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The Sediment and Hydrographic Characteristics of Three Horseshoe Crab Nursery Beaches in Hong Kong

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Abstract Horseshoe crab juveniles have been recorded from sand and sandy-mud nursery beaches at Pak Nai (western New Territories), San Tau and Shui Hau (Lantau Island), Hong Kong. In order to provide a better understanding of these beaches and to identify those plausible factors which have made them preferred by spawning horseshoe crabs, environmental parameters, including temperature, salinity, pH and dissolved oxygen content of the water, and particle size distribution and organic matter content of the sediments at the three sites, were determined and compared. The hydrographic and sediment data obtained for the three study sites have revealed some common environmental features. The three nursery beaches are relatively remote, and far (in Hong Kong terms) from urbanized and densely populated areas. The beaches are generally well sheltered from strong wave action and inundated regularly by estuarine waters. Horseshoe crab adults tend to select these beaches for spawning as their protected features ensures the laid eggs are less likely to be washed out of the sand, and hatched juveniles can feed on the meiofauna and grow. Sediments of the three beaches largely comprise medium-sized sand particles and are moderately sorted, suggesting medium porosity and good water permeability. Such a sand type, with the generally high oxygen levels in incursing waters, may help create a well-oxygenated micro-environment for the normal development of horseshoe crab eggs, larvae and juveniles. Lantau Island beaches at San Tau and Shui Hau are relatively free from organic pollution, as reflected in generally high dissolved oxygen level, and low BOD_5 and ammonia nitrogen values. Pak Nai is, however, more polluted.

Key words sediment; hydrography; horseshoe crab; nursery beaches; Hong Kong

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1 Introduction

The life cycle of horseshoe crabs is lengthy when compared to other marine arthropods such as blue crabs and shrimp species (Sekiguchi *et al.*, 1988). The two species, *Tachypleus tridentatus* and *Carcinoscorpius rotundicauda*, known to occur in Hong Kong require, respectively, between thirteen to fourteen and ten to eleven years to mature before departing their nursery beaches for deeper waters (Chiu and Morton, 1999a; Sekiguchi *et al.*, 1988). The living environment of the nursery beaches where the eggs are laid and incubated, and from which the young hatch, and the intertidal flats the juveniles inhabit are, thus, important for the survival of the three Asian species of horseshoe crabs.

Botton *et al.* (1988) studied the influence of geochemical factors at beaches in Delaware Bay, U.S.A., on spawning horseshoe crab (*Limulus polyphemus*) adults and demonstrated that at such times they are capable of discriminating between different beaches. This implies that the crabs are able to determine beach sediment characteristics (Botton *et al.*, 1988), possibly, by chemoreceptors on their legs (Barber, 1956; Wyse, 1971) and can, thus, avoid those beaches with undesirable sediments, for example, oxygen deficient and/or the presence of either toxic or inhibitory chemicals (Botton *et al.*, 1988). Horseshoe crabs may, therefore, select and breed on those beaches where their eggs are best nurtured and hatched larvae and juveniles can survive best.

The present study investigates the hydrography and sediment characteristics of three known horseshoe crab nursery beaches in Hong Kong, *i.e.*, Pak Nai, San Tau and Shui Hau (Fig.1), and aims at understanding the physical characteristics of these shores and so identify those features which, particularly, make them suitable for such activities. Environmental parameters, including temperature, salinity, pH and the dissolved

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oxygen content of the water, and particle size distribution and organic matter content in the sediments, were determined and compared between the study sites. Parameters for assessing pollution levels at the sites, *i.e.*, BOD_5 and ammonia, were also included in this study.

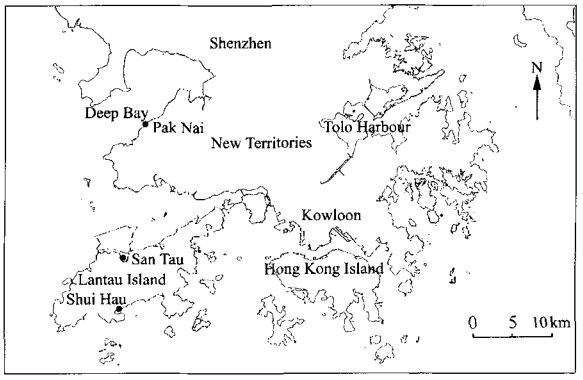

Fig.1 A map of Hong Kong showing the locations of the three identified horseshoe crab nursery beaches

2 Site Descriptions

2.1 Pak Nai

Pak Nai, with an area of 15.5 hectares was gazetted as a Site of Special Scientific Interest (SSSI) on 5 February 1980 because it was a unique roosting site for gulls and terns. Morton (1999), however, argues that it should now be re-designated as an SSSI for the resident horseshoe crabs as it is the only (known) location in Hong Kong where juveniles of *Tachypleus tridentatus* and *Carcinoscorpius rotundicauda* are sympatric. The sandymud flat at Pak Nai constitutes one of the largest horseshoe crab nursery grounds in Hong Kong as the area supports a substantial number (an average of 32 per visit) of horseshoe crab juveniles, mostly *T. tridentatus*; *C. rotundicauda* is much rarer. As the study site is located in outer Deep Bay, its hydrography can be affected considerably by the influx of freshwater from the Pearl River and Shenzhen River, particularly in summer. Surface runoff *via* streams and water-courses from nearby catchment areas also inputs significant freshwater to the area. Agricultural wastes and domestic discharges from local farms, together with pollutants brought down from the Pearl and Shenzhen Rivers (Anonymous, 1988) have created pollution problems in the SSSI.

2.2 San Tau

The sandy-mud flat at San Tau, situated on the north coast of Lantau Island, is largely sheltered from strong tidal action. The site was designated a Site of Special Scientific Interest on 19 October 1994 for its now locally rare seagrass beds on the mangrove flats, occupying an area of 2.7 hectares. The building of the Chek Lap Kok Airport and Tung Chung New Town, largely on reclaimed land, could have reduced tidal flushing in Tung Chung Bay and may cause deterioration in water quality and create pollution problems in the area (Wong, 1995). The gradual increase in the population of Tung Chung, from 20 000 in 1997 to 216 000 in 2006, with a possible ultimate population of 320 000 by 2011 (Territory Development Department, 1997), may add a further burden to the pollution loads in the bay. A treatment works was constructed and commissioned in 1997 at Siu Ho Wan to provide preliminary treatment for the sewage from the airport island and Tung Chung (Territory Development Department, 1997). The treated effluent is discharged *via* a submarine outfall to a point south of the East Brother's Island. Although the number of juveniles (*Tachypleus tridentatus*) observed on the San Tau mud flat was small (an average of 6 per visit) when compared to the other two study sites, this flat is still important for the local conservation of horseshoe crabs.

2.3 Shui Hau

The sand flats at Shui Hau are protected from strong oceanic waves and occupy an area of $\sim 0.2\ km^2$. The soft, sheltered, nature of the intertidal flats, with an accumulation of organic detritus, has encouraged a rich and locally unique diversity of inhabitants (Morton and Morton, 1983). As the area is remote, being far from urbanized areas and recreational beaches, for example, Tong Fuk and Cheung Sha, and only occasionally visited by tourists and study groups from local schools and associations, the environment is relatively intact and free from pollution, except for rubbish. As Shui Hau is located on the southern part of Lantau Island, the study flats are generally shielded from the direct effects of the Pearl River, although the site is still located in the western estuarine region of Hong Kong, as identified by Morton (1982). Two streams run down the beach from the catchment area and these are believed to be important freshwater inputs to the bay. An average of 28 *Tachypleus tridentatus* juveniles was recorded from the Shui Hau sand flat.

3 Materials and Methods

3.1 Hydrography

Between June 1997 and June 1998, surface water and sediment samples were collected from Pak Nai, San Tau and Shui Hau on a seasonal basis. Water temperature and dissolved oxygen levels were measured *in situ* using a YSI Inc. model 59 dissolved oxygen meter. For subsequent determinations of salinity, pH, biochemical oxygen demand (BOD_5) and ammonia nitrogen, water samples were stored in clean polyethylene bottles and transported in ice boxes to the laboratory. Salinity was determined with a S/Mill-E Atago refractometer while pH values were obtained with an Orion Ross electrode connected to a digital pH/MV

meter (Orion Research model 611), calibrated and standardized with two standard buffer solutions of pH 7 and pH 9. BOD_5 was evaluated from the difference between the initial and final dissolved oxygen levels of water samples which had been stored in air-tight, dark, glass bottles and incubated in darkness at 20 ℃ for five days. Ammonia nitrogen levels were determined by the phenol-hypochlorite method (Parsons *et al.*, 1984).

3.2 Sediment Characteristics

Particle size and organic matter content of sediments were also determined for each study site on each sampling occasion. Five surface sediment core samples (6 cm in diameter, 8 cm in depth) were collected randomly from the intertidal area of each three sites. Particle size was analyzed by the wet and dry sieving method (Holme and McIntyre, 1981), and total organic matter content was determined as the loss in weight of sediment, dried at 100 ℃ to constant weight, after combustion at 500 ℃ for six hours.

3.3 Statistical Analyses

The data obtained from the three study beaches were analyzed and compared using Kruskal-Wallis Analysis of Variance (ANOVA). A pairwise comparison test, *i.e.*, Student-Newman-Kuels (SNK) test, was conducted only after a significant ($P \leqslant 0.05$) ANOVA result was obtained. A significance level of $P = 0.05$ was chosen for the SNK test. Multidimensional scaling (MDS) ordination techniques were also applied to the data in order to examine the similarity/dissimilarity between the study sites and other sandy beaches in Hong Kong. MDS is a method for creating a low dimensional picture of the relationships between sites in a complex, multi-dimensional situation. Sediment characteristics of the three study sites, including mean grain size, skewness and kurtosis, were compared with other Hong Kong beaches using the data contained in Morton and Ong Che (1992).

4 Results

4.1 Hydrography

The results of the hydrographic investigations are shown in Figs.2-4. Air and surface water temperatures showed a similar seasonal pattern at the three study beaches (Fig.2) with generally higher values recorded in summer (>30 ℃) and lower ones in winter (<15 ℃).

Prominent seasonal variations in salinity were recorded at the three sites with comparatively lower values in summer (7.5-19) and higher values in winter (24-32) (Fig.3A). San Tau showed the greatest salinity fluctuations with a difference of 24.5 whereas for Pak Nai and Shui Hau, relatively smaller differences, *i.e.*, 18 and 16, were recorded (Table 1). No significant difference was, however, detected between the salinity values measured at the three study sites (ANOVA, $P > 0.05$).

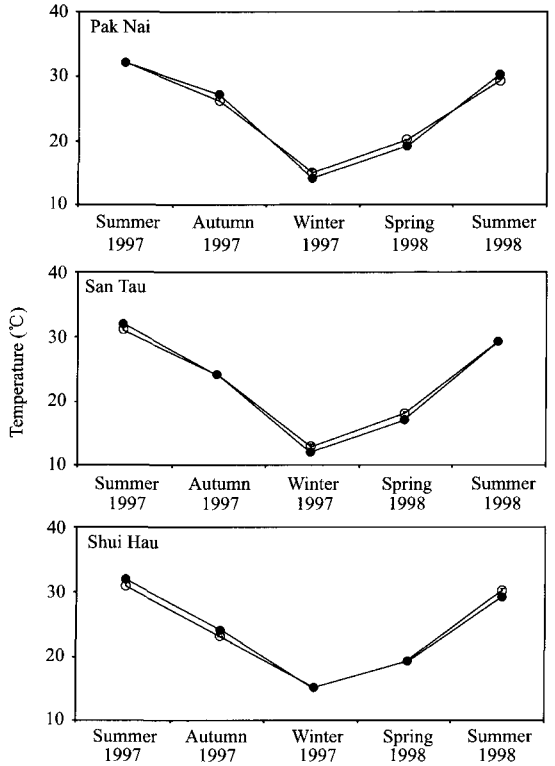

Fig.2 Variations in air (●) and water (○) temperatures at the three nursery beaches from June 1997 to June 1998

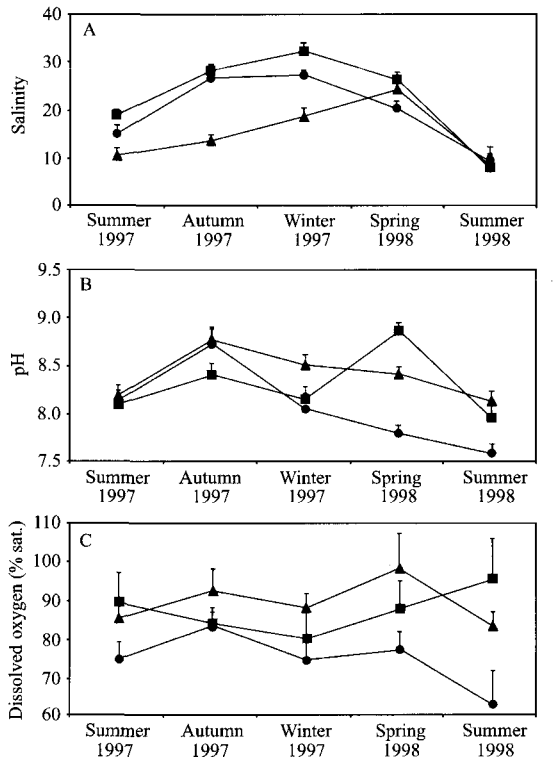

Fig.3 Variations in (A) salinity, (B) pH and (C) dissolved oxygen levels at Pak Nai (●), San Tau (■) and Shui Hau (▲) from June 1997 to June 1998

Table 1 Summary of hydrographic conditions prevailing at the three horseshoe crab nursery beaches over the period from June 1997 to June 1998

Hydrographic parameter	Nursery beach		
	Pak Nai	San Tau	Shui Hau
Temperature (℃)	24.2	23.0	23.6
	(15.0-32.0)	(13.0-31.0)	(15.0-31.0)
Salinity	19.5	22.5	14.9
	(9.0-27.0)	(7.5-32.0)	(8.0-24.0)
pH (-)	8.06	8.28	8.39
	(7.59-8.71)	(7.95-8.84)	(8.12-8.76)
Dissolved oxygen	74.6	87.2	89.4
(saturation %)	(63-84)	(80-95)	(83-98)
Biochemical oxygen	6.84	1.89	1.39
Demand ($mg\,L^{-1}$)	(3.43-10.3)	(1.11-2.81)	(0.70-2.01)
Ammonia nitrogen	21.7	3.52	1.53
(μg-at. NL^{-1})	(9.40-40.8)	(2.13-5.67)	(0.44-2.24)

Notes: Values presented are means; values in parentheses are the ranges.

Table 2 Summary of surface sediment characteristics of the three horseshoe crab nursery beaches over the period from June 1997 to June 1998

Sediment characteristics	Nursery beach		
	Pak Nai	San Tau	Shui Hau
Gravel-sand (%)	84.1	88.2	87.1
	(80.4-86.4)	(84.9-92.3)	(83.7-90.7)
Silt-clay (%)	14.9	11.8	12.9
	(13.6-18.6)	(8.69-14.1)	(9.27-16.3)
Median grain size (ϕ)	1.15	1.26	1.22
Quartile deviation (F)	1.11	0.85	1.08
Skewness (F)	-0.46	-0.34	-0.36
Total organic matter (%)	4.28	2.20	2.49
	(3.05-5.87)	(1.51-2.98)	(1.95-2.90)

Notes: Values presented are means; values in parentheses are the ranges.

There was little evidence of seasonality in pH variation at the three sites and the values ranged from 7.59 to 8.84 (Fig.3B). The pH range at Shui Hau was comparatively narrow, with a difference of only pH 0.64 whereas for the other two sites, greater fluctuations from pH 7.59 to pH 8.71 (Pak Nai) and pH 7.95 to pH 8.84 (San Tau), with respective differences of pH 1.12 and 0.89, were recorded (Table 1). The range of between-site variation was not significant at the 95% probability level.

Dissolved oxygen levels, in terms of % saturation, ranged from 63% to 84% at Pak Nai, 80% to 95% at San Tau and 83% to 98% at Shui Hau with no conspicuous seasonal trends (Fig.3C). Shui Hau had the highest mean dissolved oxygen level (89.4%), Pak Nai the lowest (74.6%), with San Tau between them (87.2%). Significant between-site differences ($P<0.01$) were detected by ANOVA for dissolved oxygen values. Pairwise comparison of sites by the SNK test showed that Pak Nai had significantly lower dissolved oxygen levels than San Tau ($P<0.05$) and Shui Hau ($P<0.01$), but no significant difference was detected between the latter two sites ($P>0.05$).

Seasonal patterns in BOD_5 values were not evident at the three study beaches (Fig.4A). BOD_5 values ranged widely from 3.43 $mg\,L^{-1}$ to 10.3 $mg\,L^{-1}$ at Pak Nai whereas for San Tau and Shui Hau, the figures fluctuated narrowly from 1.11 $mg\,L^{-1}$ to 2.81 $mg\,L^{-1}$ and 0.70 $mg\,L^{-1}$ to 2.01 $mg\,L^{-1}$, respectively (Table 1). Results from ANOVA showed significant between-site differences in BOD_5 levels ($P<0.01$) and a pairwise comparison indicated that values at Pak Nai were significantly higher than the other two sites ($P<0.01$), but no significant difference was detected between them ($P>0.05$).

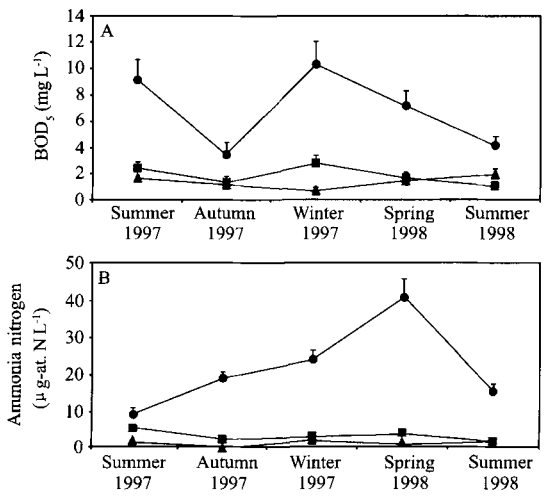

Fig.4 Variations in (A) biochemical oxygen demand and (B) ammonia nitrogen levels at Pak Nai (●), San Tau (■) and Shui Hau (▲) from June 1997 to June 1998

Mean ammonia nitrogen levels were highest at Pak Nai (21.7 μg-at. NL^{-1}) with seasonal values ranging widely from 9.40 μg-at. NL^{-1} to 40.8 μg-at. NL^{-1} (Table 1). Much lower mean values of 3.52 μg-at. NL^{-1} and 1.53 μg-at. NL^{-1}, and narrower ranges of between 2.13-5.67 μg-at. NL^{-1} and 0.44-2.24 μg-at. NL^{-1} were obtained, respectively, for San Tau and Shui Hau. No apparent seasonal changes in ammonia nitrogen values were, moreover, recorded at any of the study sites (Fig.4B). Significant between-site differences were detected by ANOVA ($P<0.001$). The range of values recorded at Pak Nai was, as indicated by the results of the SNK test, significantly higher than at San Tau ($P<0.01$) and Shui Hau ($P<0.01$). Ammonia nitrogen levels at San Tau were, moreover, significantly higher than those recorded at Shui Hau ($P<0.05$).

4.2 Sediment Characteristics

Table 2 summarises the sediment characteristics of the intertidal flats at Pak Nai, San Tau and Shui Hau. The sediment grain size of the three beaches was generally small, with median F values ranging from 1.15 to 1.26, *i.e.*, medium sand on the Wentworth scale (Buchanan, 1984). The quartile deviations of the sediments from the three beaches were broadly similar with values ranging between 0.85 and 1.11 and indicative of moderate sorting (Folk, 1966). The negative

quartile skewness values obtained for the three study beaches showed that asymmetry lay on the side of relatively finer particles. The majority of the sediments from all three sites comprised gravel-sand (84.1%–88.2%) with a generally low proportion of silt-clay (<20%). Results from ANOVA showed that no significant difference ($P>0.05$) in the relative proportion of gravel-sand and silt-clay was detected between the three study sites. The sediment organic content at Pak Nai was highest among the three study sites, with a mean value of 4.28%, whereas for San Tau and Shui Hau, mean organic matter percentages were comparatively low with, respectively, values of 2.20 and 2.49. Significant differences in the organic matter content were detected by ANOVA between sites ($P<0.0005$). The results from the SNK tests showed that Pak Nai had a significantly higher percentage of organic matter than San Tau ($P<0.005$) and Shui Hau ($P<0.005$), but no significant difference ($P>0.05$) was detected between the latter two sites.

A multi-dimensional scaling plot of dissimilarities between the three nursery sites and other sandy beaches in Hong Kong is presented in Fig.5. Sites in proximity to each other indicate similar sediment characteristics whereas sites plotted far apart are dissimilar. The results showed that the three nursery beach sediments were similar to each other. Other beaches, including Big Wave Bay, Deep Water Bay, Long Ke Wan and Turtle Cove, also clustered close to the three study sites, indicating a high degree of similarity in sediment characteristics between these beaches. Beaches on Lamma Island and Cheung Chau are, in general, plotted relatively far from the three nursery beaches, suggesting that the sediment characteristics of the beaches on these islands are different.

5 Discussion

5.1 Hydrography

Surface water temperatures recorded at the three study sites, in general, corresponded closely to ambient air temperatures with a difference of ~1 ℃ only and such a pattern of co-variation is common for coastal waters (Chiu, 1998) The prominent seasonal variations in air and water temperatures reflect the response of Hong Kong's climate and marine environment to the summer and winter monsoons. Such a seasonal pattern in temperature seems to govern the breeding activity of local horseshoe crabs as spawning pairs have been observed swimming towards the breeding beaches during spring and summer when water temperatures >20 ℃. Spawning of horseshoe crabs in other areas, for example, *Limulus polyphemus* in Delaware Bay, USA, also occurs during the warmer months from May to Angust with a peak in June (Shuster, 1950).

The average salinity of the open sea generally varies between 33 and 38 (Reid and Wood, 1976) Whereas for the coastal waters of Hong Kong, a salinity range of 20 to 30 has been reported upon by Morton and Wu (1975). The three study beaches are typically estuarine with wide ranges of salinity being recorded during the study period. Such estuarine coastal waters have also been reported upon for other local shores in the western quadrant of Hong Kong (Cheung, 1990; Chiu, 1998). The low salinities recorded at the three study sites, particularly during summer, indicated that they are under the profound diluting effect of freshwater emanating from the Pearl River, the Shenzhen River and local drainages.

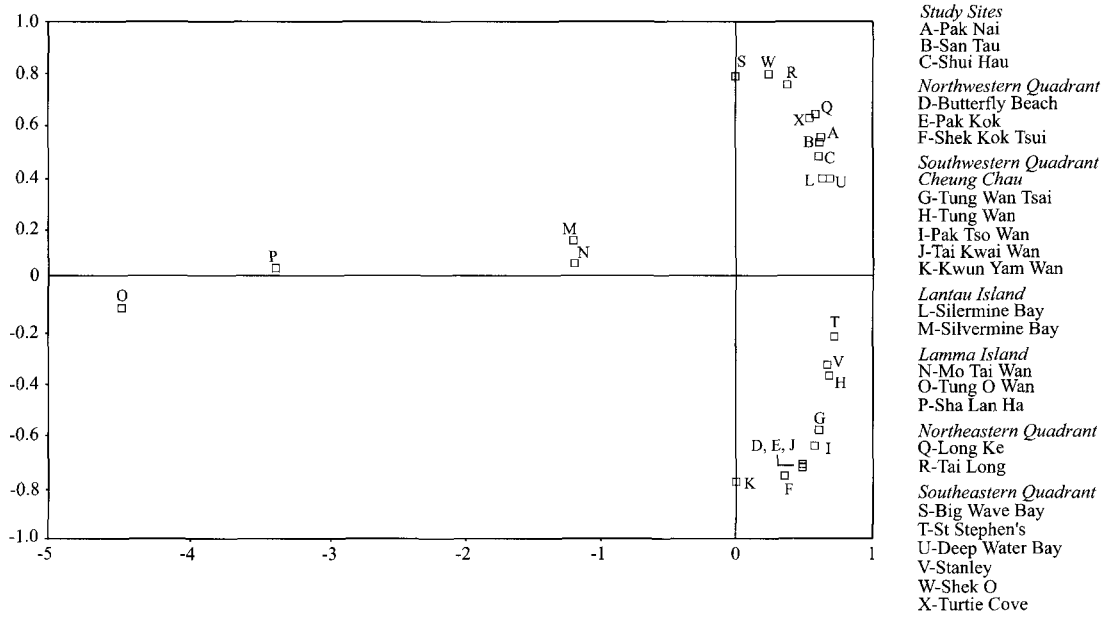

Fig.5 A multi-dimensional scaling plot of dissimilarities between the three nursery sites and other sandy beaches in Hong Kong

The pH of oceanic water is generally maintained within a narrow range from 8.0 to 8.3 (Reid, 1961) whereas in estuaries, pH is determined by the degree of seawater mixing with freshwater and values of between 6.9 and 7.8 are common (Reid and Wood, 1976). In this study, pH values recorded at the three beaches were always alkaline with values ranging from pH 7.59 to pH 8.76 which are comparable to the figures reported upon for coastal waters by Morton and Wu (1975) and Chiu (1998). pH levels in coastal waters are, moreover, not only affected by freshwater inputs, but also by algal photosynthesis (Atkins, 1923) and organic decomposition (Hodgkiss and Chan, 1983). Active algal growth uses up carbon dioxide while organic decomposition releases carbon dioxide and both cause a shift in the carbonate-carbon dioxide equilibrium leading, respectively, to an increase and a decline in pH. The relatively low pH values prevailing at Pak Nai during summer, associated with a low level of dissolved oxygen, might be a consequence of considerable organic-decay activities in the area.

Dissolved oxygen values may serve as an indicator of microbial activity in water (Wong *et al.*, 1980). An influx of either organic or industrial wastes increases the level of heterotrophic bacteria and may correspondingly deplete the oxygen in water (Moore, 1958). The comparatively low oxygen levels at Pak Nai might reflect the presence of substantial amounts of organic nutrients with considerable microbial activity. The oxygen levels at San Tau and Shui Hau were generally high (>80% saturation), suggesting that these beaches are well oxygenated with a low level of organic pollution.

5.2 Sediment Characteristics

The three study beaches generally comprised sediments of smaller grain sizes, *i.e.*, medium sand particles (0.25−0.5 mm), rather than big gravels and pebbles. The median diameter values (F) of sediments from the three sites were small when compared to those obtained from other local beaches, for example, Lobster Bay, Cape d'Aguilar (Wells, 1994) and Tai Tam Bay (Ong Che, 1990). Poorly sorted sediments are characteristic of sheltered, low profile, beaches experiencing generally weak tidal action (Hayward, 1994). The percentage values of organic matter content of the three sites were generally higher than those of local beaches with coarser sand particles (1.2%−1.7%) (Shin, 1987), but were still much lower than the extremely organic-rich sediments of Tolo Harbour and Tolo Channel (Shin, 1982) and Three Fathoms Cove (Yipp, 1982). Values recorded for San Tau and Shui Hau were comparable to those obtained for sand flats in Tai Tam Bay (Ong Che and Morton, 1994).

5.3 Pollution

BOD_5 is of prime importance in assessing the level of water pollution (Thomann *et al.*, 1968) and a BOD_5 value of $>5\ mg\ L^{-1}$, as recommended by the World Health Organization (1967), is an indicator level of pollution. In the present study, the majority of the BOD_5 values obtained for Pak Nai were $>5\ mg\ L^{-1}$, denoting significant organic pollution. Much lower BOD_5 values were, however, recorded for San Tau and Shui Hau, indicating that two sites are relatively clean and have not been contaminated substantially by organic wastes.

Watts (1973) suggested that ammonia nitrogen could be a useful indicator of pollution. As the major source of ammonia nitrogen is through the degradation of organic matter by either bacterially-mediated deamination or animal excretion (Boney, 1989), a high level of the nutrient is, therefore, likely to be associated with organic pollution. For less polluted Hong Kong waters, ammonia nitrogen levels are usually low ($<4\ \mu g\text{-at.}\ N\ L^{-1}$) (Chiu, 1998). The high ammonia levels recorded at Pak Nai ($9.40-40.8\ \mu g\text{-at.}\ N\ L^{-1}$) indicate substantial organic pollution. The mean ammonia level was lowest at Shui Hau with all values recorded during the study period being $<4\ \mu g\text{-at.}\ N\ L^{-1}$. San Tau had comparatively higher ammonia levels than Shui Hau, with sample values occasionally $>4\ \mu g\text{-at.}\ N\ L^{-1}$, indicating the presence of comparatively higher amounts of organic matter in the waters.

The hydrographic and sediment data obtained for the three study sites have revealed some common environmental features. The beaches are relatively remote from urbanized and densely populated areas of Hong Kong. They are generally well sheltered from strong waves and inundated regularly by estuarine waters. The flats are of gentle slope and largely comprised of medium-sized sediment particles. The water above then have typically estuarine dissolved oxygen levels. San Tau and Shui Hau are relatively free from organic pollution, as reflected by the generally high dissolved oxygen levels, and low BOD_5 and ammonia nitrogen levels. Pak Nai, though possessing the highest levels of BOD_5 and ammonia nitrogen, is still cleaner than some other more polluted areas in Deep Bay (Chiu and Morton, 1999 a).

5.4 Horseshoe Crabs and Nursery Beaches

Horseshoe crab adults are capable of discriminating between beaches of different geochemical regimes (Botton *et al.*, 1988). An ability to detect beach characteristics may enable them to spawn in areas where their eggs will be best able to survive and hatched larvae and juveniles grow. As horseshoe crab juveniles are generally observed on sheltered flats where they are protected from strong oceanic waves, this implies that adults tend to select such beaches for spawning. The well-protected nature of the three study beaches ensures the laid eggs are less likely to be washed out of

the sand, and hatched juveniles can occupy the sand safely. Rudloe (1979) also suggests that sheltered beaches with weak tidal action provide protection for developing eggs and hatched larvae. Reports of horseshoe crabs breeding in other areas have also indicated a preference for sheltered coves and protected beaches, for example, *Limulus polyphemus* in Delaware Bay, U. S. A. (Botton *et al.*, 1988) and *Tachypleus tridentatus* on Tatara Beach, Imari Bay, Japan (Itow, 1993).

Undisturbed beaches are the preferred habitat of horseshoe crabs (Botton *et al.*, 1988). The three nursery sites, especially San Tau and Shui Hau, are locally distant from urban areas and only occasionally visited by tourists and local villagers. The resident animals are, therefore, relatively free from human disturbance and this is, probably, another important factor in relation to the breeding and nursery values of such beaches. The building of the Chek Lap Kok Airport and Tung Chung New Town could have reduced the tidal flushing of Tung Chung Bay (Wong, 1995) and might, therefore, affect the prevailing water currents of the area. According to Shuster (1990), the movements of horseshoe crabs towards beaches during the spawning season may be guided primarily by prevailing underwater currents and the shoreline. Alterations to tidal currents in the vicinity of the beach might, already, have adversely affected, or even impeded, spawning pairs from coming to San Tau to breed. This might be a factor which has led to the currently low recorded numbers of juveniles on this beach.

Horseshoe crab embryos and larvae are well known for their ability to withstand fluctuating and sometimes harsh environmental conditions in their intertidal habitat (McManus, 1969; Jegla and Costlow, 1982; Palumbi and Johnson, 1982; Laughlin, 1983; Sugita, 1988; Sekiguchi *et al.*, 1988). *Limulus polyphemus* eggs have the ability to tolerate a wide range of salinities, *i.e.*, 8－35 (Sekiguchi *et al.*, 1988), and for larvae, normal development was observed in waters of 10－35 salinity (Laughlin, 1983). All three study beaches experienced wide fluctuations in salinity. A similar broad range of salinity has also been recorded for other horseshoe crab spawning beaches, for example, Tatara Beach, Japan (18－33) (Sekiguchi *et al.*, 1988). In his experiments on the salinity tolerances of *L. polyphemus* juveniles (<75 mm prosomal width), McManus (1969) demonstrated that they were able to survive at salinities as low as 12.5, but an increase in mortality was observed when salinities were $\leqslant 10$. *Carcinoscorpius rotundicauda* may be able to withstand even lower salinities, as breeding pairs have been observed in areas near river mouths where near-fresh or brackish water conditions prevail (Sekiguchi, 1988). Embryogenesis in all species of horseshoe crabs is, nevertheless, normal at salinities of 20－35 (Sekiguchi *et al.*, 1988).

Laughlin (1983) demonstrated that horseshoe crab larvae are capable of withstanding wide temperature ranges (20－35 ℃). The difference for both air and water temperatures between the hot summer and cold winter in Hong Kong is great (13－32 ℃), and individuals must have adaptive strategies to survive such a fluctuating environment. Chiu and Morton (1999 a) showed local *Tachypleus tridentatus* juveniles exhibit adaptive responses to varying conditions in the intertidal zone. Juveniles are, for example, capable of avoiding low winter temperatures by burying themselves in the sediments. During the hot summer, the animals generally crawl on the sand surface with a layer of water embracing the underlying vulnerable body or partly bury their bodies in the sand when crawing. This might be a strategy to maintain body temperature at a not-too-high level under conditions of strong sunlight and heat.

Adequate oxygen is essential for the normal development and successful hatching of *Limulus polyphemus* eggs and larvae (Shuster and Botton, 1985). The composition of the particles which affect the porosity and interstitial water content of the substratum (Hayward, 1994), and oxygen levels of the overlying water are, thus, important to the survival of the early stages of horseshoe crabs. Sediments of the three beaches, mainly, comprised moderately-sorted, medium-sized, sand particles, suggesting that the substrata are of medium porosity and permeability (Hayward, 1994). Such a sand type, with generally high oxygen levels in the incoming waters, may help create a well-oxygenated micro-environment for the normal development of horseshoe crab eggs and larvae, as well as juveniles.

A range of between pH 7.8－8.4 has been considered optimal for horseshoe crab egg development and larval survival (Liang and Zhou, 1987). In this study, the pH of the water at the three sites was, generally, within this optimal range with sporadic exceptions where recorded values were outside it by ~pH 0.2－0.4.

Horseshoe crab species, like *Tachypleus gigas*, usually lay eggs in comparatively clean sand (Sekiguchi *et al.*, 1977). In Hong Kong, horseshoe crab juveniles occur in clean (Shui Hau) as well as polluted (Pak Nai) areas. This suggests that, to some extent, *T. tridentatus* and *Carcinoscorpius rotundicauda* are able to tolerate some levels of pollution, though it is believed that pollution-free beaches are preferred, as evidenced by the fact that they have disappeared from other locally polluted beaches, for example, in Tolo Harbour where they used to occur (Chiu and Morton, 1999 b). Significantly, in terms of their sediment characteristics, the three identified horseshoe crab breeding beaches are similar to each other and to beaches which characterise northeastern, *i.e.* Long Ke Wan and Tai Long Wan, and southeastern, *i.e.* Big Wave Bay, Deep Water Bay, Shek O and Turtle Cove, areas of Hong Kong but which are not known horseshoe crab breeding or nesting beaches (Chiu and Morton, 1999 a; 1999 b). This is because they are all relatively

exposed, steep, shores and low in organic matter and, thus, low number of meio- and macrofauna. Conversely, the three identified horseshoe crab breeding beaches are unlike, in terms of their sediment characteristics, other beaches in the northwest, southwest and on Lantau Island. It can, thus, be concluded that a preferable horseshoe crab nursery beach is of low profile and characterised by coarse-grained particles resulting not from wave sorting but, probably fluvial-sorting, though still typified by high porosity and overlain by estuarine waters of intermediate salinity. Such beaches are typically richer in nutrients, providing habitats for a meio- and macrofauna that is the diet of juvenile horseshoe crabs①.

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