SUSPENDED SEDIMENT IN HONG KONG WATERS

GEO REPORT No. 106

S. Parry

GEOTECHNICAL ENGINEERING OFFICE

CIVIL ENGINEERING DEPARTMENT

THE GOVERNMENT OF THE HONG KONG SPECIAL ADMINISTRATIVE REGION

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PREFACE

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R.K.S. Chan
Head, Geotechnical Engineering Office
November 2000

FOREWORD

This report was produced as part of a literature review, which included existing field measurements, of suspended sediment data in and around Hong Kong waters. The purpose of the report was to provide an overview of the causes and levels of suspended sediments in Hong Kong waters.

The report was written by S. Parry. Valuable comments were provided by P.G.D. Whiteside, Q.S.H. Kwan, N.C. Evans, W.N. Ridley-Thomas of EGS (Asia) Limited and Dr J. Rodger of Mouchel Asia Limited. The Figures were produced by the technical staff of Fill Management Division. The final editorial work was carried out by P.C.T. Cheung.

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ABSTRACT

Hong Kong is situated at the estuary of the third largest river in China and is affected by changing oceanic currents, tidal effects, wave action, extreme climatic conditions and significant anthropogenic influences. In comparison with the complicated hydrological conditions affecting Hong Kong's waters today, the conditions in the recent geological past were even more extreme. The coastline was well to the south of Hong Kong 9500 years ago and the majority of the present day marine sediments were deposited between 4500 and 1000 years ago. Whilst sedimentation in Hong Kong is now limited, this is due to the seabed being in equilibrium rather than a decrease in available sediment. The main source of sediment is the Pearl River, which, on average, discharges around 36 million tonnes of sediment each year. A further factor affecting suspended sediment concentrations is the resuspension of sediments due to wave action. On average 5 typhoons a year affect Hong Kong, with elevated suspended sediment concentrations in excess of 350 mg/l being recorded and the impact of the typhoon lasting over 60 hours. The northeast monsoon has a similar, albeit reduced, effect. In addition to the naturally occurring sediments, human activities such as trawling, sewage discharge, shipping, dredging and reclamation all generate suspended sediments. However, in comparison with natural events, these increases in suspended sediment are usually relatively limited in their extent and impact. Consequently, the use of monthly or bi-monthly data, which may be suitable for determining the trends of anthropogenic pollutants, is not sufficiently frequent to capture the highly variable naturally occurring suspended sediment concentrations where large scale effects occur over much shorter periods.

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1. INTRODUCTION

Prior to the commencement of a designated project it must be demonstrated, through an Environmental Impact Assessment (EIA), that the resulting impacts can be controlled and mitigated to acceptable levels. The most frequent concern during the EIA process for sand dredging and mud disposal is the impact on the marine environment of the suspended sediments generated during the works.

The Water Pollution Control Ordinance, 1980, established Water Control Zones (WCZ) for Hong Kong's marine waters. There are currently ten WCZ (Figure 1) and for each zone, specific Water Quality Objectives (WQO) are established. With respect to suspended sediments, the WQO for all zones is that "waste discharges shall neither cause the ambient level to be raised by 30% nor give rise to accumulations of suspended solids which may adversely affect aquatic communities". However, the ambient levels for the zones are not defined in the Ordinance. Consequently, the "ambient level", and therefore by definition the impact of generated suspended sediments is based on "professional judgement" of individuals and this varies amongst the parties involved in the EIA process. The Agriculture, Fisheries & Conservation Department (AFCD) has similarly used the WQO as a basis for determining the effect of a project on marine life. With respect to sedimentation, there are no specified WQO and consequently the levels at which adverse effects are considered to occur are not defined.

In the past, EIA consultants have frequently used the upper 95 percentile of the results from the Environmental Protection Department (EPD) routine water quality monitoring data as the "ambient level". This monitoring is carried out monthly or bi-monthly by EPD at 82 open water monitoring stations. However, it has been noted that more frequent monitoring, such as that undertaken for Environmental Monitoring and Auditing (EM&A) purposes during the course of construction works, which are usually monitored twice a day at ebb and flood tide, show greater variations in suspended sediment concentrations. There is no routine monitoring of sedimentation undertaken in Hong Kong.

Hong Kong's location adjacent to the estuary of China's third largest river, the constraints on tidal flow imposed by numerous islands and its location in an area where typhoons regularly occur, results in a highly dynamic and variable hydrological regime. It is therefore logical to expect that suspended sediment concentrations will vary greatly depending on factors such as tides, seasons, weather and geographical location. Consequently, given the limitations of EPD's routine water quality monitoring data, it is not surprising if it does not reflect the actual variations of suspended solids in a particular area.

The objective of this report is, based on the findings of a literature review, to summarise the present day hydrological conditions in Hong Kong in order to better understand the likely variations in natural sedimentation and suspended sediment concentrations which might occur in the region. A follow on study will help examine the existing EM&A data in the light of the conclusions of the literature study to further enrich our knowledge of the range of natural concentrations of suspended sediment and sedimentation.

2. GEOLOGICAL SETTING

Present day hydrological processes affect both suspended sediment concentrations and sedimentation rates. To put these into perspective it is necessary to consider the recent geological record of the South China area.

Of particular interest is the most recent geological period, the Holocene. About 18,000 years BP, at the end of the last glacial maximum, the sea level was at approximately -120 mPD, placing the paleocoastline near the edge of the present day continental shelf. As the climate warmed, the ice sheets melted and the sea level rose. The rise would have been slow initially, as the extensive ice-sheets had a significant effect on climate. The rate of rise would have increased rapidly as the size of the ice sheets and their consequential effects on climates decreased. It is estimated that the sea level reached its maximum elevation about 5000 years BP, which may have been up to 4 m higher than today's level (Figure 2) (Fyfe and Shaw, 1995). The inundating sea drowned the early shoreline of the South China coast, resulting in a ria coast with rock promontories and bays.

The Holocene marine transgression was diachronous being older in the south. By about 9500 to 9000 years BP the transgression reached -20 mPD affecting the present day Hong Kong coastal area. Prior to the transgression these areas were traversed by a braided river system, with scattered lakes, depositing the Chek Lap Kok Formation sediments. The transgression, and its associated sediments of the Hang Hau Formation, varied in both its timing and character across the region. Initially the area was covered with mud flats and intertidal channels (the Pok Liu Member of the Hang Hau Formation), often within discrete and isolated channels in the surface of the Chek Lap Kok Formation sediments. There is evidence that a brief period of sub-aerial erosion, related to a minor sea level fall, occurred around 8200 years BP (Fyfe and Shaw, 1998).

About 8000 years BP deepening water gave rise to the modern shallow shelf sea environment that deposited the Tseung Kwan O Member. This now forms the seabed over the majority of Hong Kong (Fyfe and Shaw 1998). The basal portions of the resulting clayey silts of the inundating sea are diachronous, younging to the north as the transgression progressed. Fyfe and Shaw (1998) assumed a rate of sea level rise of 20 mm/year, suggesting a fast coastal regression of about 4 to 5 m per year. However, it has been suggested that the main supply of sediments from the Pearl River, which forms the main source of sediment for the Tseung Kwan O Member, did not affect Hong Kong waters until after 5500 years BP (Fyfe et al 1998), possibly related to the opening of new tidal pathways associated with the onset of maximum sea levels.

By 6000 years BP the transgression had inundated the bay occupied by the modern Pearl River delta, with the sea extending to beyond Guangzhou (Figure 3). At this time Hong Kong would have lain in the shelf zone of the delta rather than in the present pro-delta zone. Towards the end of the transgression the sedimentation rate of the Pearl River began to exceed the rate of sea level rise resulting in the slow emergence of the Pearl River delta plain. The area around Guangzhou was infilled about 2200 years BP. There was little change until about 1000 years BP when the delta rapidly extended outwards, capturing islands, at a rate of 50 to 60 m per year. Much of this rapid rate of advance is considered due to man's deforestation for agriculture in the headwaters region (Shaw and Fyfe 1992). With the movement outward of the delta, Fyfe et al (1997) suggested that the area of deposition migrated away from Hong Kong with the result that deposition in Hong Kong waters virtually ceased. Equivalently, the seabed in Hong Kong reached equilibrium with the new tidal flows and sediment supply and was unable to accommodate any further sedimentation.

As stated previously, the rate of sea level rise was not constant. At the type section for the Hang Hau Formation four phases were tentatively identified. These comprise an initial transgression, a period of more stable sea level, a period of slight shallowing and a final phase of fairly stable shallow marine conditions (Strange and Shaw 1986). Similarly, whilst the results of a detailed study of a borehole in the West Lamma Channel show only a marine environment after 8000 years BP, it was subject to periodic change, with five diatom zones suggesting fluctuating sea levels and the occasional influence of fresh/brackish water (Owen et al 1995).

Many authors have stated average sedimentation rates. However, the values quoted are net results and may reflect significant erosional episodes followed by significant depositional episodes. Owen et al (1995) suggested average marine sedimentation rates of 0.84 mm per year and 0.97 mm per year for the East Lamma Channel. In the eastern waters of Hong Kong, the Tseung Kwan O Member sedimentation is considered to be predominantly post 6000 years BP, again suggesting the introduction of a Pearl River sediment source at this time, with an overall sedimentation rate of almost 2 mm per year (Fyfe et al 1998). Yim et al (1995) quoted rates of sedimentation for the Hang Hau Formation ranging from 0.19 to 2.23 mm per year. Fyfe and Shaw (1998) noted that assuming a thickness of 10 m of mud represents a deposition rate of 1.25 mm per year.

However, the above estimates assume continuous deposition. If the main sediment supply from the Pearl River was not available until after 5500 years BP (Fyfe et al 1998) and deposition virtually ceased by 1000 years BP (Fyfe et al, 1997), this would result in higher rates of deposition. For example, Fyfe and Shaw's (1998) rate of 1.25 mm per year would increase to 2.2 mm per year. Furthermore, these values do not take into account fluctuating sea levels which result in non-constant depositional rates and sediments which have been eroded as tidal pathways changed. For example, in the East Lamma Channel it is evident from seismic records that approximately 20 m of sediment has been eroded (Strange and Shaw, 1986). Finally the effect of consolidation of the sediments after deposition also does not appear to have been considered. For instance a fluid mud with a density of 1080 kg/m^3 would require a 25% reduction in volume to achieve a density of 1350 kg/m^3, a typical value for Hang Hau Formation sediments.

Allowing for irregular deposition, erosion and consolidation it is not unreasonable to postulate depositional rates in excess of 10 mm per year occurred at times up to 1000 years BP.

In contrast, sedimentation rates in Hong Kong waters today are considered to be very low with the bathymetry maintained by strong tidal streams. Chalmers (1984) carried out a rough sediment balance and estimated that without tidal flushing there should be an estimated net sedimentation of 40 mm per year within certain areas of Victoria Harbour. He also examined hydrographic charts from 1903 to 1980 and found no persistent trends with respect to sedimentation suggesting that Hong Kong waters are in dynamic equilibrium. However, sedimentation did occur where the equilibrium was disturbed. Soundings made in the Northern Fairway of Victoria Harbour between 1976 and 1987 indicated that accretion in the fairway was 0.54 m averaged over the 2.5 km length of the fairway which, over the 11 year period, gives an average sedimentation rate of 50 mm per year (Maunsell Scott Wilson, 1991).

3. PEARL RIVER ESTUARY

3.1 Setting

The total annual discharge of sediment by rivers world-wide is estimated to be $7x10^9$ tons, with Asian rivers carrying in excess of 75% of this (Dyer, 1986). Within China itself the three largest rivers are the Yellow River (Huang Ho), the Yangtze River (Changjiang) and the Pearl River (Zhujiang).

The Pearl River, which is ranked 17th in the world in terms of sediment discharge (Milliman & Meade, 1983) and the third largest in China (Wang and Aubrey, 1985), is composed of three tributaries, the rivers Xijiang, Dongjiang and Beijiang, draining a catchment of over 425,000 km^2, or almost 5% of the surface area of China. These rivers are in turn connected to the sea by eight main distributaries (Figure 4). The eastern and western parts of the delta are formed by two funnel shaped bays, the main Pearl River estuary (Zhujiangkou) and the Huangmaohai Bay at Yamen. Between the bays is an arc like siltation zone with its apex at Modaomen. Four of the eight main distributaries, the Humen, Jiaomen, Hongqimen and Hengmen, discharge into the main Pearl River estuary. Of the remaining channels three, the Yamen, Hutiaomen and Jitimen, discharge to the west of Macau, and one, the Modaomen, adjacent to Macau.

The main Pearl River Estuary, which is 4 km wide at Humen, 65 km wide at its mouth and 60 km in length, is microtidal, with an average tidal range of 0.86 - 1.89 m increasing towards Humen. Only the Humen and Yamen channels are dominated by tidal action, the remainder being dominated by run-off. The Humen and Yamen channels are also characterised by large salt-water intrusions over a large range of 80 km in the Humen and 40 km at Yamen. The remainder have only short salt water intrusions which fluctuate over a limited range (Li and Wang, 1987).

Within the main estuary there are two channels and three shoals. The eastern or Fanshi channel has an average water depth of 11.5 m and extends into Hong Kong waters as Urmston Road. The western or Lingding channel, which forms the main navigation channels to the port at Huangpu, has an average water depth of 8.6 m and extends into Hong Kong waters as the Lantau channel. Between the two channels lies the Fanshi shoal with an average water depth of 4.3 m. The large western shoal is associated with the discharges on the west side of the bay at Hengmen, Hongqi and Jiaomen and has a water depth less than 2 m, whilst the smaller eastern shoal has a water depth of 2-4 m (Weng and Dong, 1992).

3.2 Suspended Sediments

The Pearl River estuary is dominated by sedimentary accretion with the delta advancing seaward at between 50-150 m/year (Ravensrodd 1991). A range of annual water discharges and sediment loads for all the tributaries are quoted in the literature but are generally in the order of $320x10^9$ m^3 of water and $71x10^6$ tons of sediment. Ninety percent of runoff occurs in the wet season between May and September and it is estimated that approximately 20% of the sediment load is deposited at the river mouth, the remainder being transported out to sea (Ren, 1987). The four channels of the main Pearl River estuary discharge a total of approximately 170M m^3 of water and some $36x10^6$ tons of sediment per year (Chen & Che, 1992).

Kot and Hu (1995) stated that the mean annual sediment content of the estuary is 100 to 300 mg/l, with a wet season depth average of 300-500 mg/l and a dry season depth average of 20-100 mg/l. Kirby (1992), however, reported much larger depth averaged suspended solid concentrations, with concentrations of over 1400 mg/l. Gu and Zu (in Kirby, 1992) reported that satellite photographs, calibrated with suspended sediment samples, showed a pronounced lateral asymmetry in suspended sediments within the estuary. A sharp division occurred between the eastern and western zones, which for much of its length is coincident with the western margin of the Lingding channel. This strong asymmetrical distribution of suspended sediment concentrations is a result of the major river inputs being located on the west side of the estuary, combined with residual tidal flows from east to west, giving rise to an anticlockwise circulation within the estuary, possibly enhanced by the Coriolis effect. These effects are also likely to result in an asymmetrical turbidity maximum within the estuary.

Turbidity maximums are a feature of all macrotidal estuaries, with the tidal flow maintaining higher concentrations of suspended sediment in the upper estuary than in the river or sea. Within the Pearl River estuary, they are known to be located to the north of Neilingding and Shekou in the wet season (Montgomery Watson, 1997).

Turbidity maximums are formed by river sediment moving down the estuary in the freshwater discharge which rises over the denser saline layer. The lack of mixing due to the suspension of turbulence allows the sediment to be carried in the freshwater surface layer. In freshwater the settling is negligible. However, once the salinity exceeds 1-2 ppm, flocculation can occur and settling commences from the surface seaward moving layer to the landward moving saline layer. The sediment then travels as part of the salt intrusion back to the head of the estuary where it becomes trapped (Figure 5). As a general observation low tidal ranges tend to result in turbidity maximums with suspended solid concentrations of 100-200 mg/l, whereas large tidal ranges result in concentrations of 1,000-10,000 mg/l (Dyer, 1986).

During the tidal cycle, the suspended solids concentrations of the turbidity maximum will vary in both magnitude and position. For instance, in general the turbidity maximum is usually more pronounced on the flood tide than the ebb tide due to higher velocities resulting from deformation of the tidal wave as it propagates upstream (Dyer, 1986). However, the flood is typically of a shorter duration than the ebb with the result that the period of high water slack becomes longer than low water slack. The concentration also varies with the neap - spring cycle, with the highest concentration occurring on spring tide when currents are able to erode and sustain more sediment in suspension. During neap tides the velocity decreases and deposition is enhanced leading to the formation of mud suspensions in some cases. Given the seasonal variations in the Pearl River estuary, the turbidity maximum is likely to migrate long distances within the estuary.

In summary, turbidity maximums act as a suspended sediment storage mechanism within the estuary and in years of extreme flow this can result in the release of massive amounts of sediment, far in excess of the volume being transported by the individual rivers.

In addition to the suspended sediment held within the turbidity maximum, the Pearl River estuary in general contains large amounts of suspended sediment. Kirby (1992) showed unpublished vertical profiles off Shekou, Neilingding and Jin Xing Men (Figure 6) that exhibit lutocline-like distributions. Lutoclines occur in many estuaries around the world and are stable, sharp step like, layered structures comprising of elevated suspended sediment concentrations (Kirby, 1992). For example in the Severn estuary in the United Kingdom, over a single tidal cycle on spring tides, a vertically homogenous suspended sediment profile is present at maximum ebb or flood tide flows with concentrations of 2000-5000 mg/l. As the current diminishes, settlement commences forming a lutocline in the profile. As settlement continues, the lutocline gradually sinks resulting in an increasing suspended solid concentration in the lower water column until, near to slack water, the lutocline will become stationary for a short period with concentrations of up to 60,000 mg/l (in the Severn estuary) measured at this stage. As the current accelerates on the changing tide the suspended solids are gradually re-entrained and the lutocline rises within the water column again. As the tidal range diminishes towards the neap tides, the static suspension at slack water will remain for longer periods eventually allowing it to consolidate with the result that the material may not be fully eroded on the following neap to spring cycle (Kirby, 1992).

Published data with respect to sedimentation in the Pearl River estuary gives a maximum sedimentation rate of 90 mm/year and an average of 60 mm/year is recorded for the Taipa Channel in Macau, whilst in the inner harbour at Macau the average rate is almost 30 mm/year (Chen and Che, 1992). Kot and Hu (1995) quoted an annual sedimentation rate of 130 mm/year in the inner Pearl River estuary.

4. OFFSHORE HYDRODYNAMICS OF THE HONG KONG REGION

4.1 Currents

The boundary between the oceanic wind driven currents and inshore tidal flow is transitional and varies seasonally, fluctuating between 1 and 3.3 km south of Lamma Island (Ravensrodd, 1991).

The inshore waters around Hong Kong are subjected to extensive mixing movements by water masses which in turn are strongly influenced by the shallow nature of the sea area, the tidal and wind induced currents and the complexity of the coastal topography. Consequently, adjacent coastal areas, particularly bays may show quite different properties at any one time of the year (Watts, 1973).

The offshore waters of Hong Kong are influenced by two seasonal currents. In June and July the waters are affected by the northeast flowing South China Sea water (Hainan Current), associated with the southwest monsoon, which is characterised by high salinity (34.4 to 34.6%) and variable temperature. In winter from October to March, this current is replaced by the southwest flowing Taiwan Current (South China Coastal Current), associated with the north east monsoon (Watts, 1973). This brings cooler water with low salinity (31 to 33%) from more northerly latitudes to Hong Kong. However, the Taiwan Current also mixes with the Kuro Shio current, from the Pacific and invades the South China Sea via the Luzon Straits (Figure 7). The Kuro Shio current has a high salinity (34.5 to 35%) and high temperature and its influence keeps the coastal waters around Hong Kong relatively warm in winter (Morton and Wu, 1975). In April to May and August to September, during the transition between these currents, the current directions are unstable and reversals are common. Reversals have also been recorded as late as November (DRL, 1994).

Hong Kong's inshore waters are also influenced by the offshore waters. In summer the rise in atmospheric temperature results in a corresponding increase in surface water temperature. Also in the summer the prevailing southwest monsoon has minimal influence on the water column with the result that little mixing occurs. As a consequence the water column becomes stratified. This stratification in turn results in the dampening of turbulence, with the result that the mixing is even further reduced. The discharge from the Pearl River is greatest at this time of year and, due to its lower density, this tends to flow southward as a surface current. This in turn induces a counter movement of colder deeper offshore water, with high salinity and low oxygen content, inshore in the bottom layers. This produces a small horizontal and a large vertical saltwater gradient (Figure 8). There is however a delay between the onset of the discharge from the Pearl River and the appearance of shelf water indicating that the onshore flow is a relatively slow process (Watts, 1973). In the dry season the offshore water retreats and the freshwater outflow decreases with the result that the salt water is able to intrude up the Pearl River estuary resulting in a large horizontal and small vertical gradient.

Territory-wide suspended sediment surveys were carried out in both the wet and dry season to attempt to provide a snapshot of suspended sediments at a particular time. The low water spring tide, wet season, survey (DRL, 1994) clearly showed the influence of the Pearl River at this time, with large amounts of suspended sediment recorded north of Lantau, extending into the Western Harbour where concentrations of between 25-50 mg/l were recorded. Large amounts of suspended sediment were also recorded as being swept around south Lantau, extending beyond the Sokos with concentrations of up to 100 mg/l present. The concentrations were slightly lower at high tide although concentrations in excess of 250 mg/l were still recorded in the Pearl River estuary (Figure 9).

4.2 Tides

The tidal range, defined as the difference in water level between high and low water, varies periodically corresponding to the phase of the moon in a given month. Tides of maximum range, known as spring tides, occur twice in 29 days when the lunar and solar tidal generating forces reinforce each other around full and new moon. These tides are dominated by diurnal tidal components. Similarly tides of minimum range, known as neap tides, occur when the solar and lunar constituents oppose each other and are dominated by semi-diurnal tidal components. As a consequence in Hong Kong spring tides result in large range diurnal tides with a semi-diurnal inequality, i.e. one large and one small high and low water, at the full and new moon phases. Neap tides however occur during the half moon phases and result in a semi-diurnal tide with a single small high and low water. Consequently, Hong Kong is classified as having a mixed tidal regime.

The two sets of tidal components move in and out of phase over a period of 182 days, i.e. a 6-month period. As a result the largest and smallest amplitude tides occur in both December and June, each 7 days apart. The diurnal inequality creates a lower low tide in the morning from October to March and a lower low tide in the evening from April to September.

The flood and ebb tides form reversing tidal flows that dominate the near shore Hong Kong waters (Figure 10). Tidal currents in Hong Kong have a westerly directed residual component. Even in the summer when the Pearl River discharges induce easterly flows in the surface layers, a westerly residual is maintained in the lower layers (Ravensrodd, 1991).

In general, tidal current speeds are moderate. Ma Wan and Kap Shui Mun show the highest current speeds, with a maximum of 2.5 m/s being recorded. In Victoria Harbour the maximum speed is approximately 1.0 m/s, 1.2 m/s in East Lamma Channel, 0.5 m/s in West Lamma Channel and 1.3 m/s in Urmston Road (Ip, 1995). In Hong Kong, based on typical water depths and Hang Hau Formation soft silty clay composition, a dry season depth average water speed of 0.7 m/s has been found to be the limit for seabed stability. If the depth average speed is >0.7 m/s the seabed will be eroded until the water depths increase sufficiently to allow the speeds to decrease below 0.7 m/s. If the Hang Hau deposit is removed exposing stronger material and the channel is unable to deepen the speeds will remain above 0.7 m/s (Rodger, 1998).

The Environmental Protection Department's (EPD) 1995 routine water quality data showed higher suspended sediment concentrations at East Sha Chau at all depths in the dry season than in the wet season (ERM, 1997a). A similar phenomenon, with reduced suspended sediments in summer, was also noted in the Airport Core Project (ACP) environmental audit. Monthly peaks, related to the occurrence of high tidal ranges at new or full moon, were also recorded (Figure 11) (EPD, 1996). Kot & Hu (1995) noted that the eastern channel of the Pearl River estuary is in siltation in the wet season and erosion in the dry season under the action of flood currents. It is known that settling lag results in an hysteresis of concentration with current velocity, with the decreasing current concentrations at any one level higher than those on the increasing current. Consequently if there is insufficient time for the material in the water column to settle before the subsequent ebb or flood current this could also result in a higher suspended sediment content.

However, the background water quality monitoring carried out for the East Sha Chau mud disposal pits (EGS 1996a & 1996b) showed higher suspended sediment in the wet season than the dry. This apparent contradiction of results may simply be a product of the frequency of monitoring. EPD data was recorded monthly and the ACP data daily. In comparison, the monitoring at East Sha Chau was carried out every two hours. Figures 12 & 13 show hourly measurements of suspended solids over 24-hour periods during wet and dry season spring and neap tides at East Sha Chau. All results clearly show the influence of tides on suspended sediments, with increases in suspended sediments associated with mid ebb and flood tides and proportional to the tidal range. The smallest fluctuations are associated with dry season neap tides (Figure 12a). The suspended sediment concentrations are similar at all depths and fluctuate from <2 mg/l to >17 mg/l at mid ebb. A similar pattern is shown for dry season spring tides resulting in suspended sediments typically fluctuating from <5 mg/l to 20 mg/l except on the mid ebb, which has the largest tidal range, where >40 mg/l was recorded (Figure 12b). As with the neap tides, the spring tides in the dry season result in similar suspended sediment concentrations at all depths, reflecting typical dry season homogeneous conditions.

In the wet season, similar fluctuations with respect to the ebb and flood tides occur but the suspended sediment concentrations are higher than the dry season and their variations increase with depth. The neap tides (Figure 13a) show only slight variations in suspended sediment concentrations in the upper 5 m of the water column, whereas the lower layer shows regular fluctuations from 10 mg/l to 20 mg/l. Similarly with the spring tides (Figure 13b) the fluctuations in suspended sediment concentrations in the upper 3 m are limited although the actual base levels are elevated in comparison with the neap tides (10 mg/l as opposed to 5 mg/l on the neap tides). The lower water layers however show rapid increases in suspended sediments with typical basal concentrations of 15 mg/l increasing to in excess of 50 mg/l during the mid ebb and mid flood. It appears that the stratification and the associated damping of turbulence results in the lower waters, which are affected by re-suspension of sediments, being unable to mix with the upper layers.

4.3 Seabed

Divers in Hong Kong have reported the presence of mud suspensions to a height of approximately 0.75 m above seabed (Shaw, 1992). The presence of mud suspensions at or close to seabed was noted in the territory-wide suspended sediment survey (DRL, 1994) and during a survey at the East Ninepins Marine Disposal Site where a large area of seabed (>12 km^2) was covered by a thin layer of between 0.5 m and 2.1 m thick with concentrations of between 100-2500 mg/l (DRL, 1996a). Due to its location and the current flow at the time of survey this was considered to be either a natural feature, unrelated to the disposal operations, and or possibly to be due to the frequent disturbance of the seabed by fishing activities (DRL, 1995b). During the EIA study at East Sha Chau (ERM, 1997a) it was noted from the REMOTS (Remote Ecological Monitoring Of The Seafloor) survey that the seabed in this area was also highly mobile, again possibly reflecting the presence of suspended mud.

A similar feature was observed during a REMOTS study of Hong Kong's eastern waters where three distinct seabed types were noted (BCL, 1995b):

i) weakly consolidated gelatinous mud occurring as discrete patches with a thickness of 20-60 mm (Plate 1),

ii) "puzzle fabric" comprising loosely packed mud clasts (angular to sub-angular, 2 mm to 150 mm in diameter) (Selby and Evans, 1997) in mud suspensions with a thickness of 20-100 mm (Plate 2), and

iii) "normal" compact homogeneous seabed.

The puzzle fabric and gelatinous mud did not occur together and normal seabed was only apparent in 57% of the images. During a further REMOTS study in Hong Kong's eastern waters, it was noted that over-penetration of the camera occurred in 7 of the 16 stations and this suggested the presence of mud suspensions (ERM, 1997b).

Work carried out by HWR (1990) determined critical bed shear stresses for typical Hang Hau Formation mud at differing densities (Table 1). Table 2 shows peak bed shear stresses obtained for Hong Kong's eastern waters by combining waves and currents. This suggests that a 0.1-year wave event will erode mud suspensions and may erode consolidating layers, a 1-year storm will erode consolidating mud suspensions and that a 10-year storm will begin to erode in-situ Hang Hau Formation seabed (Selby and Evans 1997).

These data suggest the presence of a layer of easily remobilised, soft mud over most of Hong Kong's seabed giving a ready supply of suspended sediments during storms and that re-suspension of unconsolidated or slightly consolidated suspensions are frequent events.

4.4 Storms

In June 1972 Tropical Storm Agnes hit the Chesapeake Bay region of the United States. As a result of 300 mm of rainfall in two days the Susquehanna River, which discharges in to the north of Chesapeake Bay, discharged more than 50×10^6 tonnes of sediment in one week (Figure 14**)**, which was more than the total discharge of sediment in the previous half century. Post-storm cores showed an average of 170 mm of newly deposited sediment in the upper reaches of the bay. Coring also showed that the so called "great flood" in 1936 deposited 300 mm of sediment and it is estimated that the two events accounted for at least half the sediment deposited in this century (Schubel, 1974). Similar studies in the UK have shown that typically 90% of suspended sediment yield occurs in only 5% of the time period (Figure 15) (Dyer, 1986).

Ravensrodd (1991) suggested that the storage capacity of the Pearl River Estuary was at least 80×10^6 tonnes, similar to the average annual sediment input, although it was considered that this was probably an underestimate. As discussed in Section 3.2, the Pearl River Estuary as well as gradually releasing sediments over time also acts as a sediment store. Consequently, when affected by a storm, such as that in 1994, a combination of river input and stored sediment could be released together resulting in massive sediment loads.

In 1994, a 1 in 100-year rainfall event in southern China resulted in a 100-year record Pearl River Estuary discharge in mid June 1994. This reduced the surface layer salinity throughout Hong Kong waters as far as Mirs Bay and resulted in stronger than normal up welling of oceanic waters (BCL 1995a). The extent of the Pearl River Estuary influence in such extreme events is illustrated by the hypoxia event in Mirs Bay. Whilst hypoxia conditions are common in Mirs Bay they are normally restricted in size. However, there was also an unusual lack of storms until the end of August 1994 with the passage of Typhoon Harry on 27 and 28 August 1994 allowing the stratification to remain intact for a prolonged period.

The low oxygen water resulted in the death of benthic infauna and epifauna including sea urchins and bivalves. This gave rise to the deposition of microbial mats which further decreased the available oxygen. By mid August the low oxygen water had reached -2 mPD affecting the coral reefs, resulting in severe damage by September 1994. REMOTS results suggested that up to 200 km^2 of seabed was affected, representing the single most damaging marine environmental impact for the past 100 years, based on the size and estimated growth rates for the corals killed. It was concluded that during years of unusually high, although not necessarily extreme rainfall, the Pearl River Estuary discharges could affect waters throughout Hong Kong, including Mirs Bay and as far afield as north of Daya Bay (BCL 1995).

The dry season territory-wide suspended sediment survey carried out in November 1994 (DRL, 1995a) showed that high suspended sediment concentrations, associated with the Pearl River Estuary flood waters, were still affecting Hong Kong. Depth-average concentrations of >250 mg/l were present north and south of Lantau at low tide and in more central Hong Kong waters concentrations of between 25-100 mg/l were recorded. In addition a stream of water extending from Ma Wan through the Western Harbour to Lamma with concentrations of 100-250 mg/l was present (Figure 16**)**. The extent of the suspended sediment from the Pearl River Estuary is also evident on the composite Landsat image for November 1994 (Plate 3). As with the previous year's wet season survey, the suspended sediment concentrations were higher at low tide than high tide.

In addition to the discharge from the Pearl River Estuary, the high summer rainfall (total average rainfall between May and September is 1700 mm (Hong Kong Observatory, 1998)) associated with monsoon conditions also reduces the salinity and increases the suspended sediment. For example, during the wet season territory-wide suspended sediment survey (DRL, 1994) high concentrations of suspended sediments were recorded in the shallow waters of southern and southeast Lantau thought to be due to a combination of wave action at high tide and surface runoff (Figure 9) (see also Section 4.5).

Discharge from the Pearl River Estuary in the summer of 1997, combined with intense local run-off may also have been responsible for the high rate of hard coral mortality at the Soko islands. The corals were estimated as being 10-15 years old and were present from sea surface to -3 mPD. Barnacles, mussels and Bryozoa were also affected. In the same period bleaching (evidence of stress) and mortality of hard corals were also reported at Ping Chau, Hoi Ha Wan, Port Shelter and Sham Wan to similar depths. The restriction of impacts to shallow depths and the lack of evidence of predation suggests the most likely reasons to be related to low salinity (BCL, 1997). There was severe rainfall in Hong Kong in June and July 1997, with the 31 day duration rainfall ending on 4 July 1997 representing a 1:500 year event for Hong Kong (Halcrow, 1997). This resulted in intense local run-off which, combined with the Pearl River Estuary discharges and the relatively calm weather, probably resulted in a low salinity near surface layer for an unusually long period of time (BCL, 1997). Whilst there were no detailed measurements of suspended sediments during this period, it is likely that elevated concentrations would also be associated with these events.

In addition to the seasonal summer monsoons periodic typhoons also occur, with an average frequency of 5.3 per year affecting the Pearl River area and 1.25 per year making landfall in the area (Kot and Hu, 1995). The typhoons usually last 2-3 days and cause torrential rain and storm surges, raising tidal levels by up to 2.6 m. They also result in mixing throughout the water column and reduced stratification. At the same time they increase suspended sediment concentrations by both seabed disturbance and the larger discharge from the Pearl River and local rivers.

During dredging at the East Po Toi Marine Borrow Area, simple silt traps were installed and continuous suspended sediment monitoring was carried out using silt meters to detect possible impacts on nearby coral communities. Prior to deploying siltmeters ADCP surveys were carried out to determine current direction and velocity together, with a side scan sonar survey to locate suitable deployment locations (Plate 4). During the first phase of sand extraction, three siltmeters were placed around Fury Rock, a low rock outcrop with soft and hard coral communities. Monitoring was carried out from June to August 1994 (Figure 17).

In addition to the siltmeters, regular dive surveys were carried out to inspect the corals. Dredging close to Fury Rock was restricted to times when the predicted current directions would transport any dredging plumes away from the area. Generally the suspended sediment concentrations measured during the extraction period varied from 20 to 30 mg/l, occasionally increasing to peak around 100 mg/l during actual dredging activities. No impacts on the corals from sedimentation were evident. However, a dive survey on 9th August 1994 reported some soft corals between -8 and -12 mPD appeared to have necrotic body parts (decomposed tissue) and some were in an unhealthy state (flaccid and flat lying). The following dive survey on 19th August 1994 found the corals in a healthy condition in all areas. It is likely that the effects observed on 9th August were due to the hypoxia event, which affected Mirs Bay.

The second phase of sand extraction at the East Po Toi Marine Borrow Area was undertaken from May 1994 to November 1995 and again silt meters and simple silt traps were deployed. One silt meter was placed at Fury Rock, the two other siltmeters were placed near a second extraction area, also in the vicinity of known coral communities, at Sung Kong and Waglan (Figure 17). At the Sung Kong and Waglan locations only short duration, increased suspended sediment concentrations were apparent from the siltmeters. Very little fine grained sedimentation occurred in the silt traps and there was no evidence of sedimentation from dive surveys all suggesting minimal impacts from dredging at these locations. However, elevated suspended sediment concentrations did occur over a period of 24 hours during the passage of Typhoon Sibyl which resulted in the raising of the Tropical Cyclone Warning Signal Number 8. During the typhoon all dredging operations ceased. Sibyl formed as a tropical depression on 28th September 1995 about 1170 km east-southeast of Manila. It caused serious damage in the Philippines before crossing the South China Sea where it attained typhoon strength on 2nd October. Travelling northwest it made landfall on the west coast of Guangdong on 3rd October (Figure 18). The typhoon passed closest to Hong Kong about 8 am on the 3rd October when it was 290 km southwest of Hong Kong. This resulted in maximum gust wind speeds of 113 km/hr and a storm surge of 0.52 m at Waglan Island with up to 272 mm of rainfall (Royal Observatory, 1995). This resulted in suspended sediment concentrations increasing from the background value of 20 mg/l to in excess of 250 mg/l recorded at Sun Kong and 350 mg/l at Waglan. This is the first known instance of suspended solid data being recorded during a storm in Hong Kong. The limited impacts, in terms of duration and magnitude, of the dredging generated plumes, as measured by the silt meters, in comparison to elevated suspended sediment levels resulting from the typhoon is clearly shown (Figure 19). Closer examination of the data also shows the influence of tidal conditions on the typhoon generated suspended sediments with the result that elevated concentrations are present for over 60 hours, including 16 hours after all typhoon signals were lowered (Figure 20).

In addition to typhoons, the strength of the northeast monsoon generated waves are sufficient to disturb seabed sediments. Low visibility occurs in Hong Kong waters in October-December and this is at least partly due to the strong wind induced wave action of the northeast monsoon (Watts, 1973). The actual wind data for Hong Kong's eastern waters in 1994 was used to recreate the wind induced wave climate from which it is possible to determine wave induced bed shear stress (Hyder, 1997a). Hyder's work showed that the highest mean monthly predicted bed stresses were for November to March associated with the north east monsoon (Figure 21). The high mean bed stresses in June and September are associated with tropical storms Russ and Gladys. The predicted wave-induced bed-shear stresses in Hong Kong's eastern waters based on 1994 wind data are shown in Table 2. Based on the critical bed shear stress values shown in Table 1, the periods for which these critical values would be exceeded are shown in Table 3. Some re-erosion of bed mud would have occurred for a total of almost 10% of that year, and even the critical shear stress required to erode in-situ Hang Hau Formation mud would have been exceeded for 4 hours that year.

The effect of the northeast monsoons is also reflected in the EM&A water quality monitoring data for Tseung Kwan O Area 36. Figure 22 shows the variability of suspended sediment in basal waters at monitoring station B9, approximately mid way between East Tung Lung Chau and Ninepins, remote from the sand dredging area at East Tung Lung Chau. The dredging for Tseung Kwan O Area 36 was relatively small in scale and was completed by July 1995. Using a 28 day moving average plot, suspended sediment concentrations are shown as peaking in spring, decreasing until July, slightly increasing until December before increasing rapidly to a peak again in spring. Also shown on Figure 22 is the variability in wind direction over the same period, with increases in suspended sediment related to the wind direction of approximately 060 degrees or less. This results in the introduction of mobilised sediment from along the South China coast to the east of Hong Kong which is clearly evident on satellite images (Plate 5). This results in the basal suspended sediment concentrations increasing from a monthly average of 20 mg/l in July to in excess of 40 mg/l in March. A similar pattern is shown for surface waters (Figure 23) with concentrations increasing from 5 mg/l to 20 mg/l over a similar period. It is important to note that even though these data were collected daily it does not reflect the effects of typhoons, such as Typhoon Sybil, because the monitoring was suspended during these periods. The effects of the north east Monsoon were also reported by BCL (1995c) where monsoon-generated waves were observed as having a strong impact on a granular seabed at a depth of -17 m.

4.5 Rivers/Stream Courses

Figure 24 shows the location of EPD's routine river water quality monitoring stations, with the range of suspended sediments and flow shown for selected stations in 1996. The majority of stations are measured at monthly intervals, consequently it is unlikely that extreme rainfall events, such as typhoons which result in intense runoff, will be recorded. Even without such events being measured, significant sediment loads have been recorded in river discharges throughout Hong Kong, with flows in excess of 4,000 l/s and suspended sediment concentrations of up to 1900 mg/l. An exceptionally high concentration of up to 24,000 mg/l was noted in one river due to construction activities (EPD, 1997). These data only cover natural stream courses and do not include stormwater drains which will also carry significant sediment loading during periods of high rainfall. A number of rivers were studied as part of the Territorial Land Drainage Flood Control Study (Hyder, 1997b) which estimated an average annual sediment yield of over 50,000 tonnes, of which 67% was attributed to natural erosion and the remainder from construction/quarries. 80-90% of the sediment yield was expected to occur in the period April to October.

5. HUMAN ACTIVITIES

In addition to natural effects, human activities can cause changes in suspended sediment loads. These are briefly described as follows;

5.1 Shipping

In 1996, there were over 82,000 ocean vessel movements and over 130,000 Macau and mainland passenger vessel movements in Hong Kong (Hong Kong Monthly Digest of Statistics, December 1997). In addition to these vessels there are numerous ferries, fishing vessels, lighters etc. moving within Hong Kong every day. As shown in Plate 6, marine vessels, especially deep draught and high speed vessels, result in the re-suspension of seabed sediments or bed layers with higher suspended sediment concentrations due to the action of propeller wash. However, there are no data available for the extent, duration and cumulative effects of these activities.

5.2 Sewage and Drainage

Some 1.5M m^3 of sewage is released into Victoria Harbour waters every day (EPD, 1995). Assuming an average suspended solids concentration of 220 mg/l for untreated sewage (Metcalf and Eddy, 1991), would result in some 120,000 tonnes of sediments per year being released into Victoria Harbour. In addition, stormwater drains also contribute significant amounts of suspended sediment to the marine environment. As an example, it has been estimated that the relatively small (357,000 m^2) future development at Jordan Valley will result in between 141 and 430 tonnes of sediment per year being discharged by the storm drains into Victoria Harbour (Scott Wilson, 1998). It has also been estimated that the average suspended solids content of storm drain discharges in Hong Kong varies between 190 and 235 mg/l (Montgomery Watson, 1998).

5.3 Sand Dredging and Mud Disposal

When extracting sand using a Trailing Suction Hopper Dredger (TSHD), the hopper of the dredger quickly fills with a soil-water mixture. Depending on the dredging depth and soil characteristics, the hopper may only contain 10% solids when it becomes full of water and overflow commences. Obviously it would be uneconomical to finish dredging at this stage and sail to the reclamation site. Therefore to obtain an economical load the trailer discharges the excess water as overflow, carrying with it most of the fines, together with a proportion of the fine and medium sand that does not settle in the bottom of the hopper due to turbulence. It is this overflow that forms dredging plumes.

As part of a continuing programme of environmental study work by the GEO, the development and decay of dredging plumes have been investigated. An initial study (DEMAS, 1994) using aerial photographs of plumes showed that low concentrations of only 10-25 mg/l above background were detectable by eye. A more detailed study (DEMAS, 1995) was carried out using four survey boats equipped with Acoustic Doppler Current Profilers (ADCP), siltmeters and water samplers together with measurements taken onboard the dredger. This study showed that approximately 70% of the sediment from the dredger overflow is carried directly to the seabed in the immediate vicinity of the dredger, as a density flow. Any sediment remaining in suspension was found to decay to background concentrations within two to three hours (Whiteside et al, 1995). The concentrations within the plume were typically less than 100 mg/l, decaying back to background within two to three hours. Similar results were also observed in a further plume test at South Tsing Yi Marine

Borrow Area in 1996 (DEMAS, 1997).

Plumes, albeit of a lesser extent, are also generated during mud disposal operations with material being stripped away from the descending mass of dumped material by the prevailing tides and currents. These losses have been studied for both trailer dredgers and barges. For trailer dredgers (DRL, 1996b) the losses varied from 0.9 to 2.1% for a split hulled trailer and from 5.3 to 8.7% for a door discharge trailer. Neither vessel was considered a "typical" trailer. However the values measured support the generally adopted value of 5% losses. For barges, losses of 1.2 to 3.1% have been recorded (DRL, 1995c).

These studies have shown that, provided the dredging works are carefully carried out, the impacts on the environment from sand dredging and mud disposal are transient and are limited to the immediate location of the works. Other studies (ERM, 1998 & Leung, 1997) have also shown that development related impacts, such as sand dredging and the generation of suspended sediments, have had little impact on fish stocks in Hong Kong.

5.4 Reclamation

Between 1990 and 1998 some 477M m^3 of fill has been used in Hong Kong to create 2100 ha of land, of which 54% was marine sourced and the reminder from land borrow areas. The General Specification for Civil Engineering Works (CED, 1992) specifies that the fines content (<63 µm) for underwater fill for marine works be less than 30%. However, many individual contract specifications stipulated values less than this, often as low as 5%. (Kwan, 1993). Reclamations in Hong Kong are sometimes carried out within edge structures to minimise the loss of fill.

By definition, sand deposits are defined as containing less than 35% fines. Where TSHD's are used for extraction the dredging process results in a reduction in the amount of fines within the sand. For example, at the Po Toi Marine Borrow Area the average fines content in the hopper of a TSHD was approximately 5% compared with the inflow material having approximately 13% fines (DEMAS, 1995). Conversely, there is little loss of fines during grab sand dredging. With respect to the fines contents at the reclamation site, these have been reported as varying from 0 to in excess of 20% with the average fines content typically varying from 2 to 4.5% (Shen et al 1997). This is in line with Kwan (1993) who noted that the typical average fines content for 13 reclamation contracts varied from 2 to 8%.

With bottom dumping there is little chance of segregation of fines. With hydraulic placement fines tend to settle further from the discharge point and are redistributed within the reclamation site. However, any migration of material from reclamation sites is usually minimised by the completed/ partially completed edge structures constructed in advance of the reclamation.

5.5 Fishing

Whilst there is no published data on the effects of trawling on the seabed in Hong Kong, related studies have been carried out elsewhere. Churchill (1989) described how trawling could generate significant amounts of suspended sediments with concentrations of between 100-550 mg/l reported 100 m astern of shrimp trawlers and it was estimated that trawling generated plumes extend to in excess of 10 m above the seabed.

During a study of Hong Kong's eastern waters (Selby & Evans 1997), side scan sonar showed disturbance to the seabed in the form of numerous pairs and sets of arcuate, parallel grooves up to 0.25 m across and estimated to be 0.2 m deep. Detailed analysis revealed that these were trawling tracks originating from both otter boards and shrimp trawling which result in a series of up to 18 pairs of tracks. REMOTS seabed camera surveys indicated that the near seabed sediments contain extensively distributed mud clasts (puzzle fabric) which are occasionally associated with mud suspensions infilling depressions in the natural seabed. The base of the depressions is around 50 mm below the surrounding seabed. The mud clasts are typically less than 15 mm in diameter and were concluded as being trawling generated (Plate 2).

The frequency of trawling probably leads to a continual re-working of the uppermost seabed with clasts and suspensions re-mobilised to form turbid plumes. It was estimated that during a three hour trawl, a single large shrimp trawler could disturb up to 0.5 km^2 of seabed. AFCD's 1997 vessel count recorded 4,857 fishing vessels in Hong Kong of which 54% are less than 5 m in length. Of the remaining vessels some 639 or 28% are either shrimp or stern trawlers. (ERM, 1998). This suggests that if all the shrimp or stern trawlers are active simultaneously over 300 km^2 of seabed could potentially be disturbed in a three hour period.

In addition to capture fisheries, there are 26 mariculture sites throughout Hong Kong producing about 3,000 tonnes of fish per annum (Wilson & Wong, 1995). The use of fixed positions for the fish cages in sheltered bays with only 3-5 m of water results in increased localised suspended sediments and sedimentation as a result of fish feeding, especially overfeeding with trash fish, and waste by-products.

6. CONCLUSIONS

In comparison with the complicated hydrological conditions affecting Hong Kong waters today, the conditions in the recent geological past were even more extreme. The coastline was well to the south of Hong Kong 9500 years ago and the majority of the present day marine sediments were deposited between 4500 and 1000 years ago, at a rate likely to be in excess of 10 mm per year during periods of maximum deposition.

Whilst sedimentation in Hong Kong is now limited, this is due to the seabed being in equilibrium rather than a decrease in available sediment. Where this equilibrium is disturbed, such as by the dredging of fairways, up to 50 mm a year of sediment has been deposited. The main source of sediment is the Pearl River which, on average, discharges about 36 million tonnes of sediment each year. Depth average concentrations of up to 1400 mg/l and siltation rates of 130 mm per year have been reported within the Pearl River Estuary close to Hong Kong. A significant amount of the suspended sediments entering the Pearl River Estuary will remain as either soft muds or suspended sediments within the turbidity maximum.

The Pearl River Estuary discharge affects the whole of Hong Kong's waters every year to varying degrees. In the wet season the Pearl River Estuary discharge containing a high sediment load coincides with the Hainan current, which results in a north easterly flow of sediment into Hong Kong waters. Superimposed on this is the development of a stratified water column, with fresh water from the Pearl River Estuary overlying an intrusion of cooler continental shelf water, which together with near shore tidal effects results in the highest concentrations of suspended sediment being associated with wet season spring tides. However, extreme rainfall events can result in the sudden release into the marine environment of the vast amounts of sediments stored within the estuary. Such conditions occurred in 1994, and probably to a lesser extent in 1997, resulting in elevated suspended sediment concentrations throughout Hong Kong.

A further factor affecting suspended sediment concentrations is the re-suspension of sediments due to wave action. On average 5 typhoons a year affect Hong Kong, with elevated suspended sediment concentrations in excess of 350 mg/l being recorded and the impact of the typhoon lasting for over 60 hours. The northeast monsoon has a similar, albeit reduced, effect. This results in a gradual increase in suspended sediment concentrations throughout the winter months peaking in the spring resulting in a 95% and 320% increase in basal and surface suspended sediments respectively. Rivers in Hong Kong also result in localised inputs of suspended sediments with concentrations of up to 1900 mg/l occurring. It has been estimated that in excess of 50,000 tonnes of sediment are discharged by rivers each year.

In addition to the naturally occurring sediments, human activities such as trawling, sewage discharge, shipping, dredging and reclamation all generated suspended sediments. However, in terms of suspended sediment generation, these are relatively limited in their extent and impact in comparison with natural events.

In summary, Hong Kong is situated at the estuary of the third largest river in China and is also affected by changing oceanic currents, tidal effects, wave action, extreme climatic conditions and significant anthropogenic influences. Consequently, the concept of a Pearl River Estuary-Mixed-Oceanic regime, with south eastern and eastern waters unaffected by the Pearl River, and that suspended sediment are high in the wet season and low in the dry is an oversimplification. Similarly, the use of monthly or bi-monthly data, which may be suitable for determining trends of anthropogenic pollutants, is not sufficiently frequent to determine the highly variable naturally occurring suspended sediment concentrations where large scale fluctuations occur over periods of hours or even minutes. Figure 25 shows again the impact of Typhoon Sibyl on suspended sediments. Also shown are the results from an EM&A monitoring station for sand extraction at East Tung Lung Chau. No EM&A data was collected during the typhoon because of the sea conditions and consequently its impacts were missed. Finally the result for EPD’s nearest monitoring station is shown for the entire period which comprises a single reading.

7. RECOMMENDATIONS

It is apparent that in order to establish true “ambient” conditions any monitoring needs to reflect the long term seasonal trends, medium duration high intensity events and the short term tidal effects on suspended sediments. Whilst it is considered that long term project EM&A monitoring data will reflect this better than EPD monitoring data, it is unlikely to record events such as typhoons. Consequently, it is also recommended that additional work, such as the deployment of seabed siltmeters for the continuous monitoring of suspended sediment be considered.

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Table 1 - Estimated Critical Bed Shear Stress for Hang Hau Formation Mud

Sediment Type	Suspensions	Consolidating Suspensions and Mud Clasts		In-situ Hang Hau Formation
Density (mg/m^3)	1.08	1.15	1.23	1.35
Critical Bed Shear Stress (N/m^2)	0.3	0.8	1.5	2.5
Note: From Selby and Evans, 1997				

Table 2 - Predicted Wave Induced Peak Bed Shear Stresses in Hong Kong's Eastern Waters

	Return Period	Peak Bed Shear Stress (N/m^2)	
		-25 mPD	-30 mPD
Spring tide currents	Wet Season	0.06	0.03
	Dry Season	0.07	0.04
Waves and wet season currents	0.1 year	0.81	0.55
	1.0 year	1.86	1.37
	10 year	3.15	2.39
	100 year	8.74	6.70
Waves and dry season currents	0.1 year	0.94	0.63
	1.0 year	2.02	1.46
	10 year	3.31	2.48
	100 year	8.84	6.76

Note: From Selby and Evans, 1997

Table 3 - Predicted Time Periods for Wave Induced Bed Shear Stresses in Hong Kong's Eastern Waters in 1994

	Time (hours)	Time (%)
Time period shear stress exceeds 0.3 N/m^2	824	9.7
Time period shear stress exceeds 0.8 N/m^2	194	2.3
Time period shear stress exceeds 1.5 N/m^2	70	0.8
Time period shear stress exceeds 2.5 N/m^2	4	< 0.1
Note: After Hyder, 1997a		

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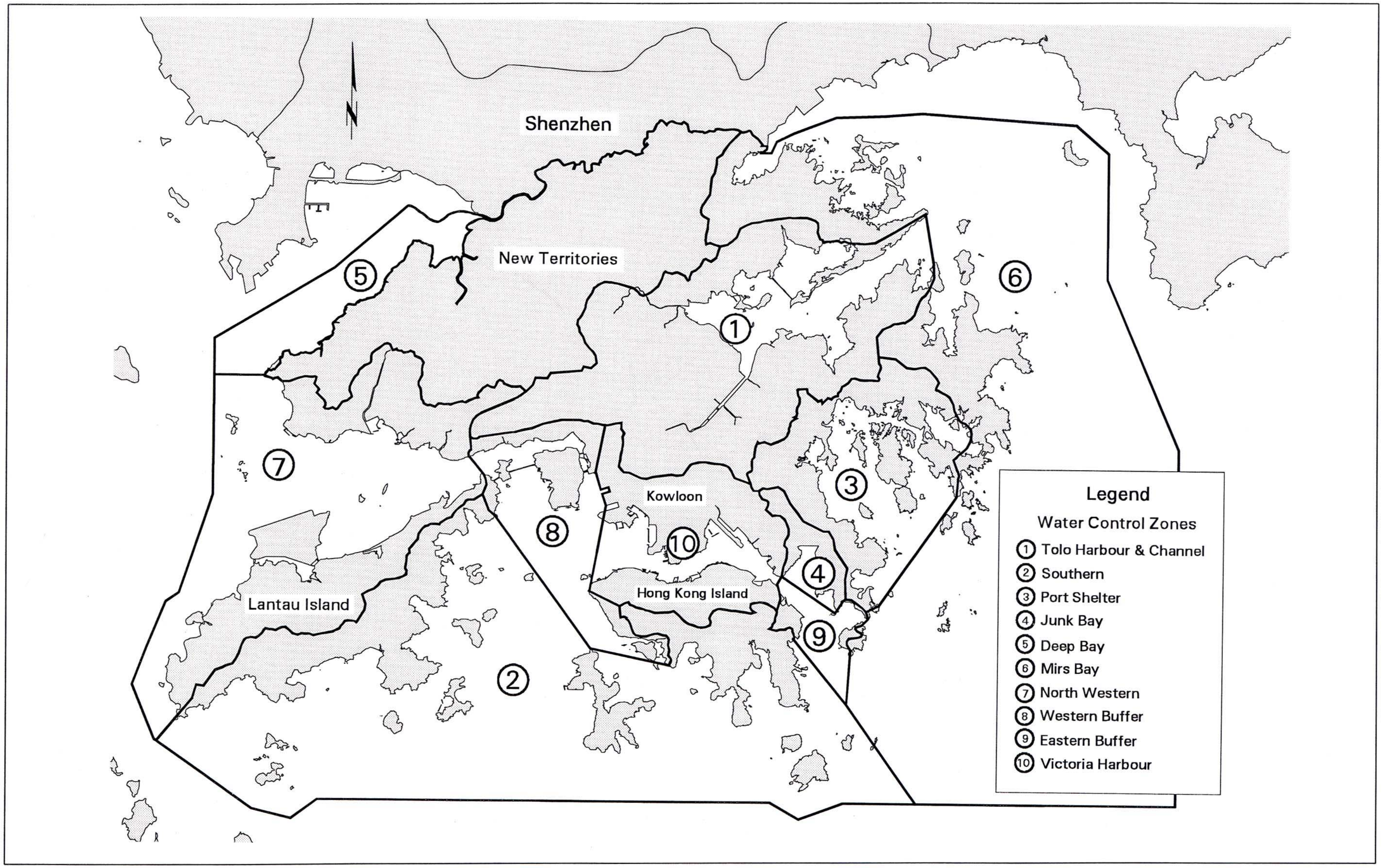
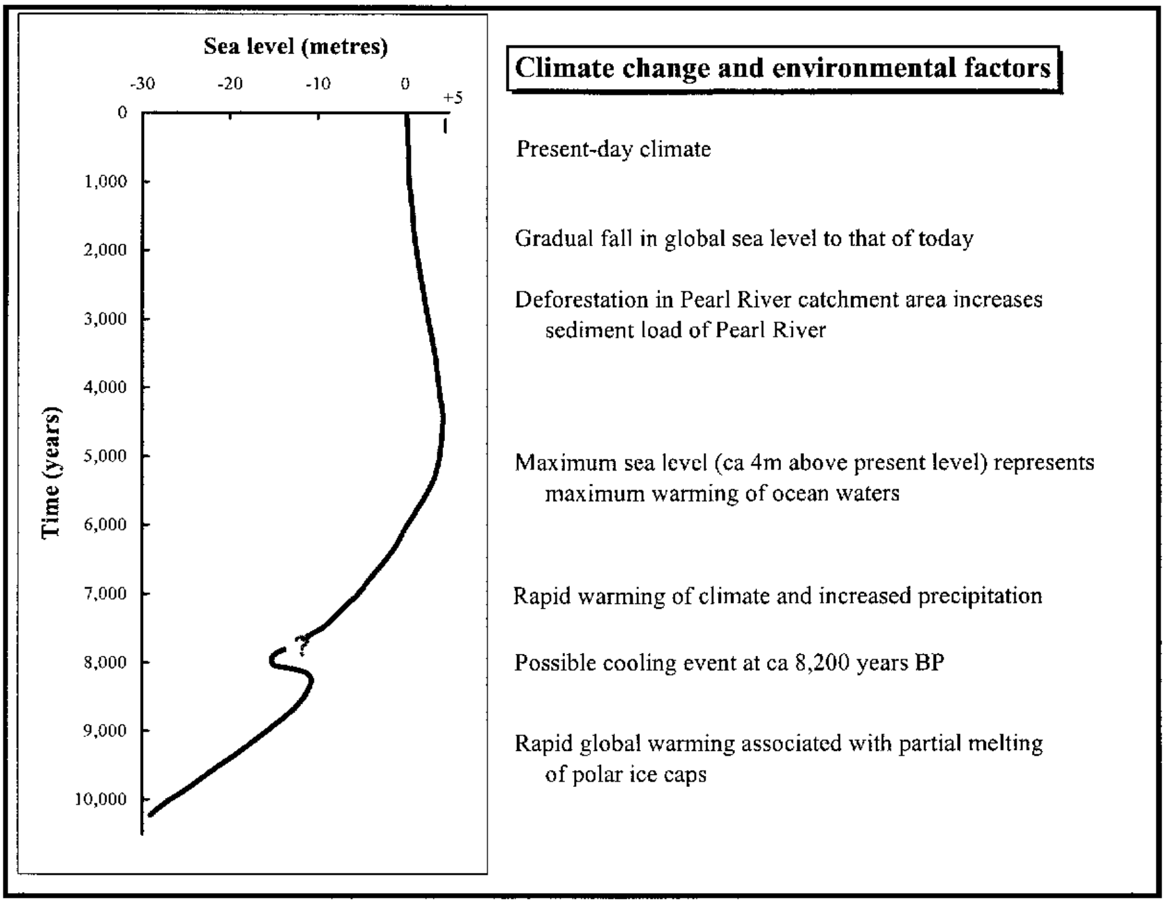


Figure 1 - Water Control Zones in Hong Kong



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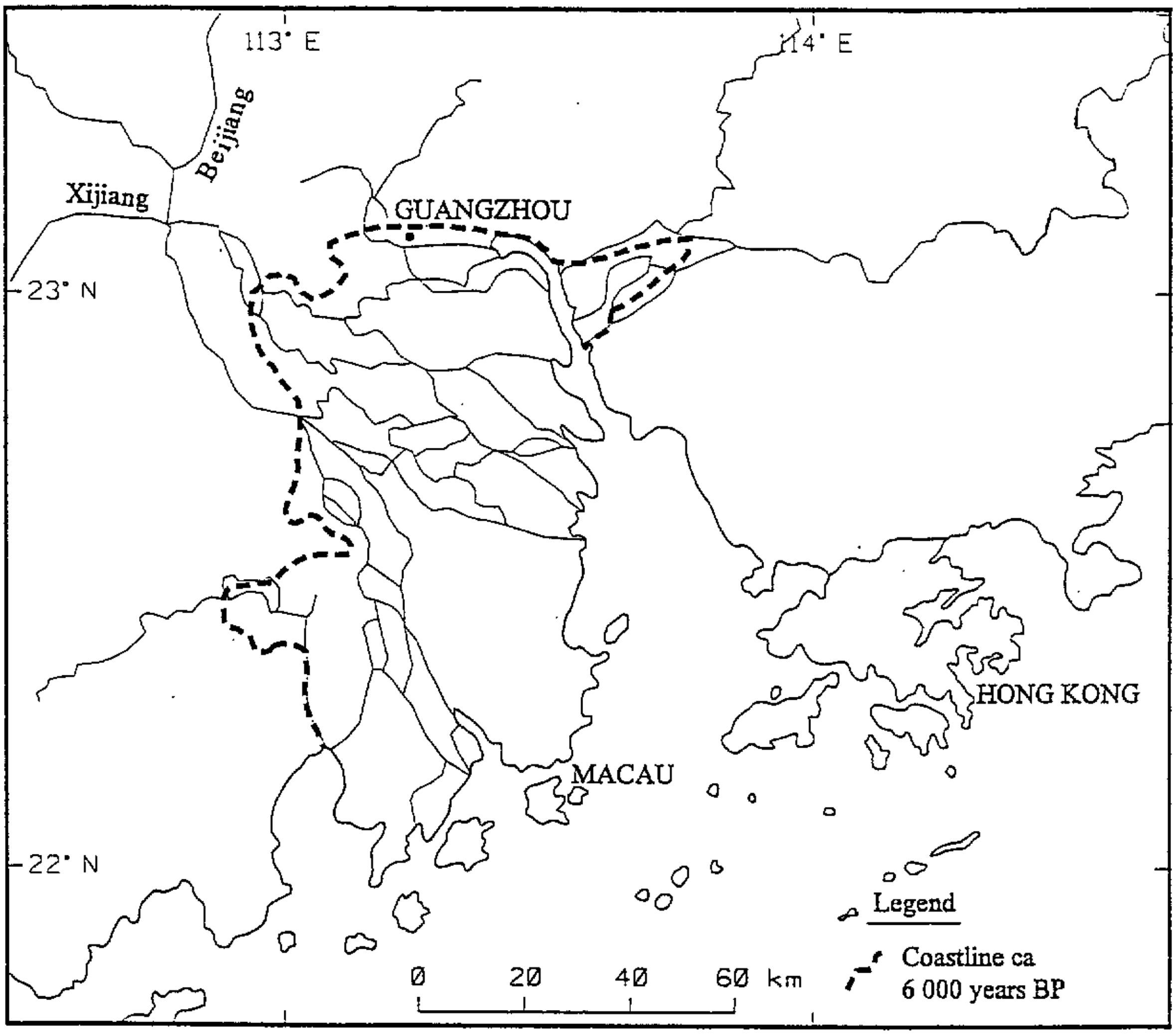

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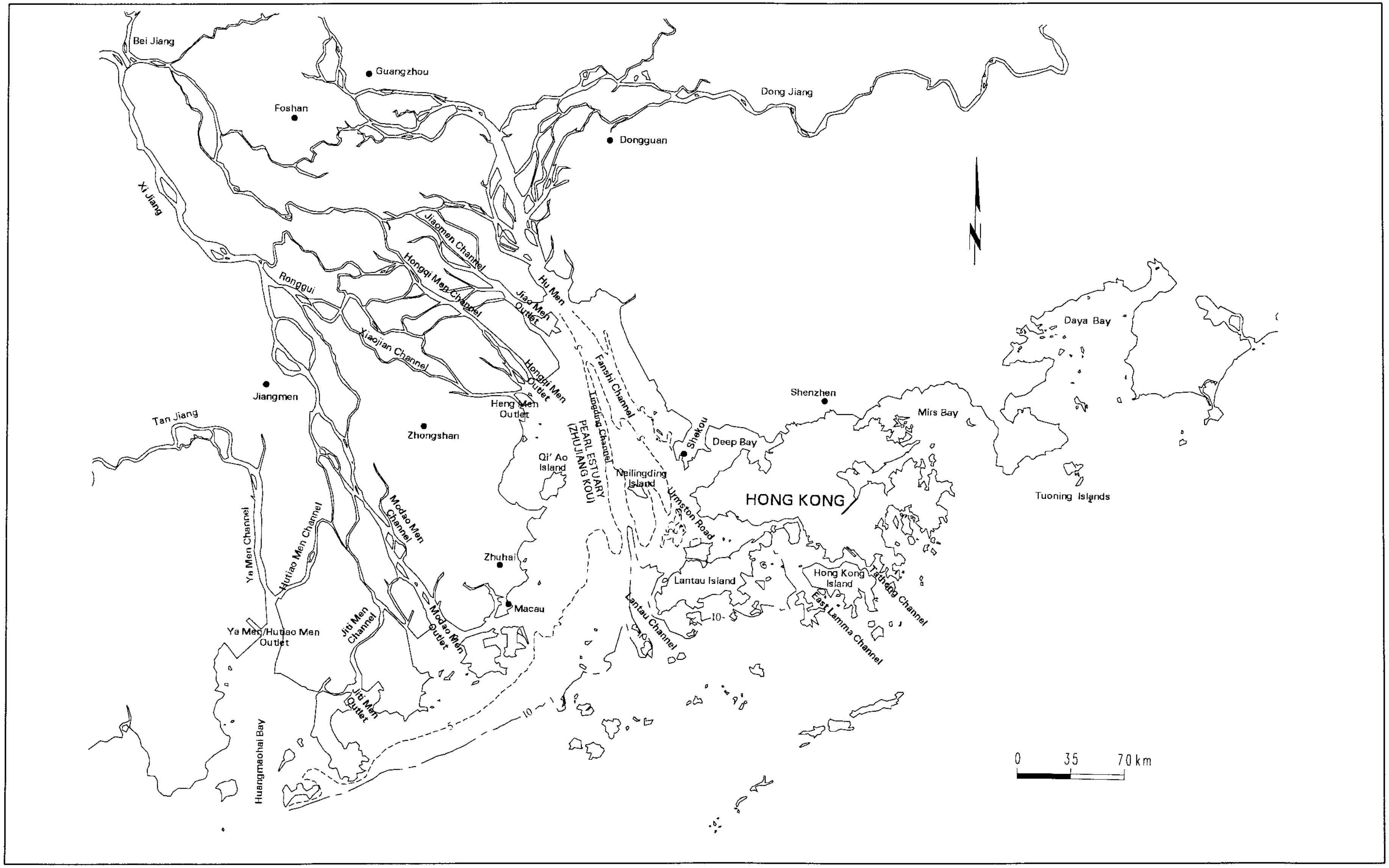

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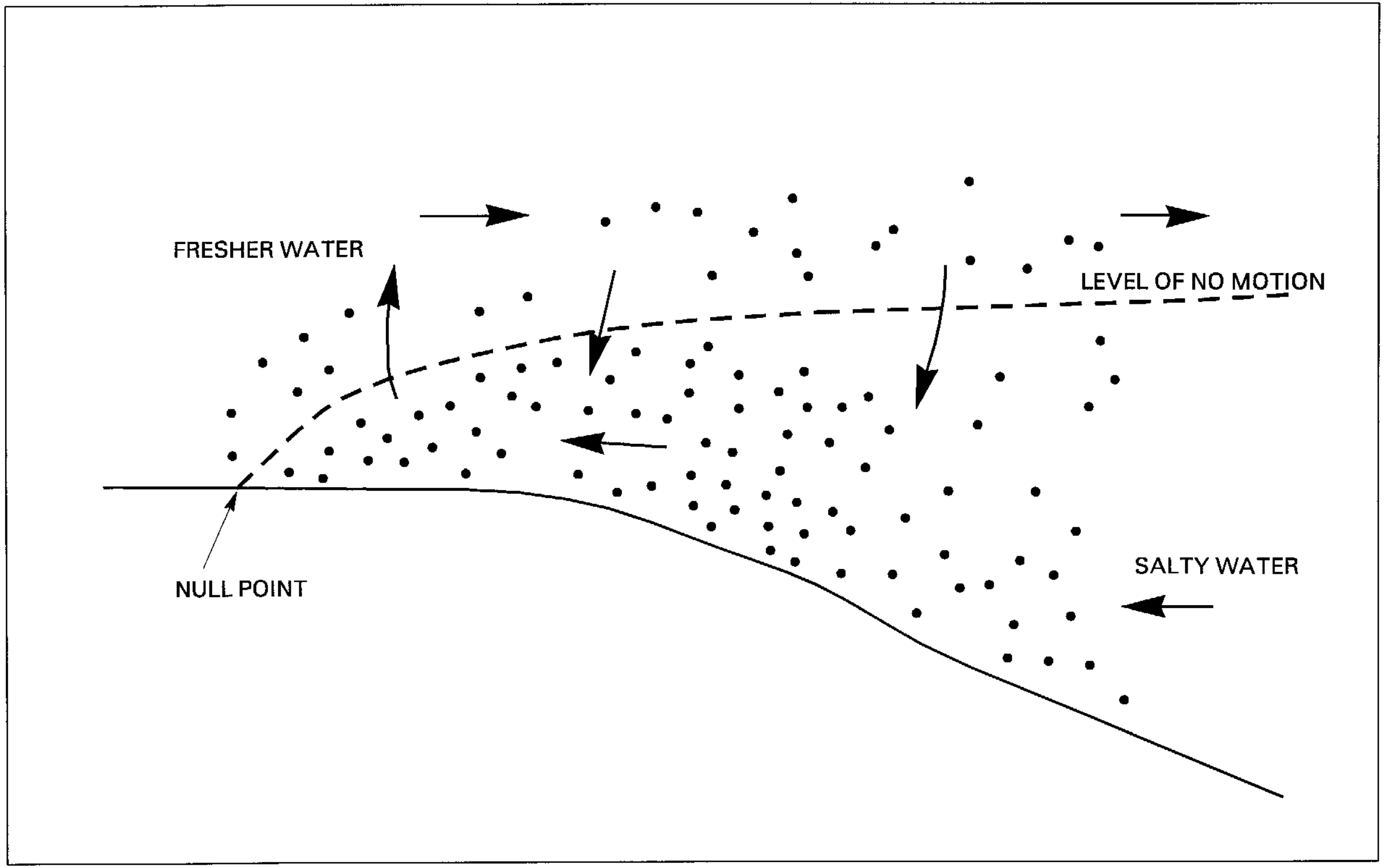

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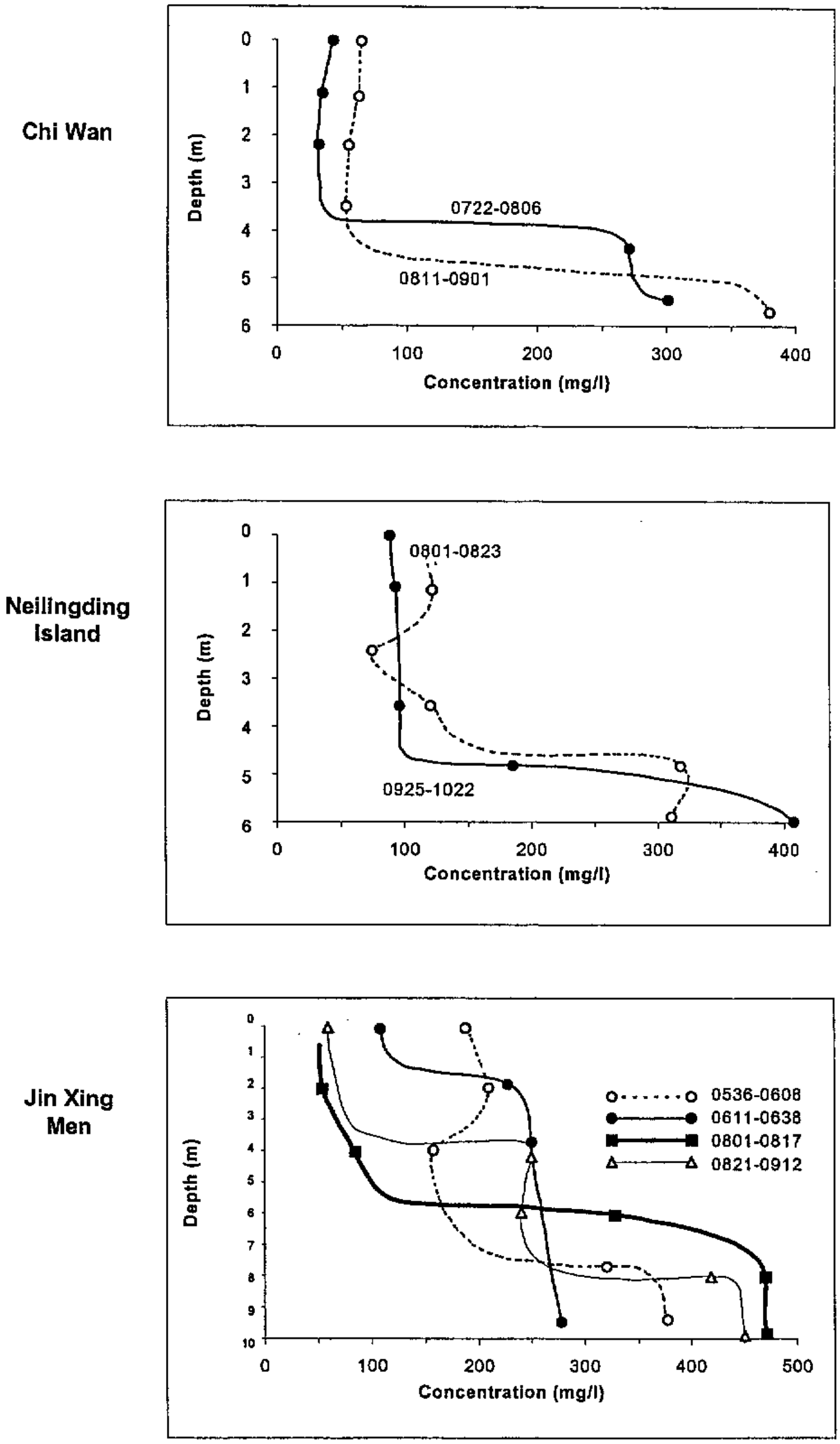
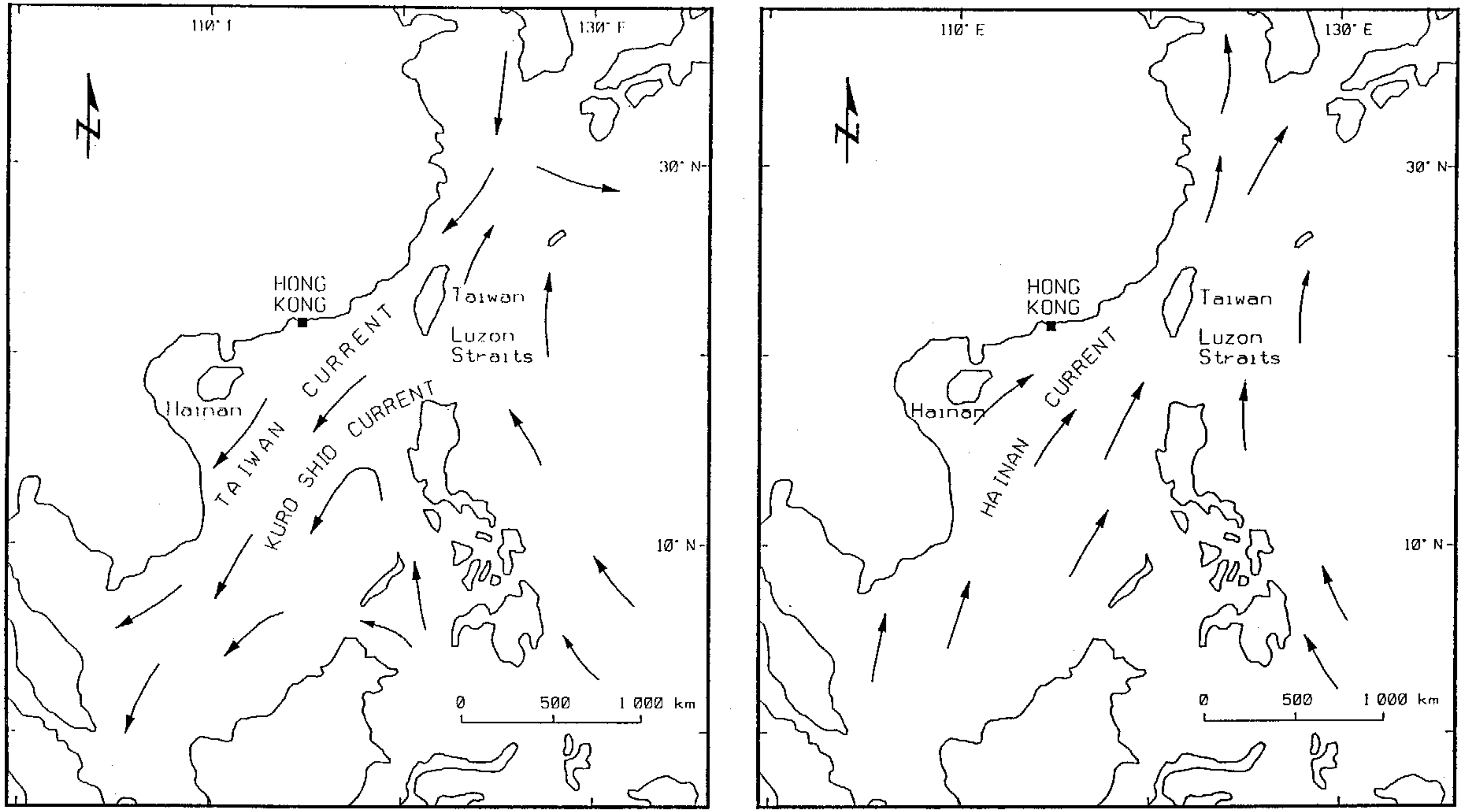


Figure 6 - Lutocline-like Structures in the Pearl River Estuary (After Kirby 1992)
(Value are the time during which sampling was undertaken)



Winter months

Summer months

Figure 7 - Oceanic Currents Affecting Hong Kong

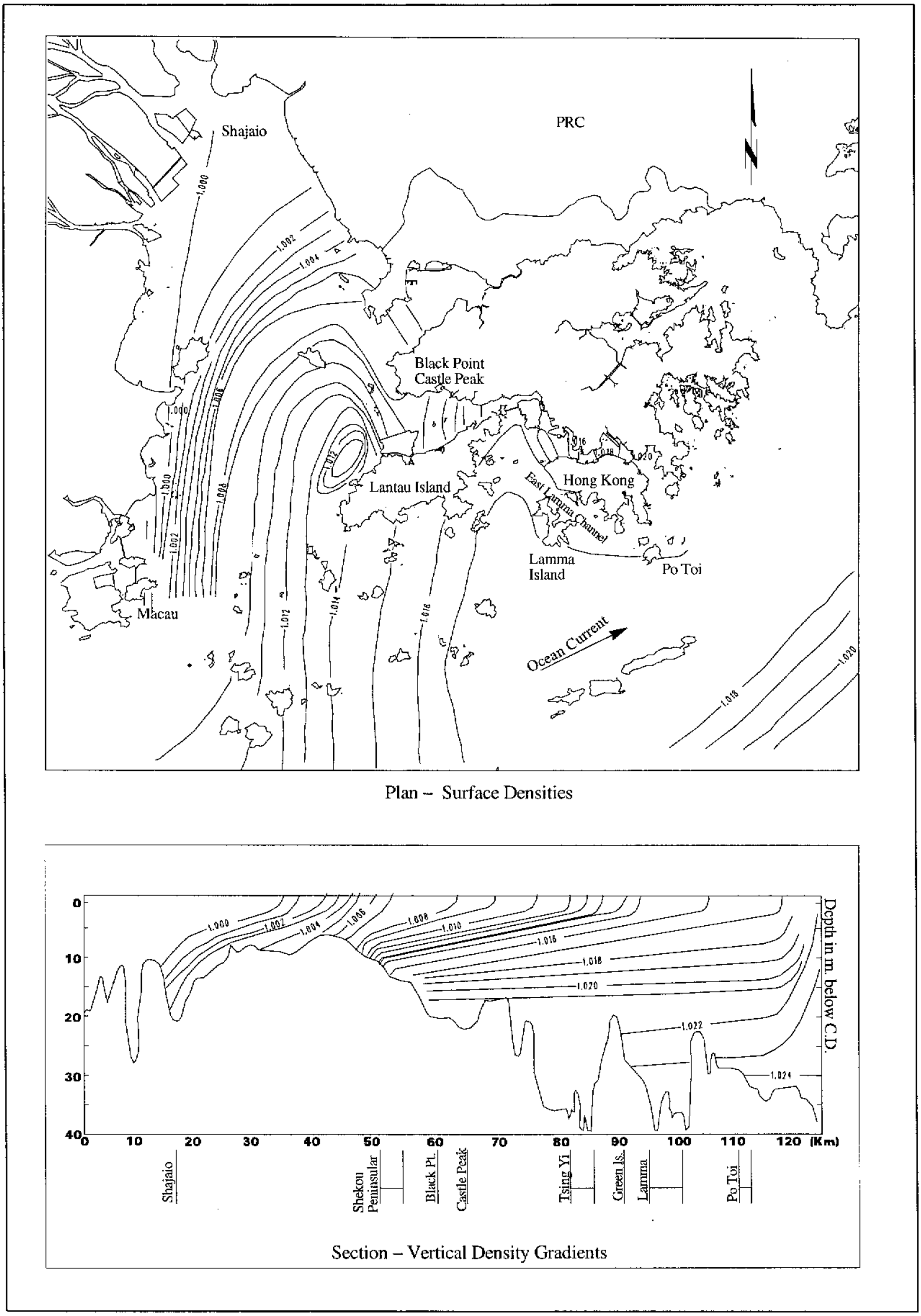


Figure 8 - Wet Season Saltwater Gradients (After Ridley Thomas & Osorio, 1992)

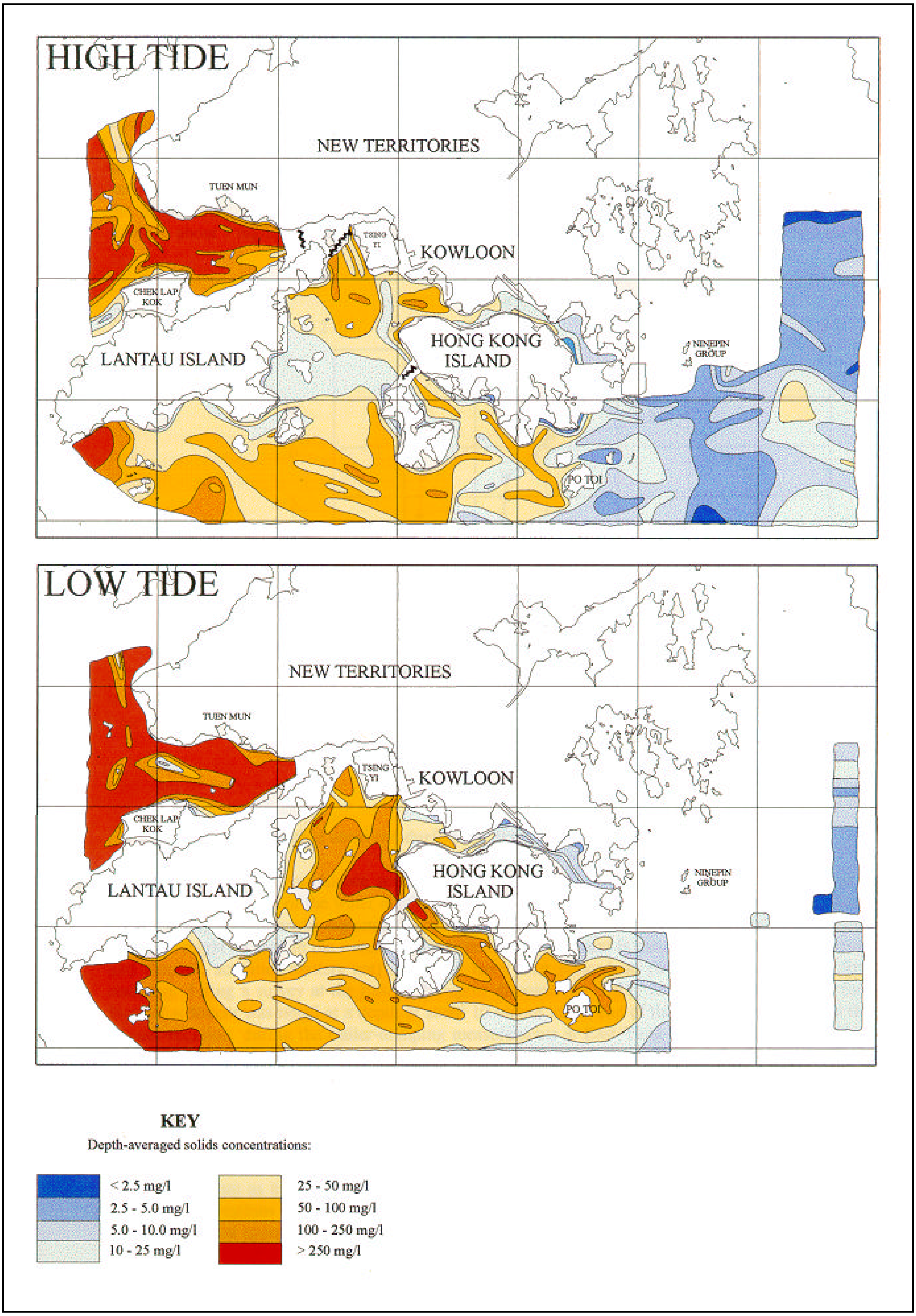
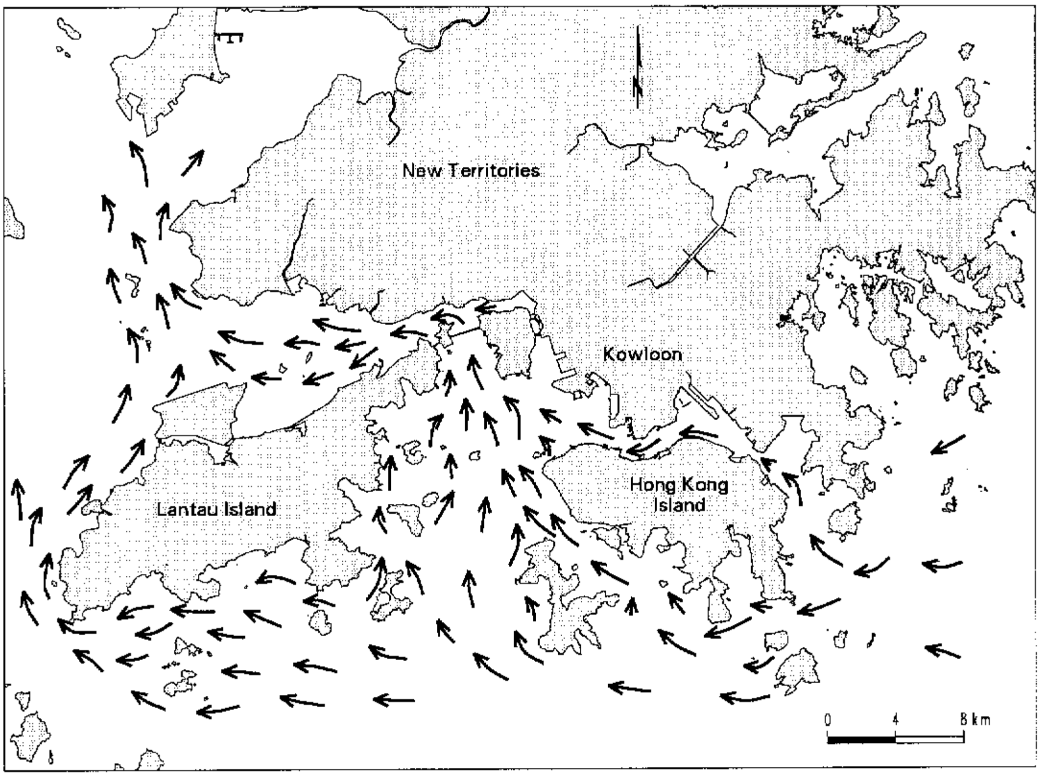
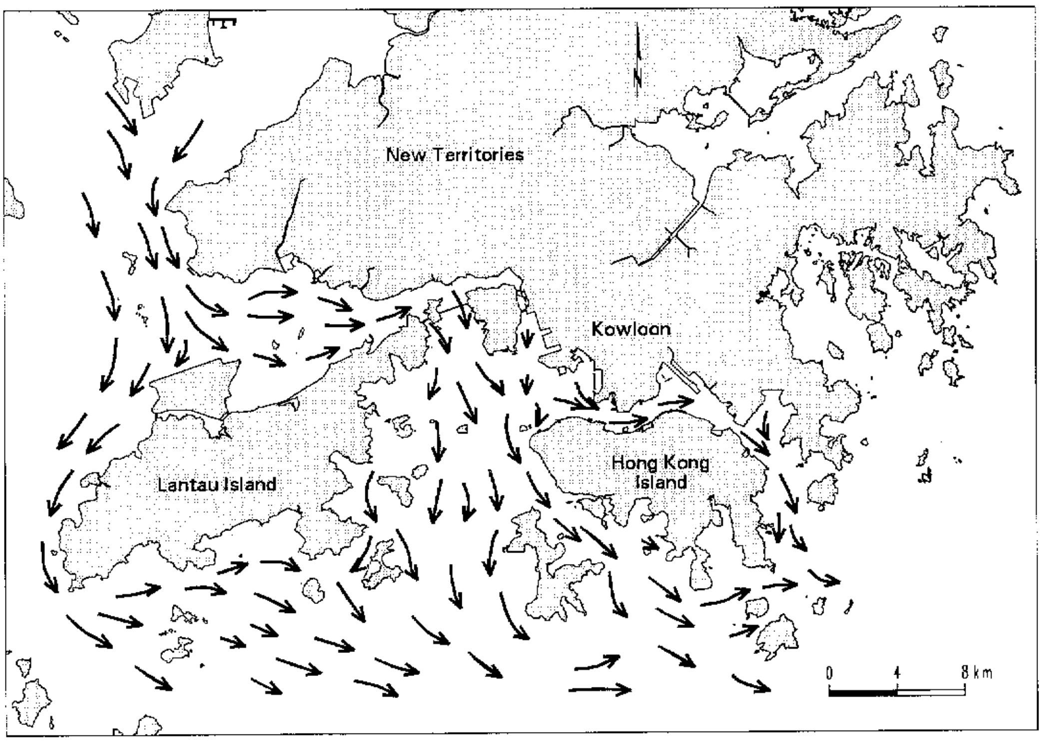


Figure 9 - Wet Season Territorial Suspended Solids Survey (August 1993)

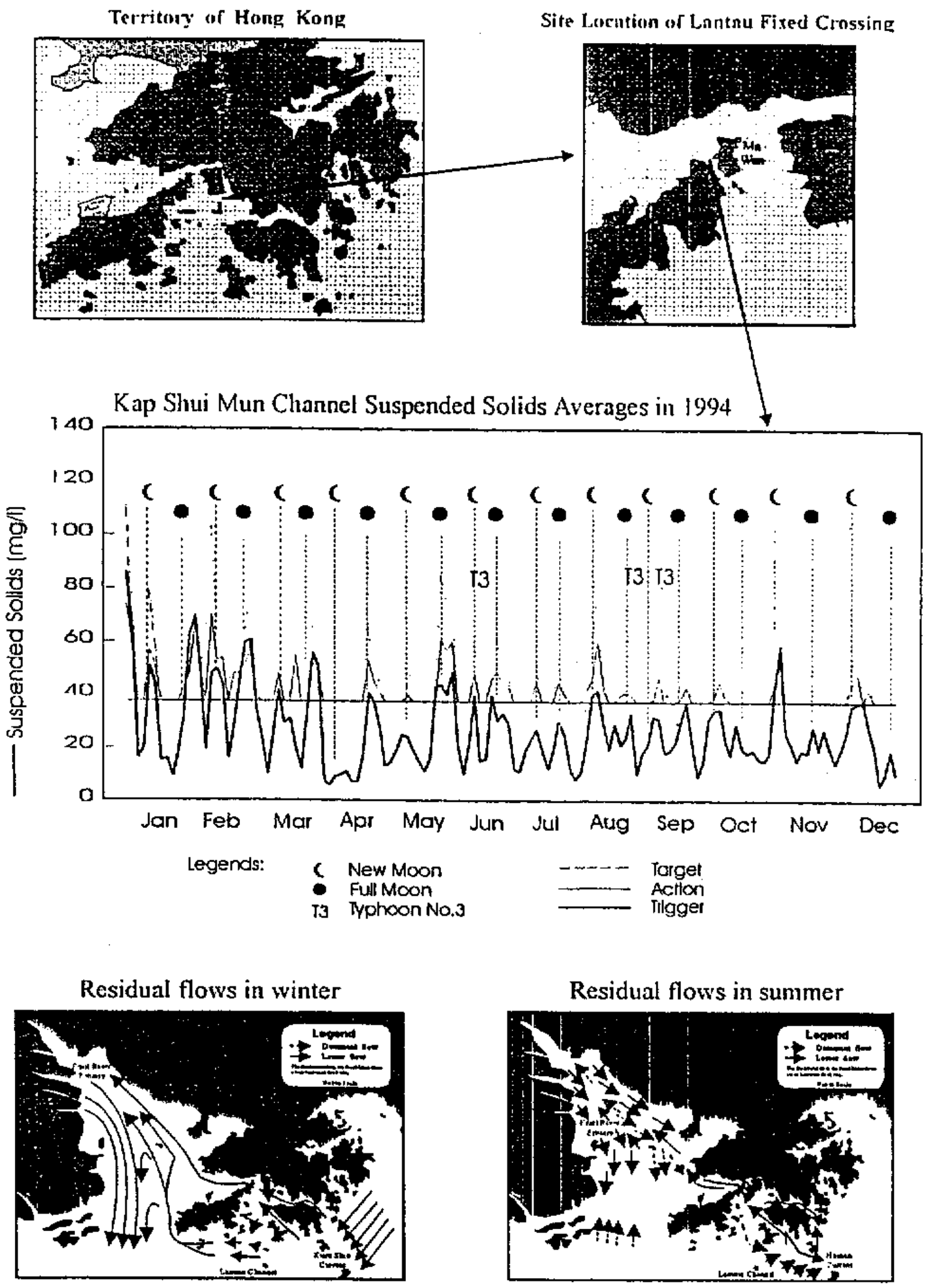


Flood Tide



Ebb Tide

Figure 10 - Tidal Currents Affecting Hong Kong



Occasional suspended solids exceedances occurred during heavy marine activities. In general, the suspended solids impact is dominated by the estuarine conditions of the Pearl River. During the winter months, seawater is characterized by its high tidal effects causing high suspended solids results. During the summer months, the tide height is less and the reduced suspended solids level is mainly due to the freshwater flows from the Pearl River. The monthly peaks are due to the new/full moon effects of the high tide periods. Local effects are also due to the typhoons and advanced earthwork in the Toll Plaza upstream of the flow path on north Lantau. This illustrates that impacts monitoring needs to take account of the background seasonal and tidal variations in order to correctly identify the water quality impacts arising from the works.

Figure 11 - Lantau Fixed Crossing - Water Quality Impacts

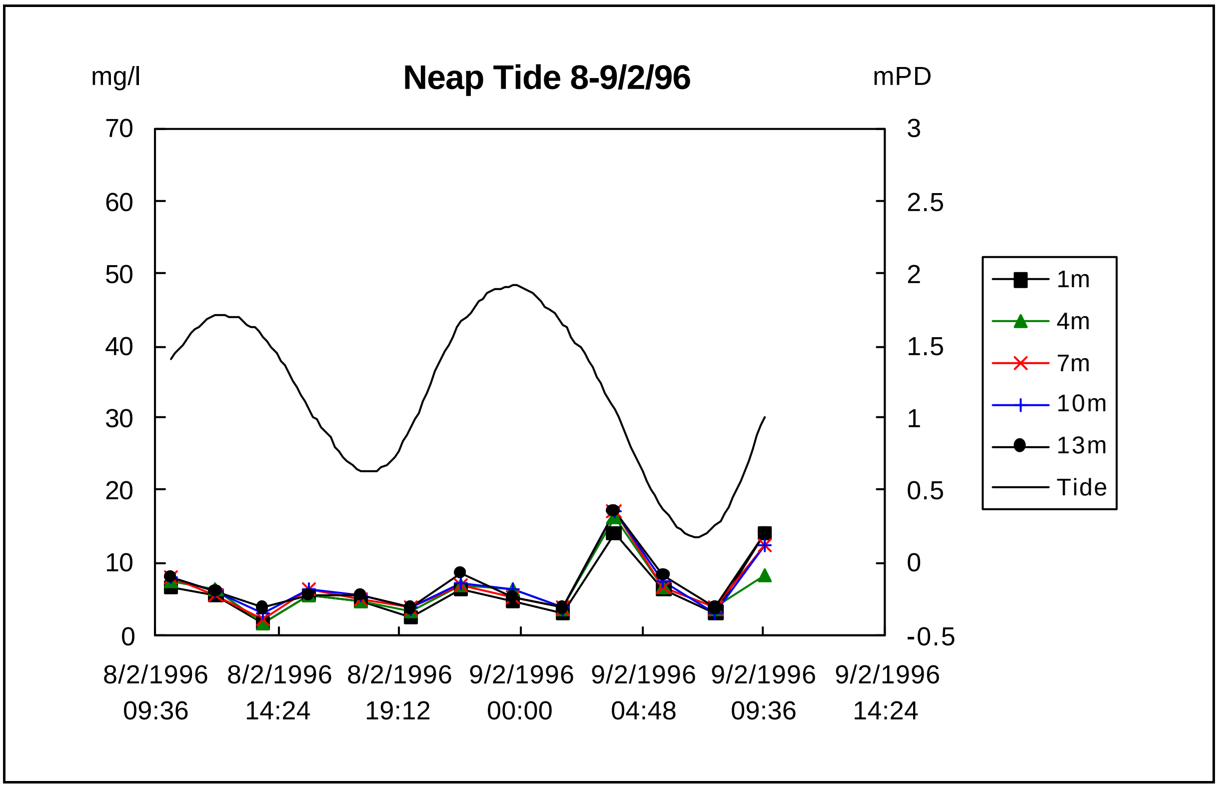


Figure 12a - Dry Season Suspended Sediment Concentrations at East Sha Chau

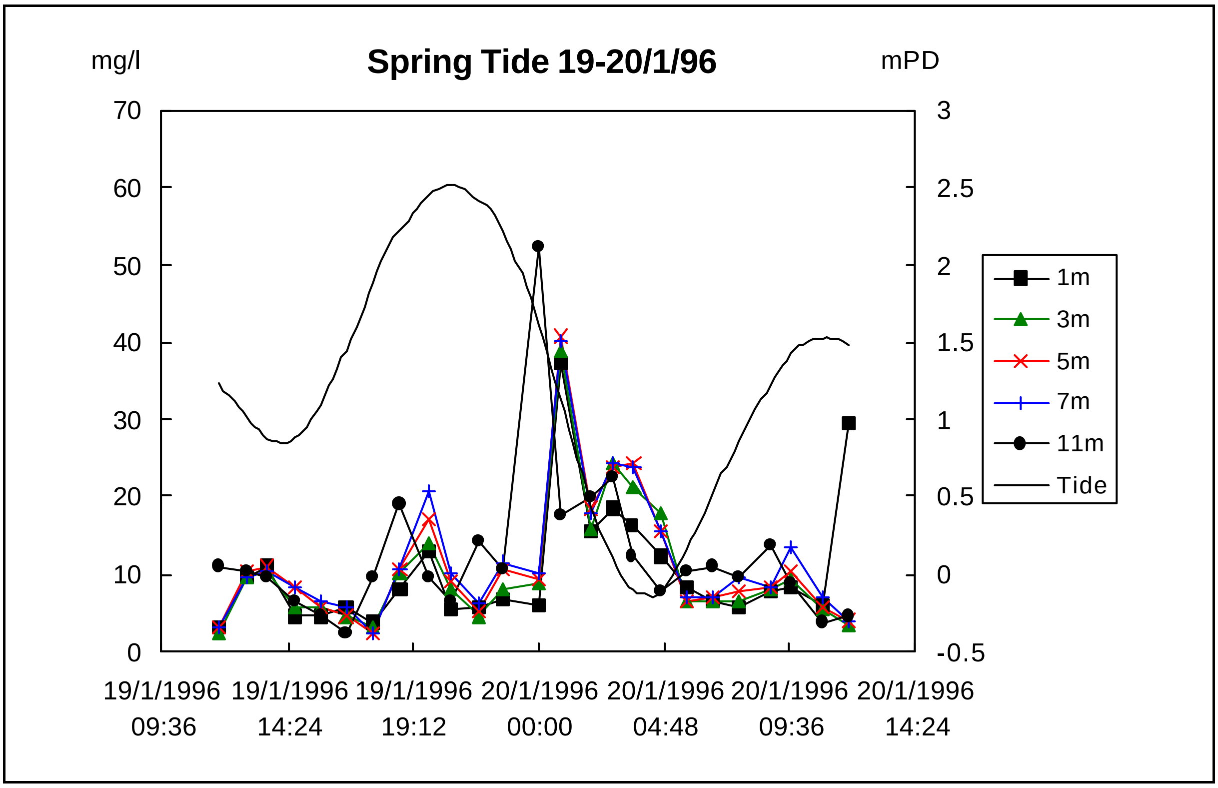
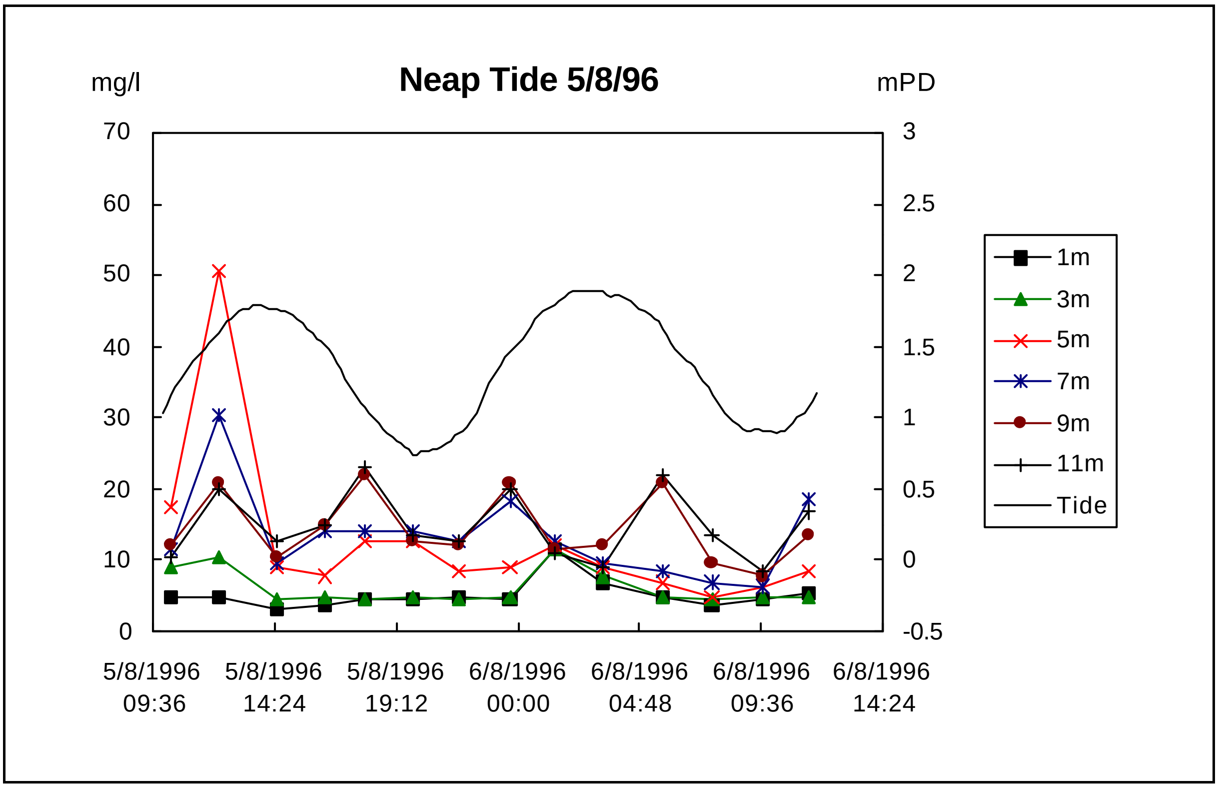


Figure 12b - Dry Season Suspended Sediment Concentrations at East Sha Chau



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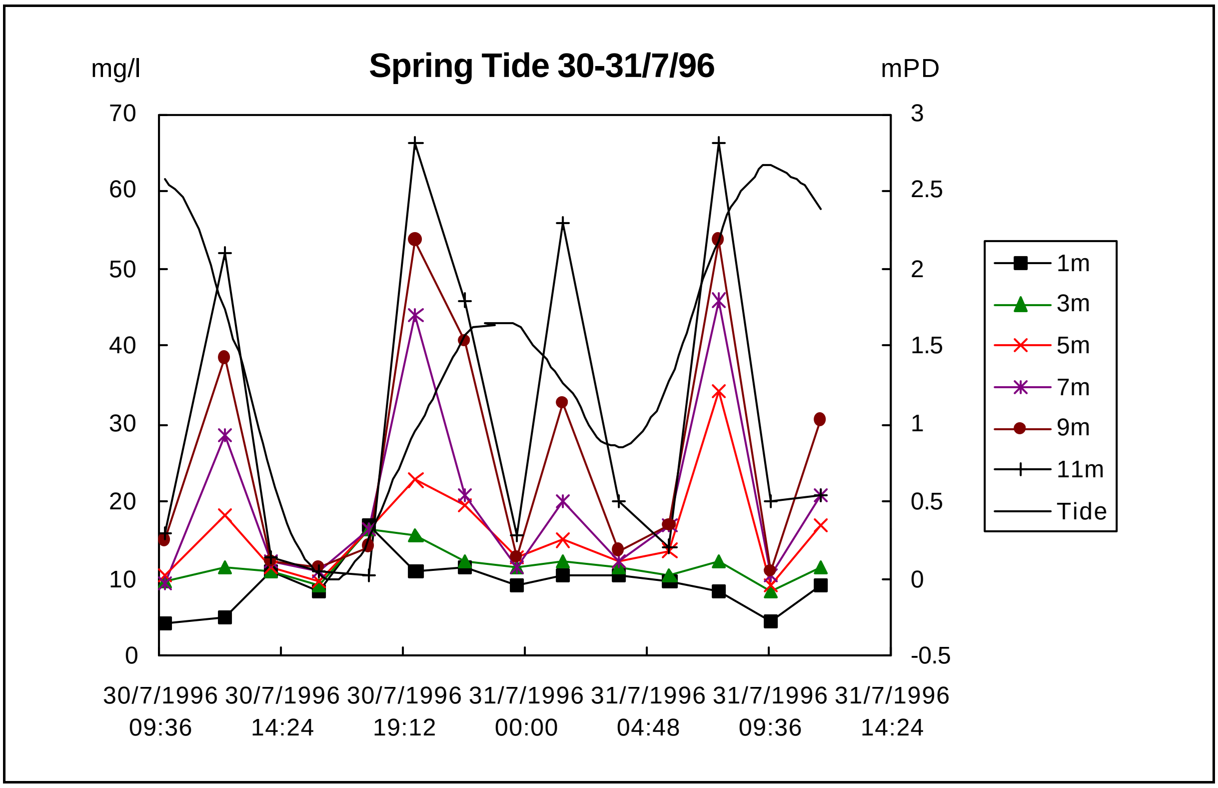

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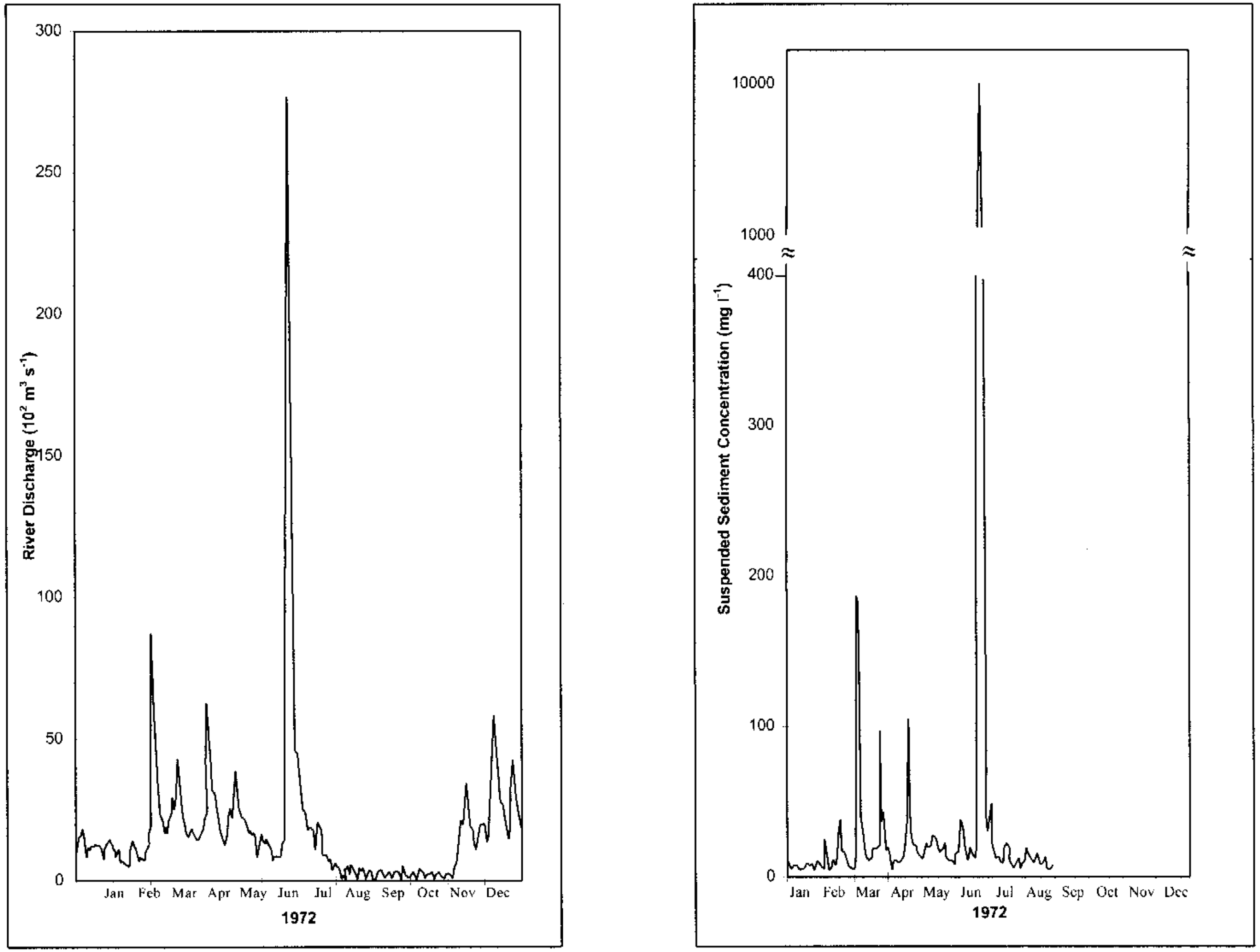

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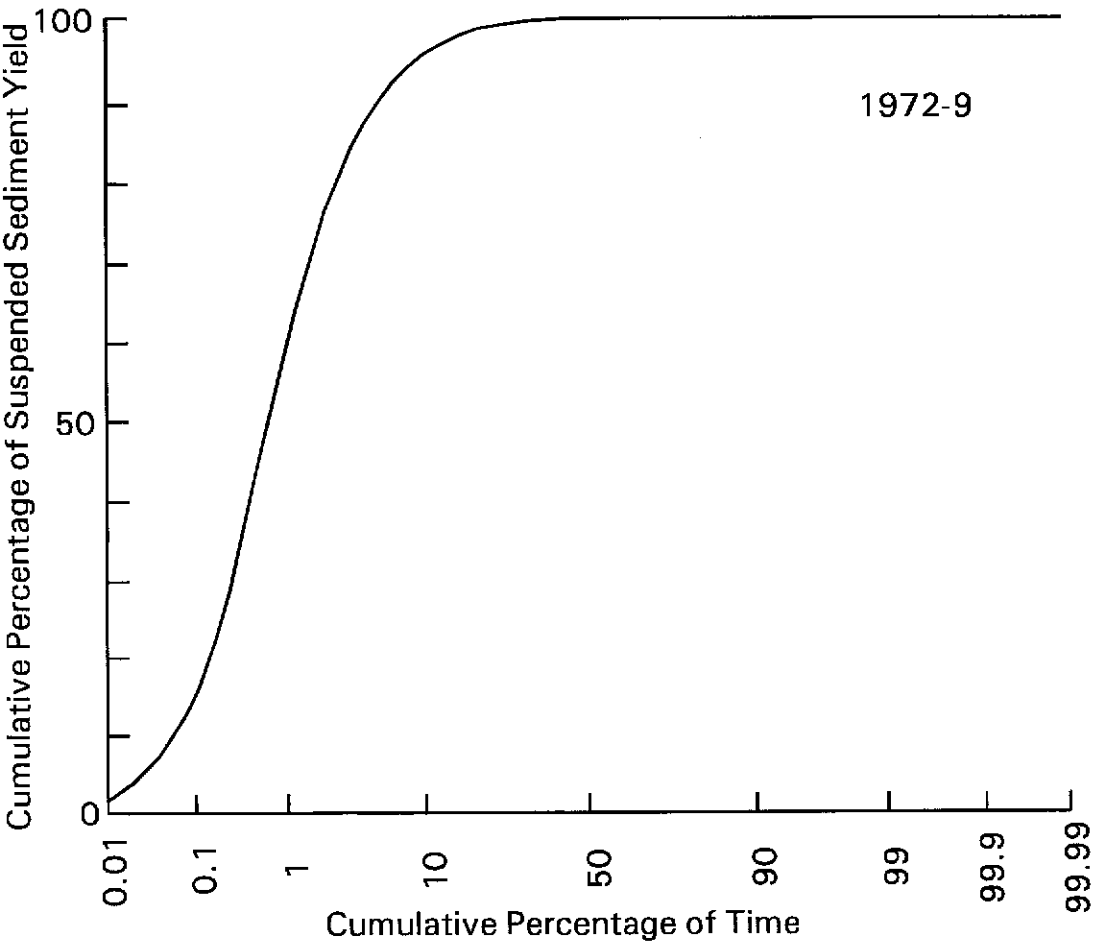

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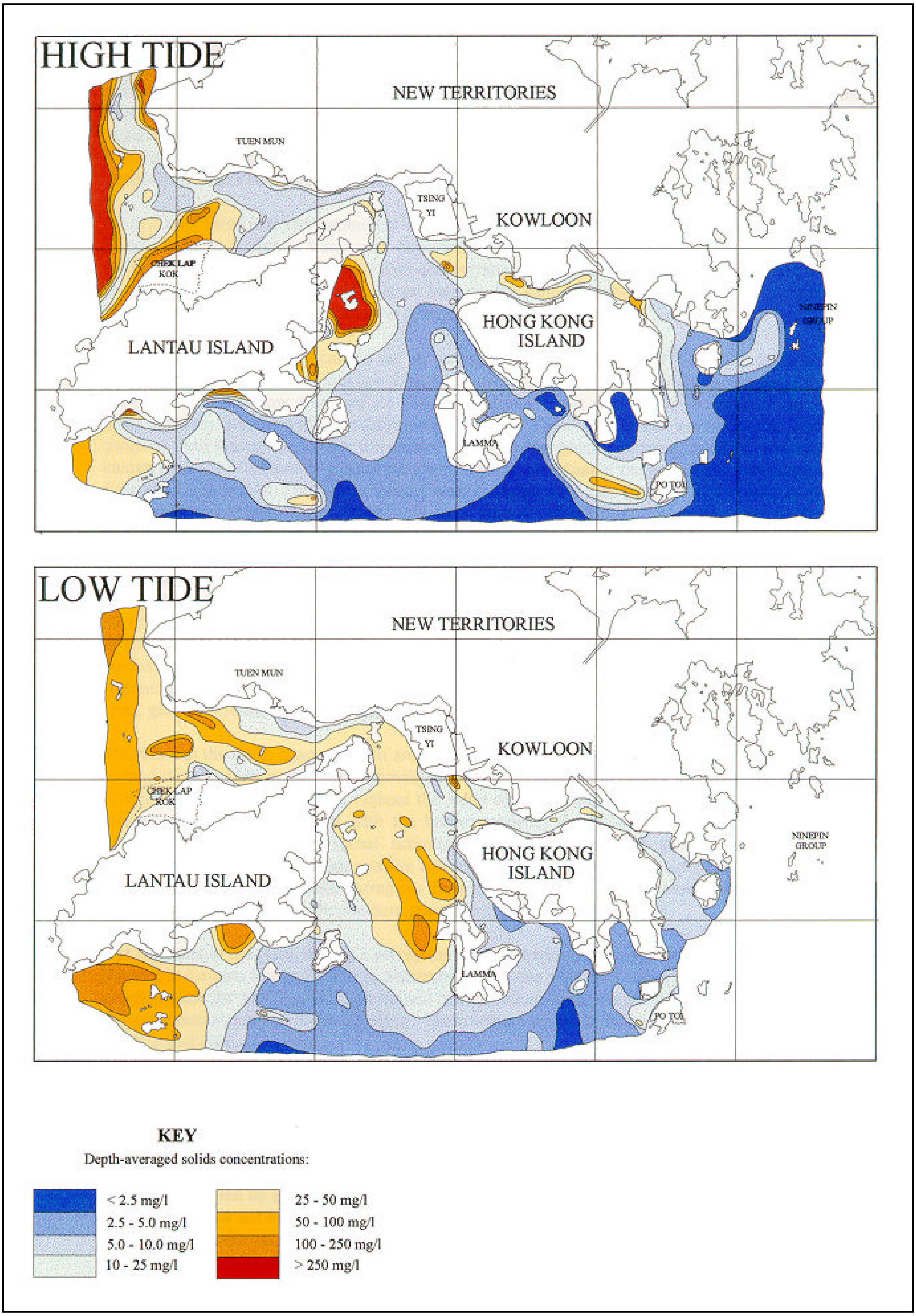


Figure 16 - Dry Season Territorial Suspended Solids Survey (November 1994)

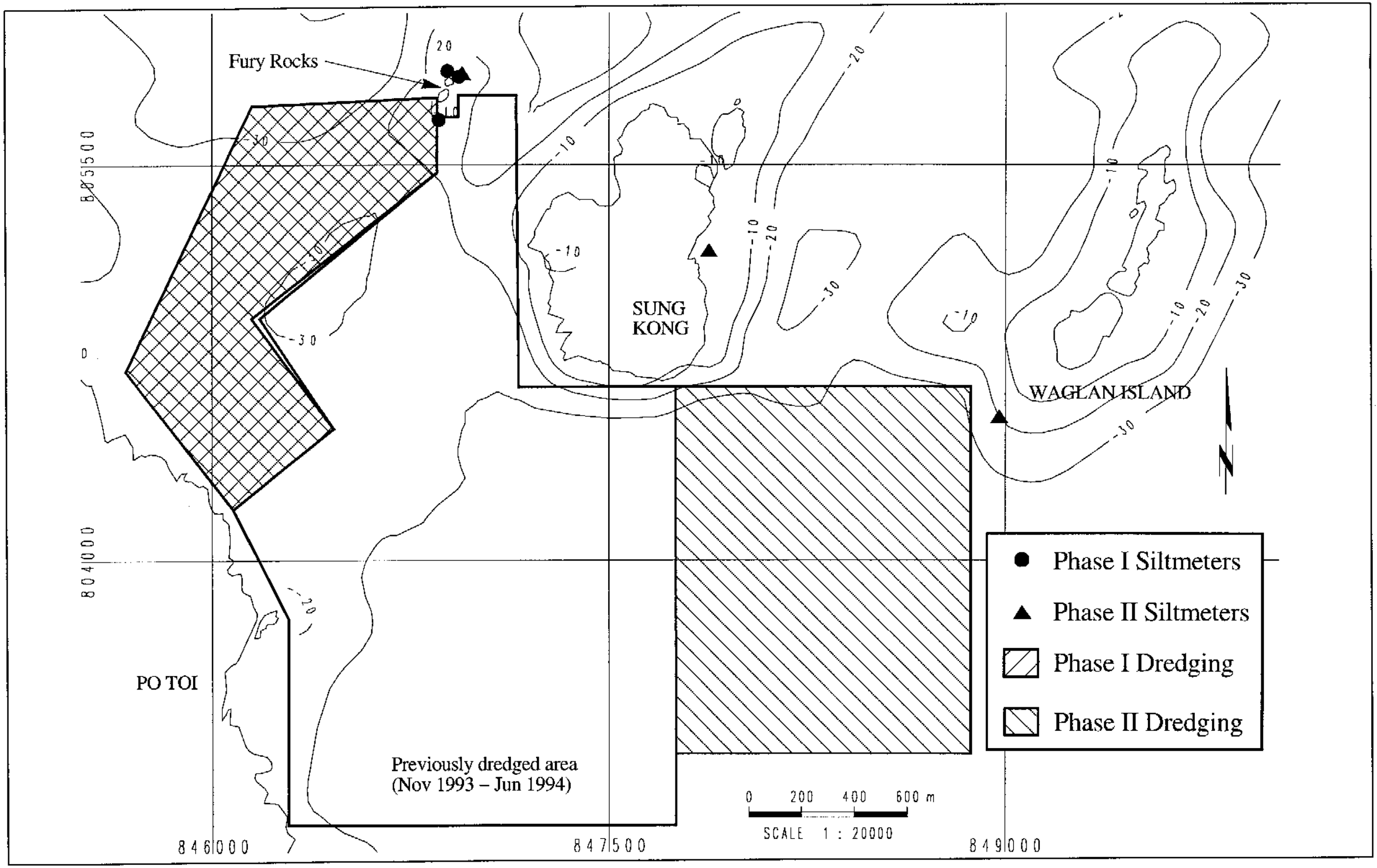
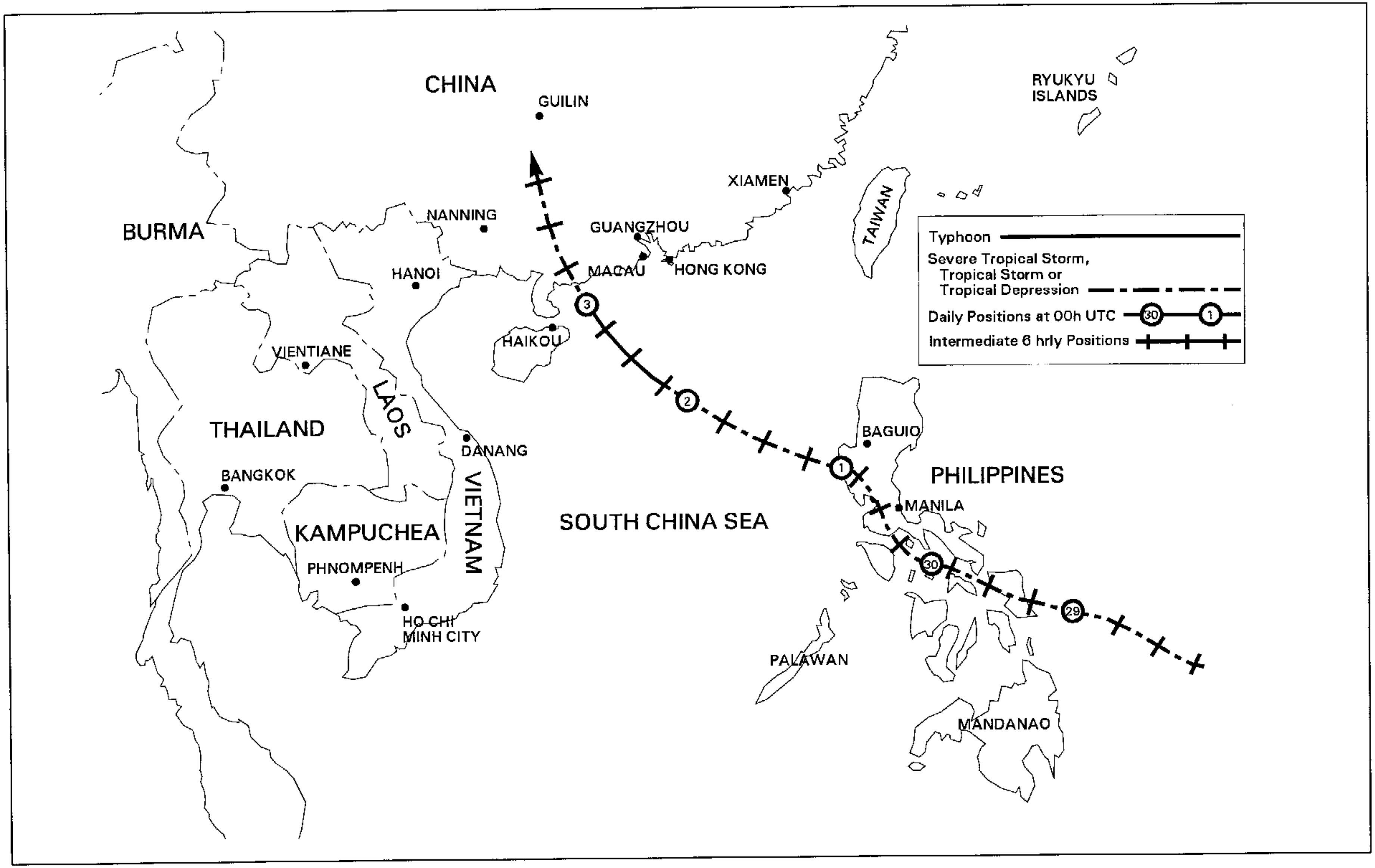


Figure 17 - Location of Siltmeters at Po Toi Marine Borrow Area



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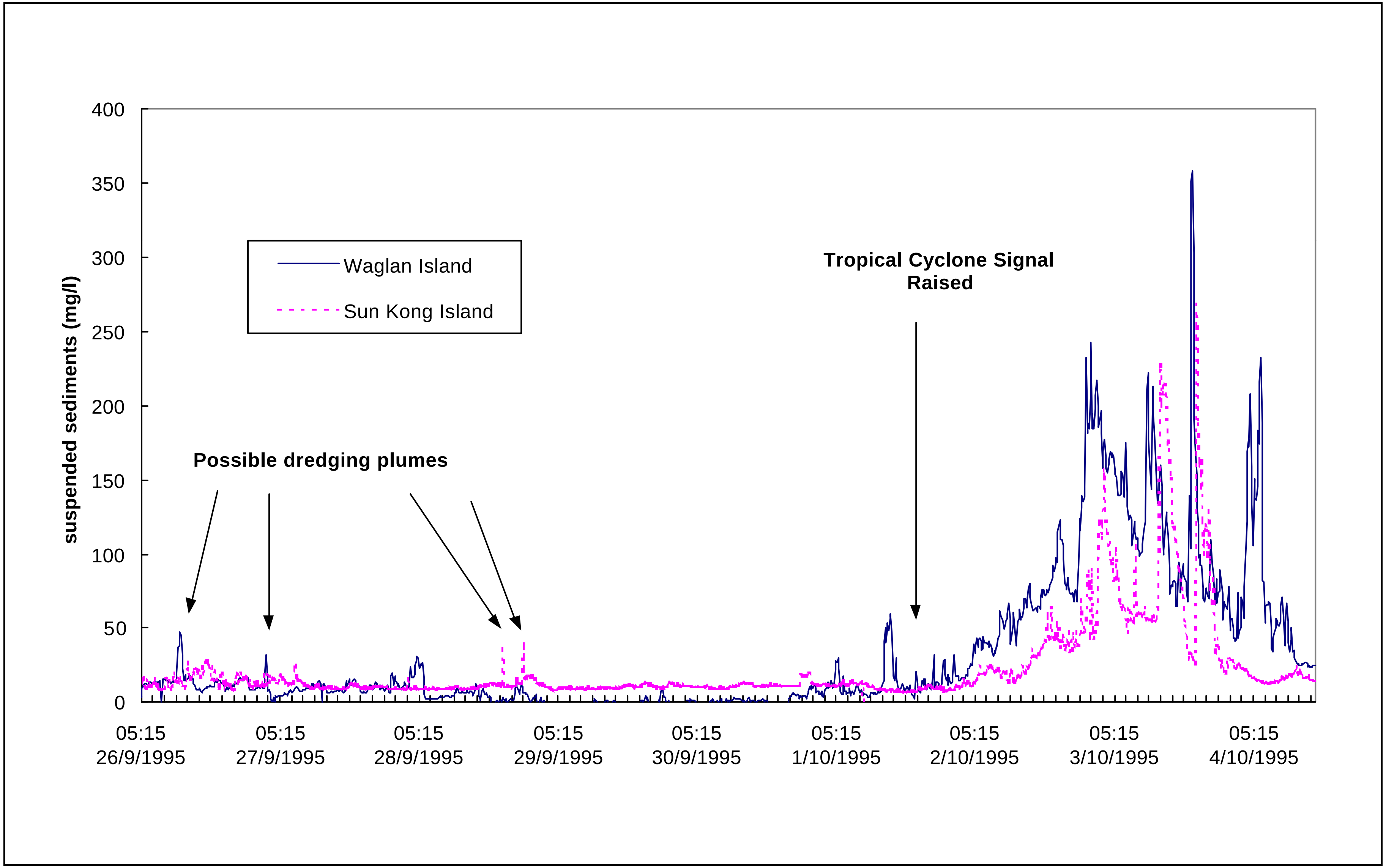

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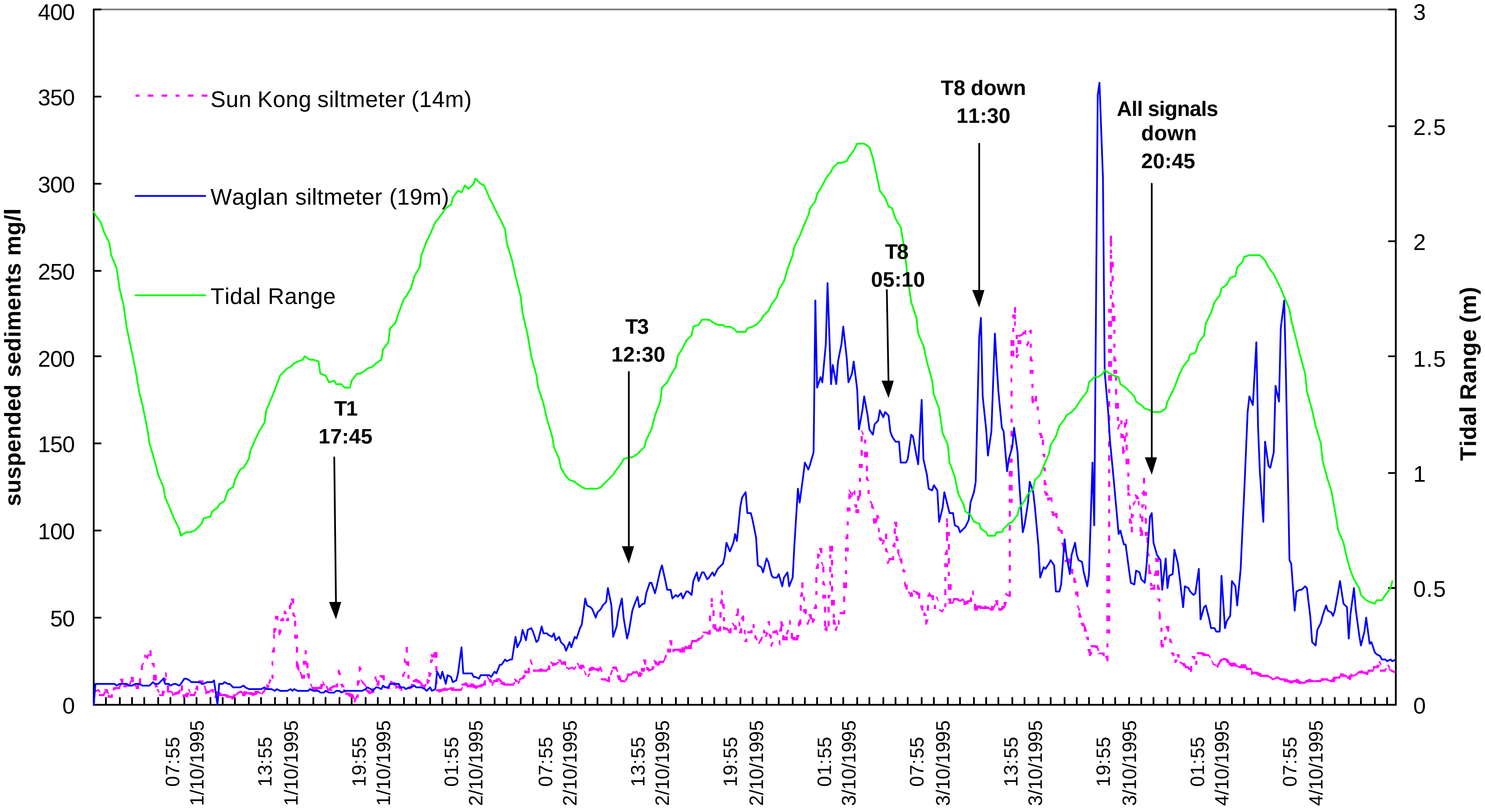

Figure 20 - Typhoon Impacts and Tidal Conditions

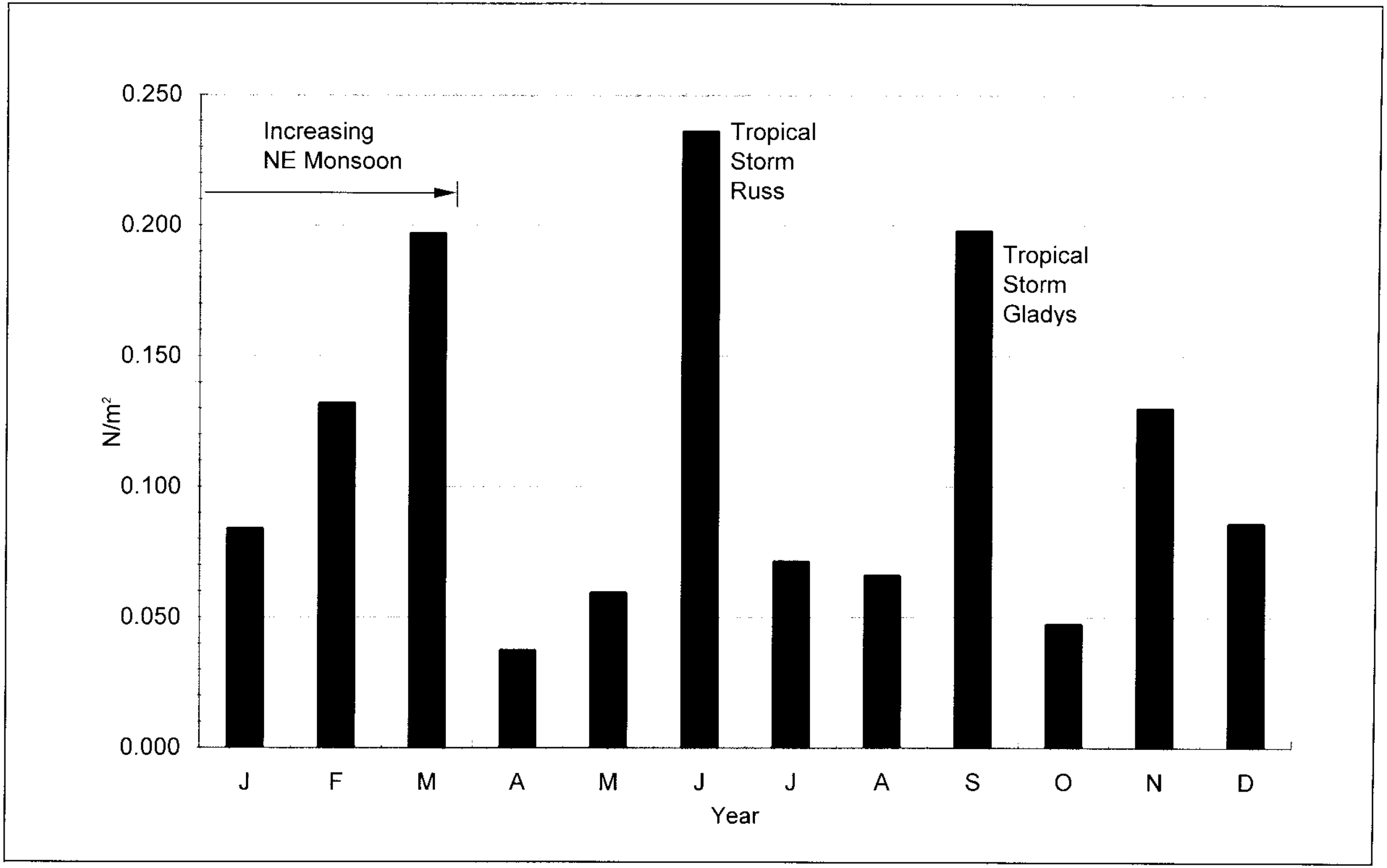

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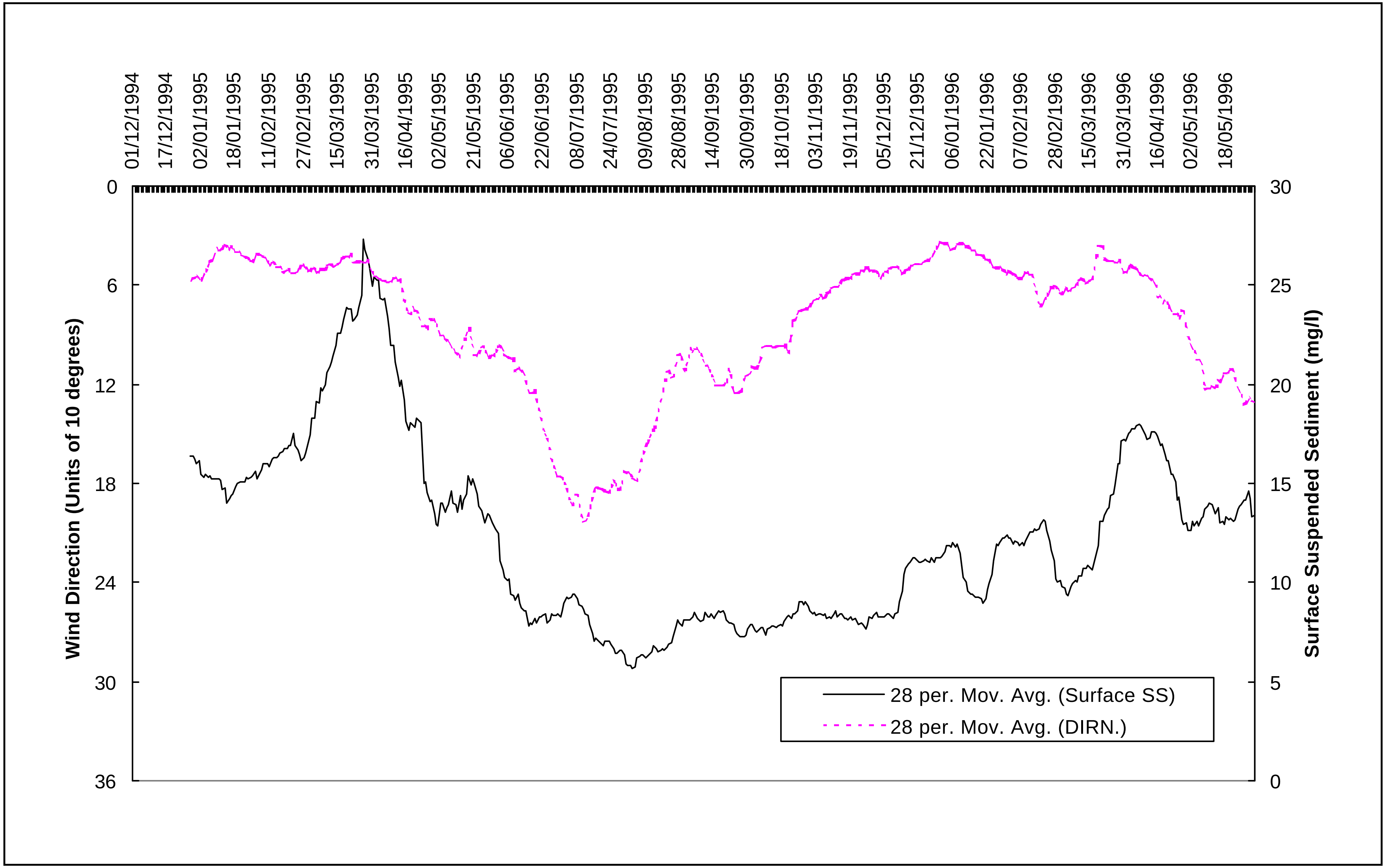
Figure 22 - Basal Suspended Sediments against Wind Speed in Hong Kong' s Eastern Waters



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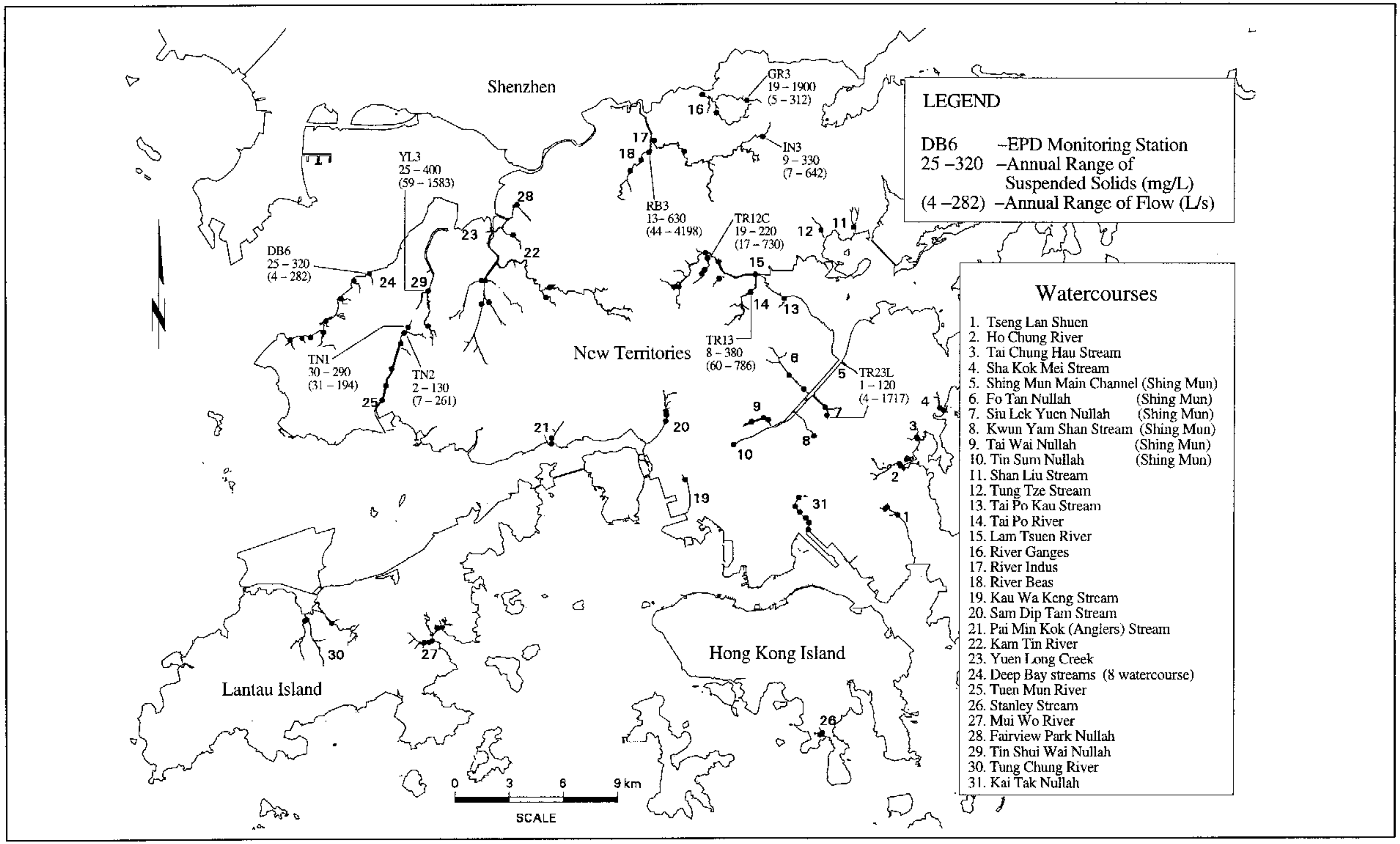

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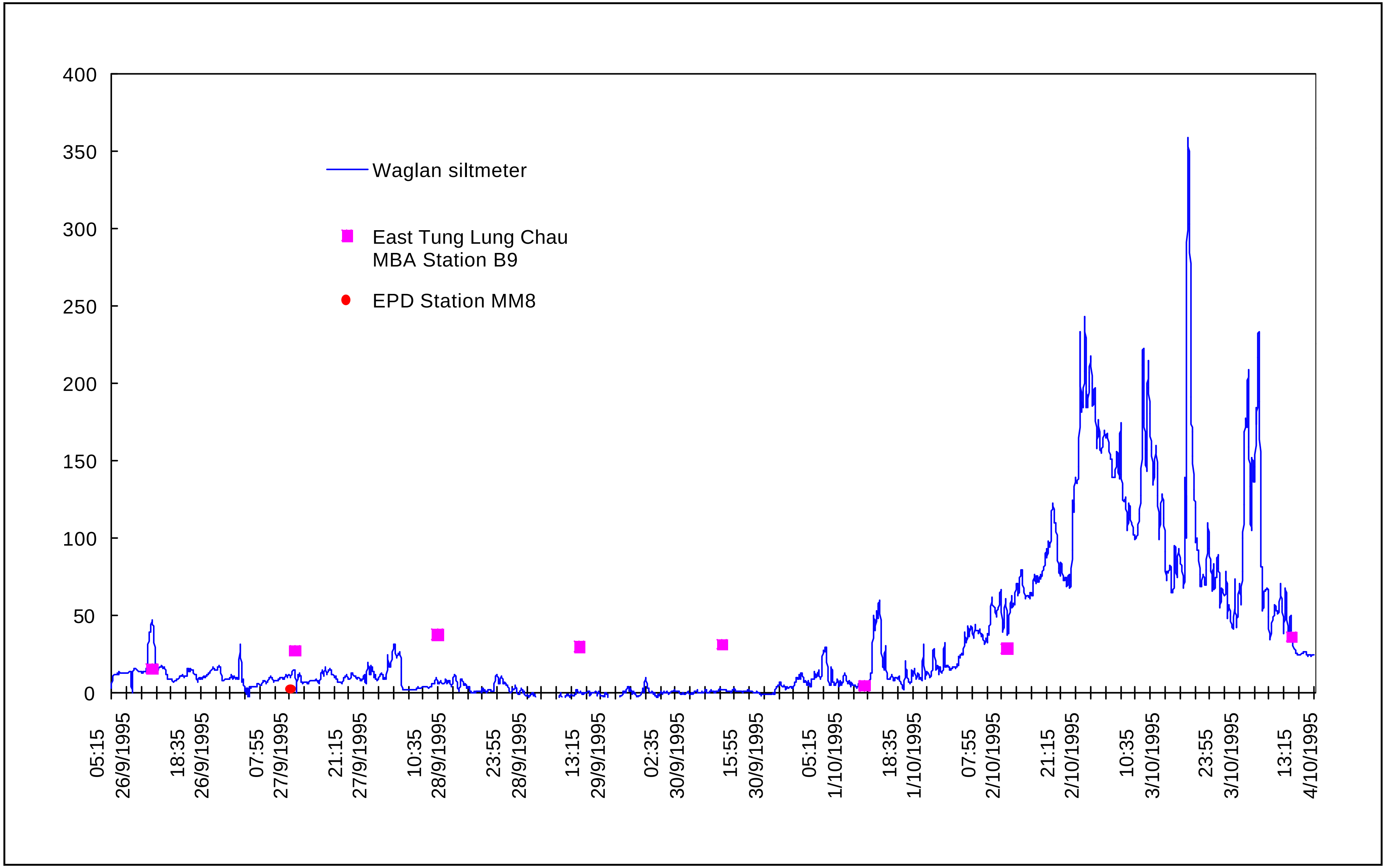

Figure 25 - Comparison of Continuous, Daily and Monthly Suspended Sediment Monitoring (Also see Figure 19)

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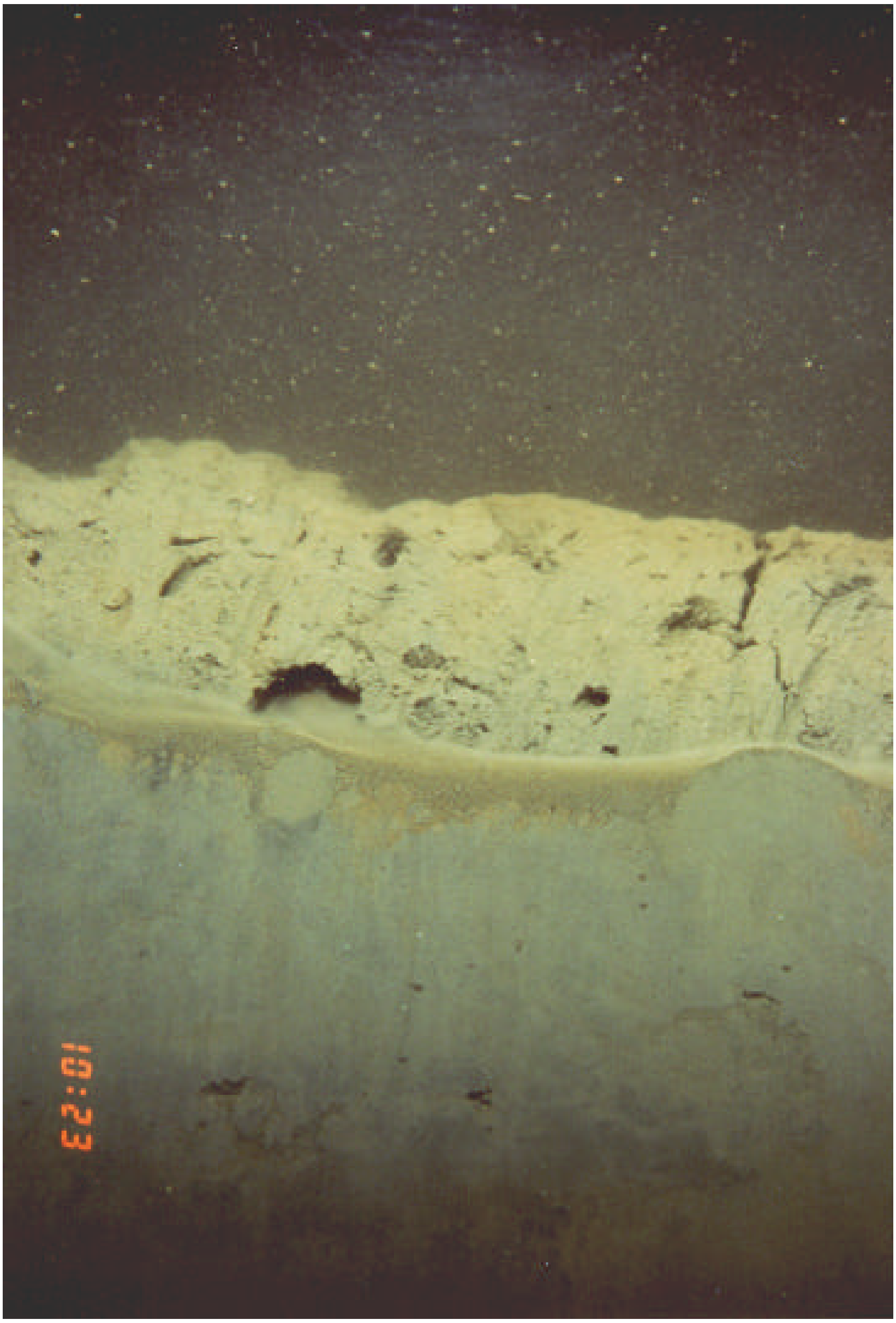
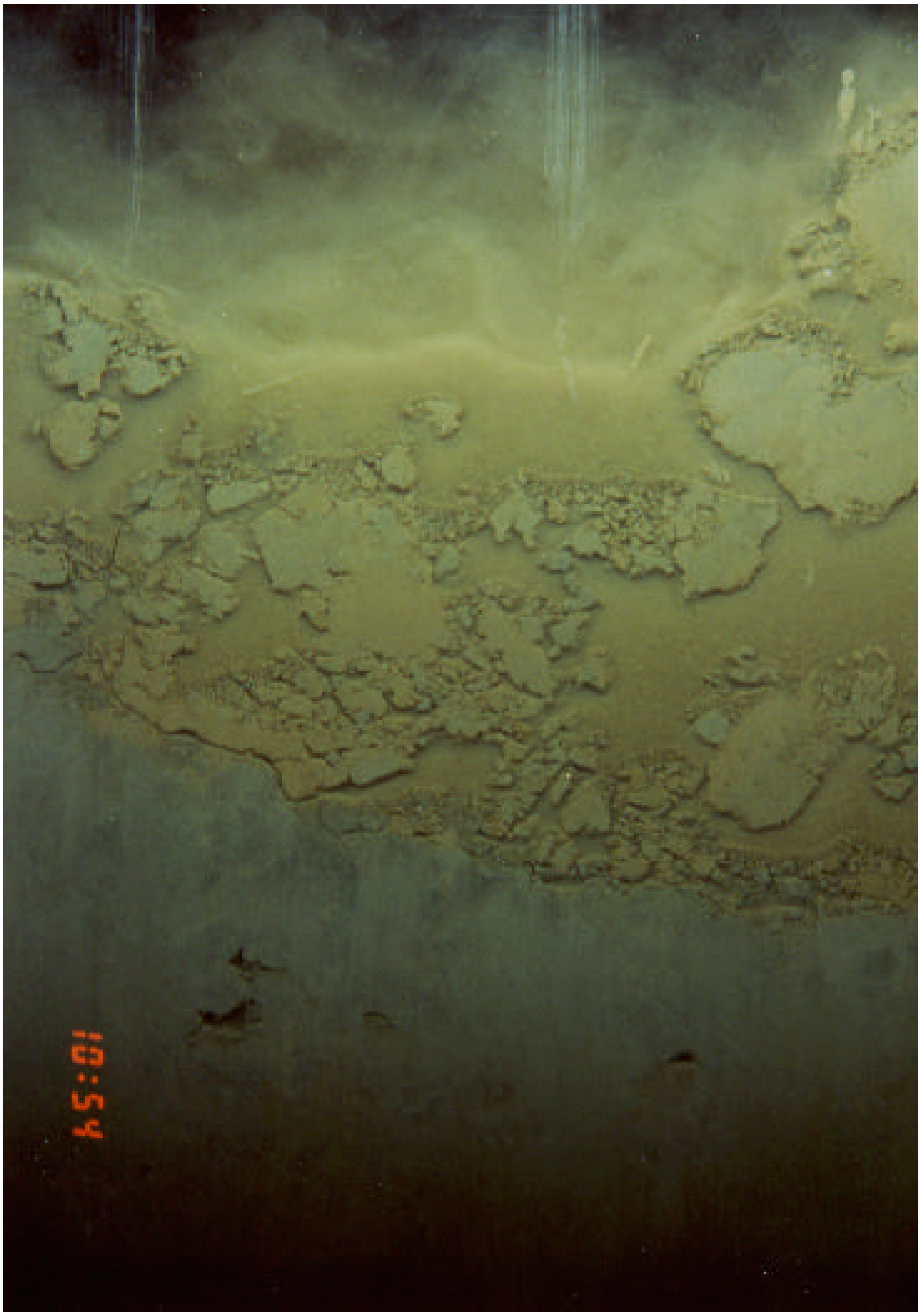


REMOTS image showing the weakly consolidated, gelatinous mud surface layer overlying more-consolidated sediment at depth. The layer has a measured thickness of 5 cm in this image and has slumped sharp contact with the underlying sediment. Scale = width of image is 15 cm

Plate 1 - REMOTS Image Showing the Weakly Consolidated, Gelatinous Mud



REMOTS image showing a surface layer of loosely-consolidated mud clasts (puzzle fabric). Scale = width of image is 15 cm

Plate 2 - REMOTS Image Showing "Puzzle Fabric"

Plate 3 - Landsat Satellite Image, Pearl River Estuary, November 1994

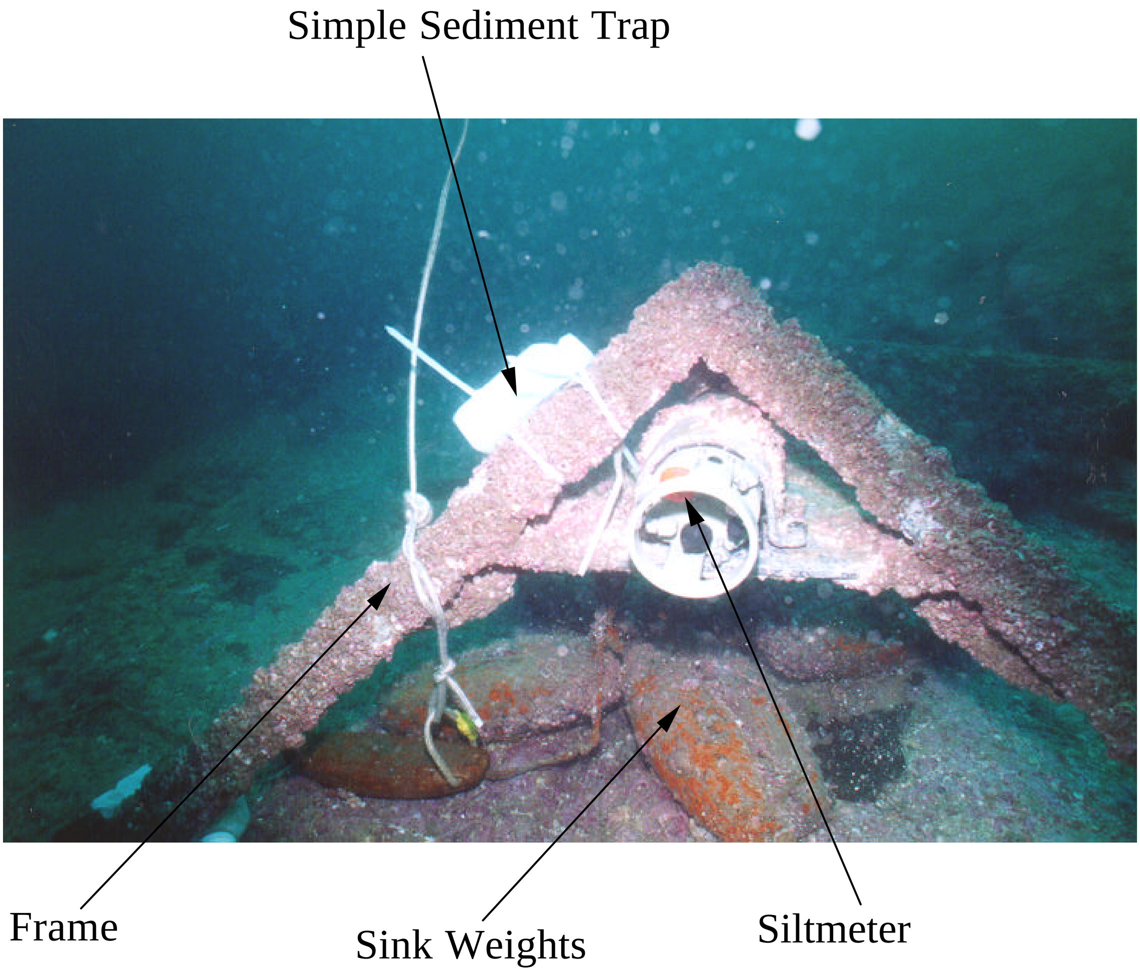


Plate 4 - Siltmeter Deployed at Po Toi Marine Borrow Area

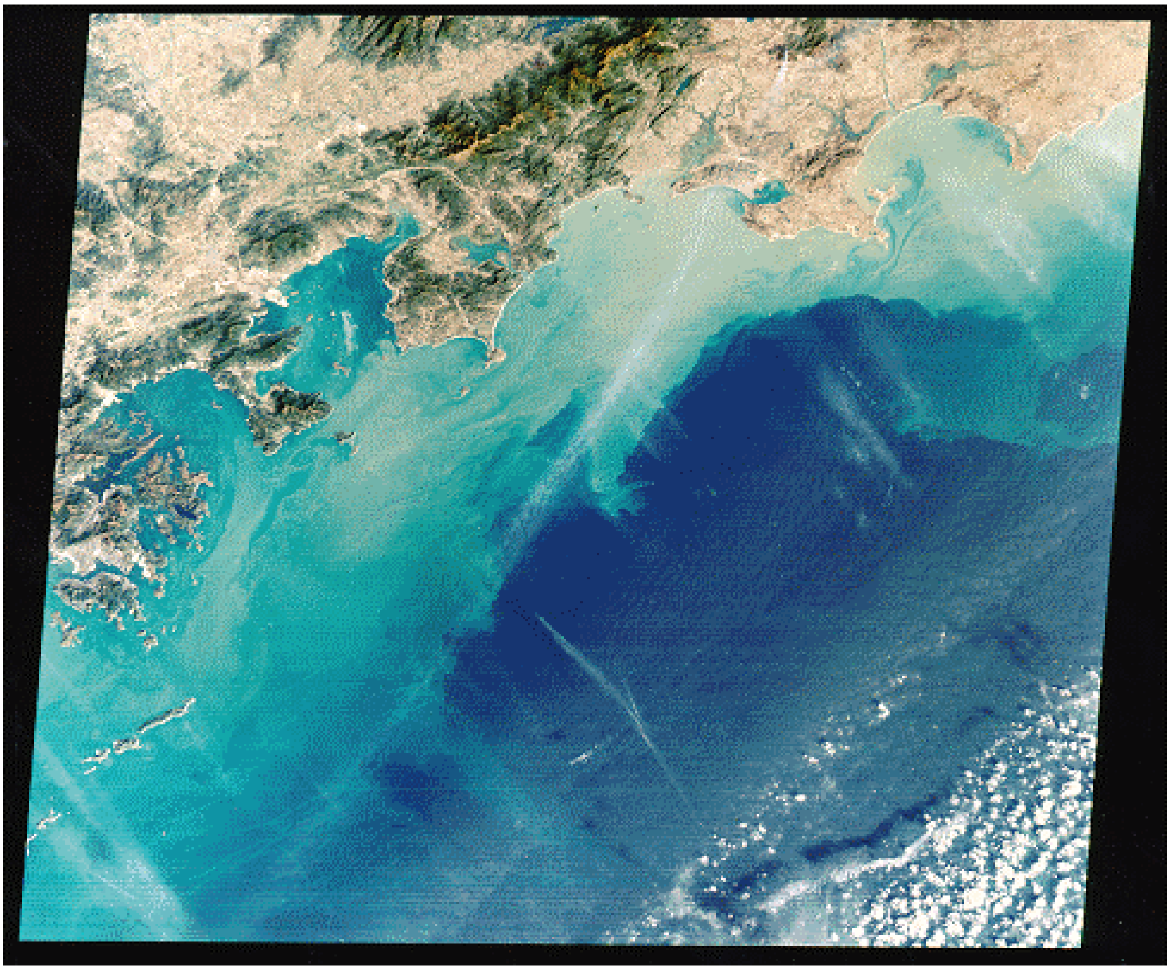


Plate 5 - Satellite Image Showing Southeasterly Movement of Suspended Sediments Due to the Winter Monsoon (Landsat Image 7 December 1995)

Plate 6 - Re-suspension of Seabed Sediments due to Propeller Wash