16-32	32-63	>63	
North	II_1	Flood Ebb	6.53 7.66	28.53 31.22	33.31 31.97	24.15 20.99	6.36 6.95	0.88 2.21	11.37 10.48
South	II_2	Flood Ebb	4.50 5.84	20.84 21.92	28.92 30.21	30.22 31.80	12.01 10.42	2.53 1.65	10.53 14.68
Bay head	II_3	Flood Ebb	8.18 7.05	27.39 26.94	23.63 32.43	27.24 27.94	5.46 5.90	0.97 2.10	11.59 12.28

Note: The data are average value over different layers.

sion of fine sediment from the Changjiang estuary whereas the southern region is influenced by the coarser material carried in from Qiantang River. These influences are further illustrated in Table 9 which shows the grain size distributions of the suspended sediment in the Bay during the flood and the ebb cycles, respectively.

Owing to the energetic nature of the Bay, the suspended load is quite heavy. In the bay proper, the average sediment concentration is about 1.2 to 1.5 kg per m^3. There are two low sediment load regions, one coincides with the deep water region along the northern bank of the Bay and the other a tongue-shaped region on the southeast corner in the shadow of Zhoushan Archipelago. Along the southern bank and into the upper reach the suspended sediment load is much heavier, reaching 3 to 4 kg per m^3. Figure 21 shows the distribution of the average suspended sediment concentration in one tidal cycle under normal wave environment.

During episodic events, sediment concentration in the Bay can reach as high as ten times the average value, or above 10 kg per m^3. This further reinforces the significance of wave activities. Unfortunately, reliable simultaneous measurements of wave, current and sediment load do not exist until the present study.

Although the origins of sediment in Hangzhou Bay are being identified as from three sources: Changjiang delta, Qiantang River and the Continental shelf (Figure 20), the transport process is far from being understood. Based upon a number of current oceanographic surveys inside the bay (Su and Wang, 1988; Su, et.al., 1989), a plausible description began to merge.

During a normal flood cycle, sediments were carried into the bay from both north and south sides. The sediment carried in from north in primarily from Changjiang. Changjiang, the longest and the largest (in terms of annual runoff) river in China, discharges 925 billion cubic meters of water and 486 million tons of

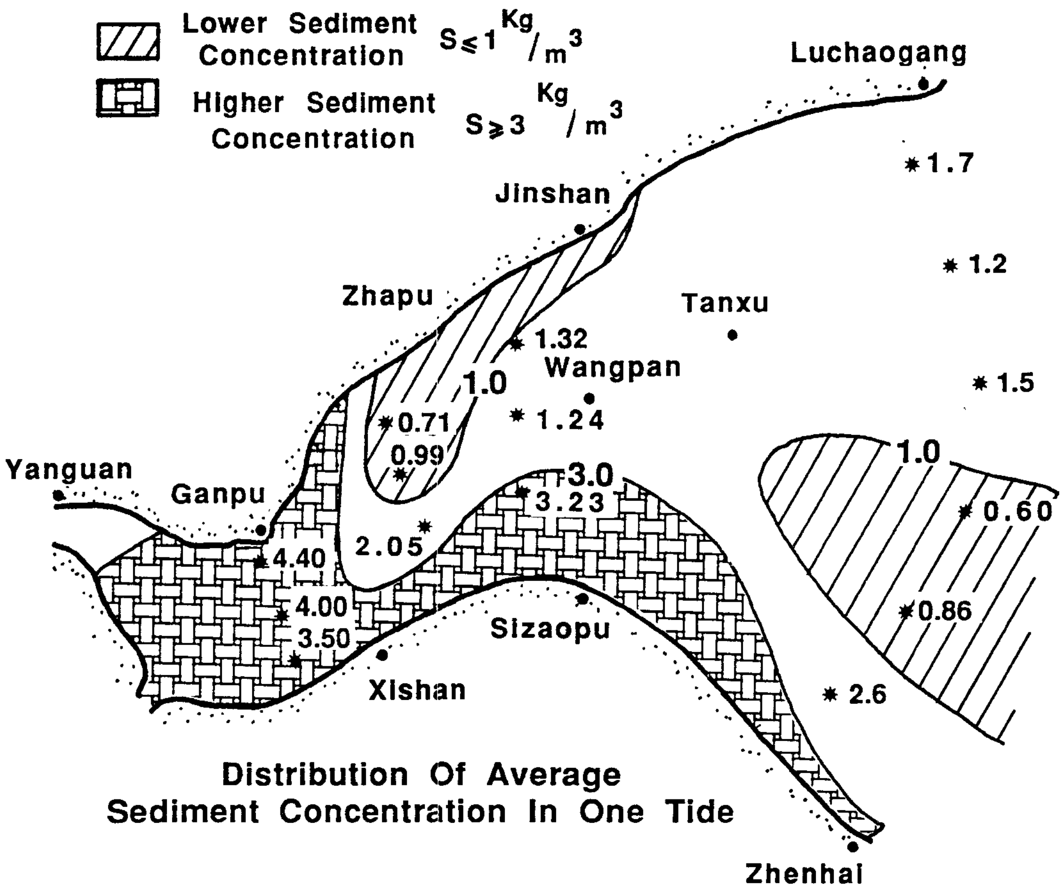


Figure 21: Distribution of Suspended Sediment Concentration in one Tidal Cycle Under Normal Wave Condition

sediment annually into the ocean immediately north of the Hangzhou Bay entrance. The coarser material settles to form the Changjiang delta but the fine material forms a giant sediment plume. This sediment plume splits into two after leaving the river mouth; the main plume jets offshore until it losses its forward momentum and a secondary plume, spinned off from the main plume due to a southward coastal current, hugs close to the shoreline. The front of the main plume oscillates between 50 km to 100 km seaward of the mouth of the Hangzhou Bay depending upon the volumtic rate of river discharge. During summer time, the plume front advances more offshore owing to higher discharge. This plume now influenced by the southeasterly winds and the Taiwan Warm Current from the south is pushed away from the bay mouth towards north, where the sediment is deposited. This sediment can be resuspended during winter storms and directed southward into the bay. In the winter season, the river discharge is smaller and the plume front is much closer to the bay mouth. The main size of the main plume is so large that it practically covers the entire east entrance. The prevailing north-easterly winds then pushes the turbid water into the bay.

The secondary Changjiang plume, on the other hand, is governed by the nearshore coastal current which flows southward most of the time. The plume size is much smaller. It enters directly into the bay from the northeast corner and stays closely along the north shore with the incoming tide. Owing to the bay convergence the current speed progressively increases as flood water propagates into the upper bay region. Thus, even though the water is heavily sediment-laden deposition is kept minimal along the north shore of the bay proper. When flood water reaches upper bay, the sediment- laden water is further energized due to bore formation and turbulent generation. The bottom material is resuspended creating a high sediment concentration zone as shown in Figure 21. At high water slack, coarser material begins to deposit to form the great bar. The finer material, on the other hand, is carried out by the ebb water which tends to push along the south shore due to Coriolis force. The ebb flow also weakens as it retreats into the Bay and deposits material along its way. This material gradually forms the great shallow bank on the south shore which is further enhanced by reclamation activities. The presence of the great bank deflects the bulk of the ebb water towards the north leaving a tongue-shaped region of light sediment load. Ebb water also cuts through the great bank forming numerous ebb channels parallel to the south shore.

In the upper reach of the bay extending into the Qiantang River is a typical macrotidal estuary. The total tidal reach from the mouth of the bay to the upper limit is more than 270 km long. It is a region of combined influence of land factors and sea factors. The sea factors are manifested by the strong tidal influence and the large quantity of marine sediment carried in by the tidal current. The influence of land factors can be described as rich in water but poor in sediment supply. The Qiantang River basin is of modest size with a drainage area of about 4,900 km^2. The average annual runoff reaches 38.2×10^9 m^3 which corresponds to an average annual discharge of 1210 m^3/sec. The discharge varies drastically during different seasons. In flood season (May to October) the flow could top 29,000 m^3/sec, whereas in dry seasons, the stream could reduce to a meager 15 m^3/sec. The average annual sediment load carried by the River is only 7×10^6 tons, or about 1.44% of that of Changjiang. More than 90% of the annual sediment discharge and approximately 80% of the runoff are concentrated in the flood season.

The water running into the Qiantang River during flood tide reaches 190,000 m^3/sec carrying with it a sediment load estimated at 10×10^6 tons per tidal cycle. Therefore, the flow ratio between river discharge and flood water varies from 0.15 to near zero. The average ratio of river discharge to mean tidal discharge is very small of about 0.01. The river-borne sediment is also negligible compared with sediment derived from the sea. Therefore, even in the upper reach of the Bay, sea factors dominate land factors. The great sand bar formed in the upper reach has a tremendous volume of 42.5 billion m^3. Most of the material is from marine origin and the contribution from land source is negligible. The river flow, on the other hand, plays a definite role in determining the location and extent of the great sand bar and also the channel location in the upper reach owing to the intermittent nature of the discharge. During the flood season of Spring and Summer the river discharge tends to follow a more northern route, thus, meets head on with the incoming secondary Changjiang plume. An energetic mixing zone is created at the confluence. Both plumes then turn toward south and merge into one. This water heavily lattened with sediment returns to the bay with the ebb tide and deposits sediment along the south shore. During dry season, the river discharge is weak and follows a more southerly path. The two plumes are somewhat distinct and follow their own path. Figure 22 illustrates the sediment suspended sediment plumes in Hangzhou Bay.

Finally, the sediment from the continental shelf finds its way into the bay mainly near the bottom. This bottom sediment is carried into the Bay from east through tidal residual current and wave–induced stokes drift and from south via the Taiwan Warm Current as channel sediment. The extent of Taiwan Warm Current intrusion can be readily identified by the appearance of a warm tongue on the south east corner in the winter season (see Figure 23). This current eventually will leave the Bay via a north- easterly direction.

The main characteristics of the flow pattern described above results in a net sediment transport shown in Figure 24. Thus, the net transport along the mouth of the Bay is actually from south to north, with the exception near the south corner. Consequently, the channels along the south side are kept clean and the spit at the north corner advances persistently.

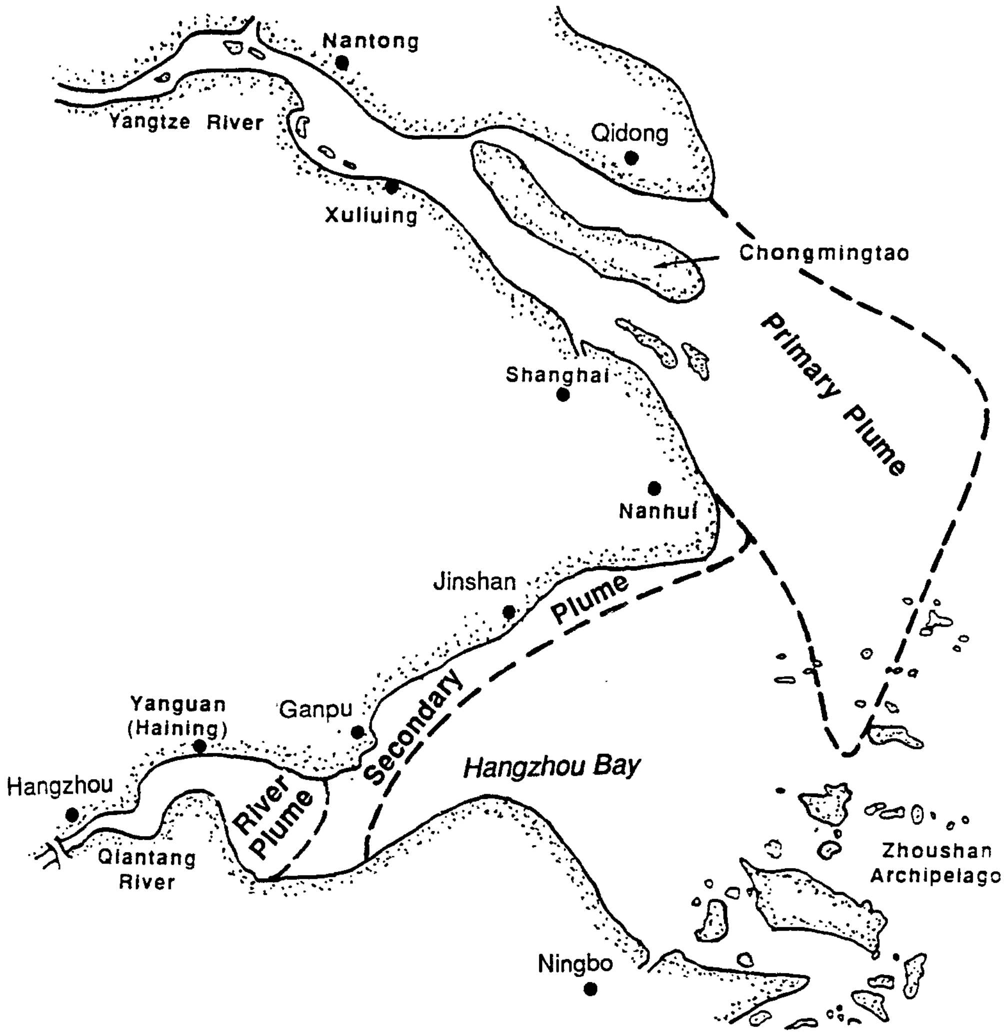


Figure 22: Dominent Sediment Plumes in Hangzhou Bay

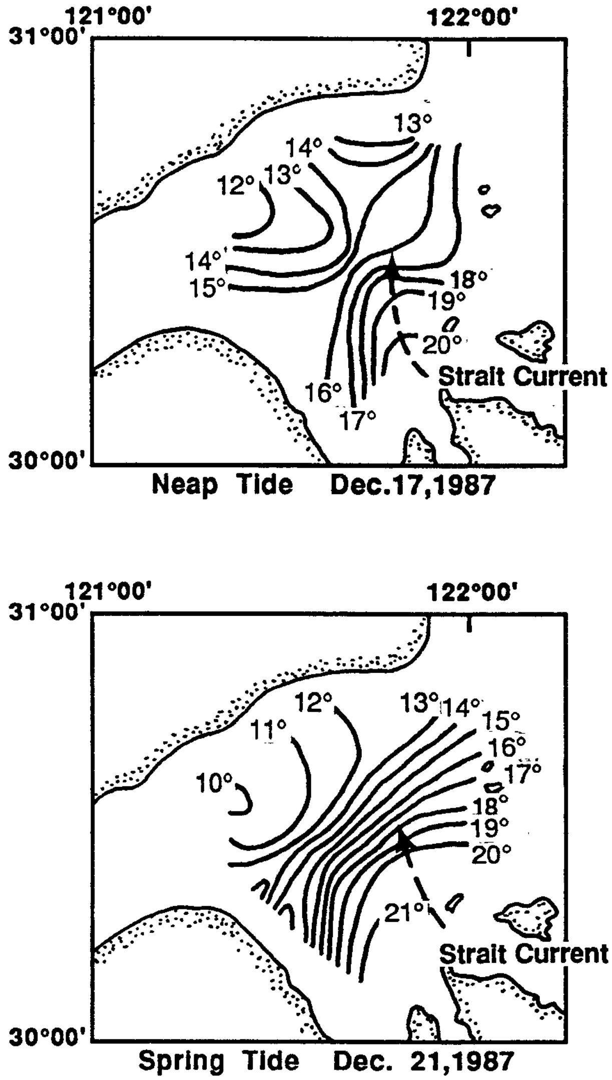


Figure 23: Warm Tongue at South Side

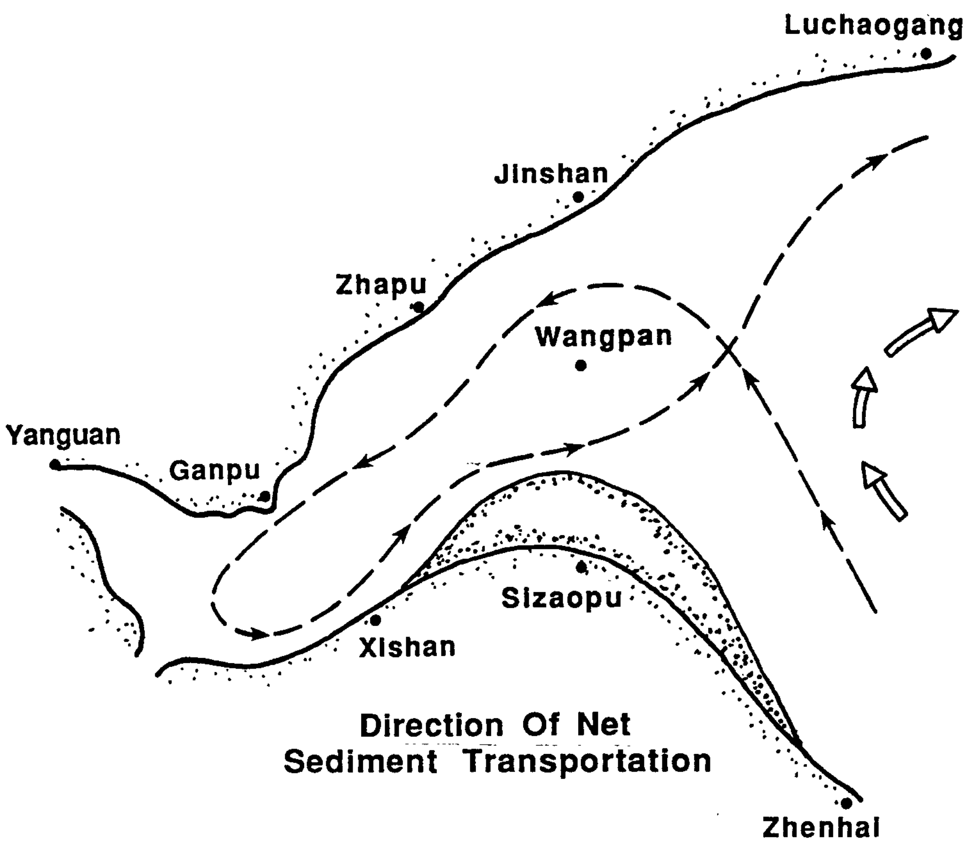


Figure 24: Net Sediment Transport

5 SUMMARY

Based upon available information, the hydrological and sedimentary processes in Hangzhou Bay, China was summarized in this Part I report. This will form a base for the planning and design of future research and engineering activities.

Hangzhou Bay has evolved from a river mouth in ancient time to its present form under the combined influence of sea level rise, strong tidal flow and the influx of sediment from the sea. It is clearly a bay environment dominated by sea factors, both in terms of dynamic forces and sediment origins.

Tidal current undoubledly is the dominant force. Waves, although are mild most of the time, could play a very important role of resuspending bottom sediment during episodic events owing to the shallowness of the Bay. The effects of esturine flows are much localized. The Bay derives its sediment supply from four sources: north from Changjiang (Yantze River), east from the continential shelf, south from the natural deep channels and west from the upper estuaries. The knowledge on the dynamic process of sediment movement in the bay proper is very limited, mainly for lack of pertinent data. Up to date, most of the field data collection efforts have been along the Qiantang River, the main estuary on the west end.

As revealed by the historical data, in a natural state the north shore should be erosional and the south shore accretional. Since the north shore is almost completely hardened with dikes, the south shore has been encroaching into the Bay at an accelerated rate. This encroachment was further augumented by land reclamation efforts in recent years. Thus, the Bay has been losing its territory at a steady rate. It is not clear whether this trend will continue or will eventually reach a state of equilibium. The question remains a profound one and as to its effect on the ecological system.

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