Developing a Mangrove Management Strategy in the Estuaries of Deep Bay, Shan Pui River and Tin Shui Wai Drainage Channel

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Abstract: *At present, the Yuen Long and North Districts are mainly served by the primary watercourses including Shenzhen River, Kam Tin River, Shan Pui River and Tin Shui Wai Main Channel. These rivers also serve the largest floodplain in New Territories and were trained in the last decade. In recent years, the significant expansion of mangrove habitat in Inner Deep Bay and the estuaries of inland rivers causes an increase in flood risk, in particular for the people living in the floodplain area. This Paper will address (1) the analysis of mangrove conditions in Deep Bay for the projection of the future extent of mangrove areas in 2030; (2) the way to assess the hydraulic impacts arising from mangrove vegetation based on survey data and advanced modelling tools; and (3) the formulation of various mangrove management options in flood risk control. The Paper will also address the vegetation roughness of both undergrowth and mature mangrove and how the mangrove properties such as density, stem diameter and height of trees are correlated to vegetation roughness. Particular attention will be paid to the selection of a low-effort approach to mangrove management to strike the balance between flood control and environmental considerations.*

Key words: mangrove, management, hydraulic resistance, vegetation roughness, hydraulic modelling

Introduction

Hong Kong is characterized by steep hill slopes. This includes the major part of the Yuen Long and North Districts leading into a deltaic plain bordering the Deep Bay. At present, the Yuen Long and North Districts are mainly served by the primary watercourses including Shenzhen River, Kam Tin River, Shan Pui River and Tin Shui Wai Main Channel. These rivers also serve the largest floodplain in New Territories and were trained in the last decade. In recent years, a significant expansion of mangrove habitat in Inner Deep Bay and the estuaries of inland rivers constitutes a potential increase in flood risk, in particular for the people living in the floodplain area. However, the mangrove stands in Inner Deep Bay represent one of the most prominent features of the Mai Po Ramsar Site. It is the largest remaining mangrove area in Hong Kong and one of the few extensive mangrove areas in Southern China, bearing high environmental and ecological values (Tam & Wong, 2000; UNEP-WCMC, 2006). To address the increasing flood risk and perceived contribution of the mangrove vegetation, a mangrove management plan has to be formulated, aiming at striking an optimal balance between flood control and environmental considerations.

Analysis of mangrove growth

Intensive surveys during 1994-1997 indicated that, besides the Mai Po area (with an estimated 172 ha of mangrove habitat), 43 mangrove stands with a total area of 178 ha still remained in Hong Kong (Tam et al., 1997). Due to the limited land space and rapid expansion in industry and population, these mangrove stands are continuously threatened by urban development (Tam et al., 1997). The importance and rapid decline of mangrove stands has led to public concern over their future stability and survival, an intensification of research into the structure and functioning of the mangrove ecosystems in Hong Kong (Lee, 1999), and calls for the conservation of the remaining mangrove stands (Tam and Wong, 2000).

With the increase in public awareness on the conservation of mangrove in recent years, it is observed that mangroves in Inner Deep Bay have been rapidly expanding, most notably over the past 15 years (Cheung, 2006). The intertidal mangroves at Mai Po Nature Reserve have been estimated to be advancing into the Bay at approximately 5 m per year (Anderson 1994; Anonymous 1994a, b) or even 7.6 m per year (Duke and Khan, 1999). Monitoring studies and interpretation of satellite imagery and aerial photographs of the mangroves in parts of the Inner Deep Bay Ramsar Site (**Figure 1**) indicate that the total area of mangroves in Inner Deep Bay has expanded from approximately 20 ha in 1945 to over 200 ha in 2005 (Cheung, 2006) (**Figure 2**).

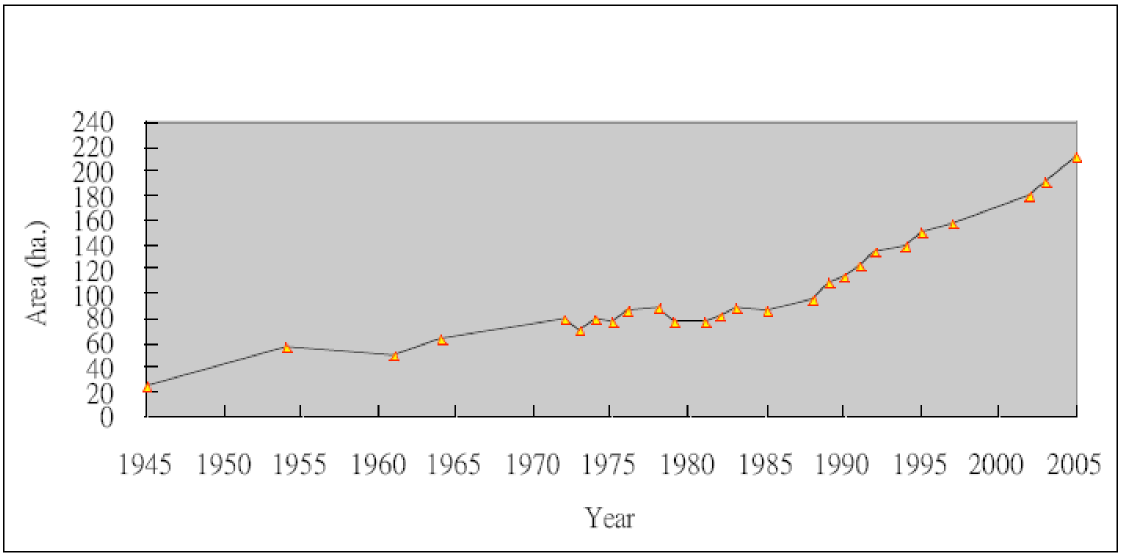
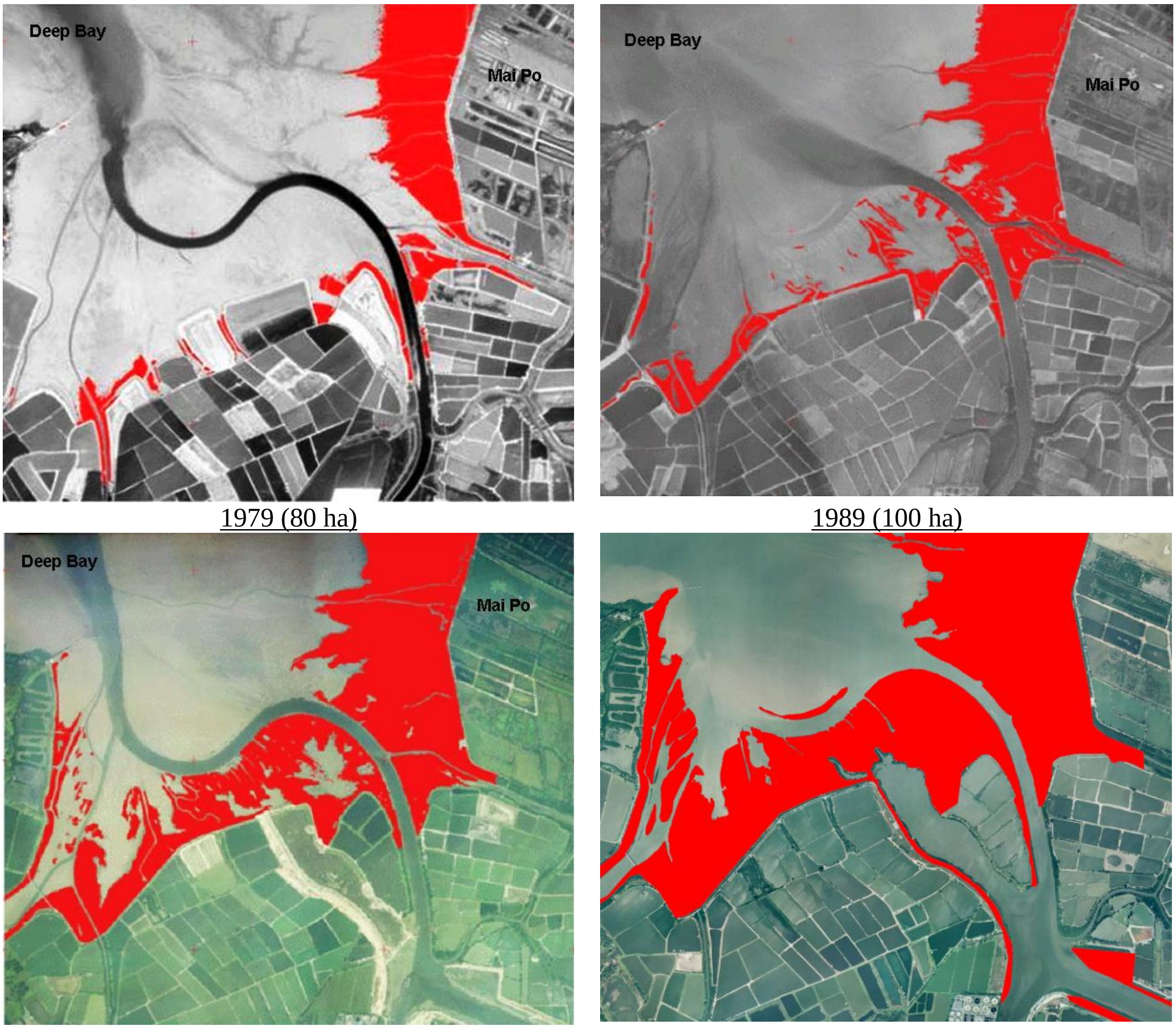


Figure 1 **Expansion of mangroves in the Mai Po and Inner Deep Bay Ramsar Site between 1945 and 2005, derived from part of the mangrove in Inner Deep Bay covered by archival aerial photos (source Cheung, 2006)**



1979 (80 ha) 1989 (100 ha)

1998 (160 ha) 2008 (300 ha)

Figure 2 Mangrove distribution (red colour) in Inner Deep Bay over the years (1979-2008)

Statistics from various sources on the mangrove coverage at the Mai Po and Inner Deep Bay Ramsar Site suggest that the mangrove expansion has been particularly rapid in recent years, with mangroves covering an estimated 258 ha in 2000 (DSD, 2001) and 290 ha in 2006 (WWF Hong Kong, 2006). The current extent of mangroves in Mai Po includes 115 ha of pure intertidal mangrove stands plus another 175 ha of scattered mangroves inside the *Gei Wai* ponds (WWF Hong Kong, 2006). The quality of the mangrove stands in some of these *Gei Wai* is deteriorating because of siltation of the *Gei Wai* and subsequent invasion by climbers.

The recent expansion of mangrove vegetation observed in the Inner Deep Bay is most likely a direct response to the increased input of sediment into Deep Bay. A large quantity of fine sediment (mainly silt) and organic material is brought down from the Pearl River and other sources in the Deep Bay catchment area (Wong & Li, 1990), and this silt slowly accumulates on the mudflats. Between 1898 and 1949, the average sedimentation rate in Deep Bay was estimated to be some 8 mm per year (Wong & Li, 1990). Hydrographic surveys in 1985 and 1986 revealed sedimentation rates (based on ^{210}Pb dating technique) in the order of 1.5 cm per year (Wong & Li, 1990). In the 1990s, the accretion rate speeded up and between 1990 and 2000, was around 3 cm per year (WWF Hong Kong, 2006). This quickening was probably due to soil runoff from deforested hillsides and runoff from a large coastal reclamation project on the Shenzhen side of the catchment. In addition, the quickening might also be related to the Shenzhen River Regulation Stage 2 project which has significantly changed the morphology and hence the hydrology of Deep Bay/Shenzhen River system. The relationship between enhanced sedimentation and mangrove expansion in Deep Bay is generally recognized by experts and responsible authorities in Hong Kong (Lee, 1999; Ecosystems Limited, 2005; WWF Hong Kong, 2006).

Further evidence for the high rate of sedimentation in Inner Deep Bay is given by the fact that Shenzhen River required maintenance dredging, with dredging quantities of approximately 284,000 m^3 in 1999 (Liu Pok), 420,000 m^3 in 2004 (Liu Pok and Lok Ma Chau) and 489,000 m^3 in 2007 (Lok Ma Chau and Mai Po). The major source of sediment causing sedimentation in the Shenzhen River and in the Deep Bay is from downstream through water exchange between the Pearl Estuary and Deep Bay, driven in part by gravitational circulation and large-scale circulations at the mouth of Deep Bay.

Why mangrove management is required?

The rapid growth of mangroves at the estuaries of Yuen Long Shan Pui River and Tin Shui Wai Main Drainage Channel is likely to have caused backwater effect to the upstream drainage system and increased the flood risk. The additional roughness due to vegetation is an important factor that influences water velocities and water levels in a mangrove estuary and therefore directly relates to flood hazard potential. To restore the flow capacity of the channel that has been blocked up by the mangrove vegetation, mangrove pruning at the estuary of Shan Pui River (see **Figure 3**) was carried out in year 2003. The mangrove forest has regenerated after a few years. There are various scientific and technical studies on the hydraulic resistance of mangrove trees and other (riparian) vegetation and its relationship with increased flood risk (Pasche and Rouve, 1985; Struve et al., 2003; Leu et al., 2008). The problem of hydraulic resistance by mangrove vegetation and its adverse effects on channel conveyance and drainage capacity is not unique to Hong Kong. There are similar cases reported from several other countries, including New Zealand, Taiwan and Singapore, where management intervention is needed in response to excessive mangrove expansion blocking waterways, reducing tidal access and causing increased flooding hazard potential.

In the absence of any vegetation management or measures to curb sedimentation rates from upstream developments in the catchments of Shenzhen and Pearl rivers, it is likely that the observed expansion of mangroves in Inner Deep Bay will continue unabated. The expansion of mangrove habitat in Inner Deep Bay and the estuaries of inland rivers constitutes a potentially significant increase in flood risk, thus, a mangrove management plan needs to be formulated, aiming at striking an optimal balance between flood control and environmental considerations.

Figure 3 Mangrove pruning at estuary of Shan Pui River in 2003

Prediction of mangrove expansion at year 2030

For developing of various mangrove management options in Inner Deep Bay and the estuaries of inland rivers, a control option “Do nothing” based on time horizon of the year 2030 has been established. To enable model prediction of the potential effects of such further mangrove expansion on future flooding risks in Yuen Long and Tin Shui Wai areas, a predicted mangrove distribution map for Inner Deep Bay for the year 2030 was made based on a geographic information system analysis of past changes and trends in mangrove distribution in Deep Bay between 1979 and 2008 and expansion rates (see **Figure 1**) of Deep Bay mangroves reported in the literature. The resulting ‘predicted’ mangrove distribution map for 2030 is shown **in Figure 4**.

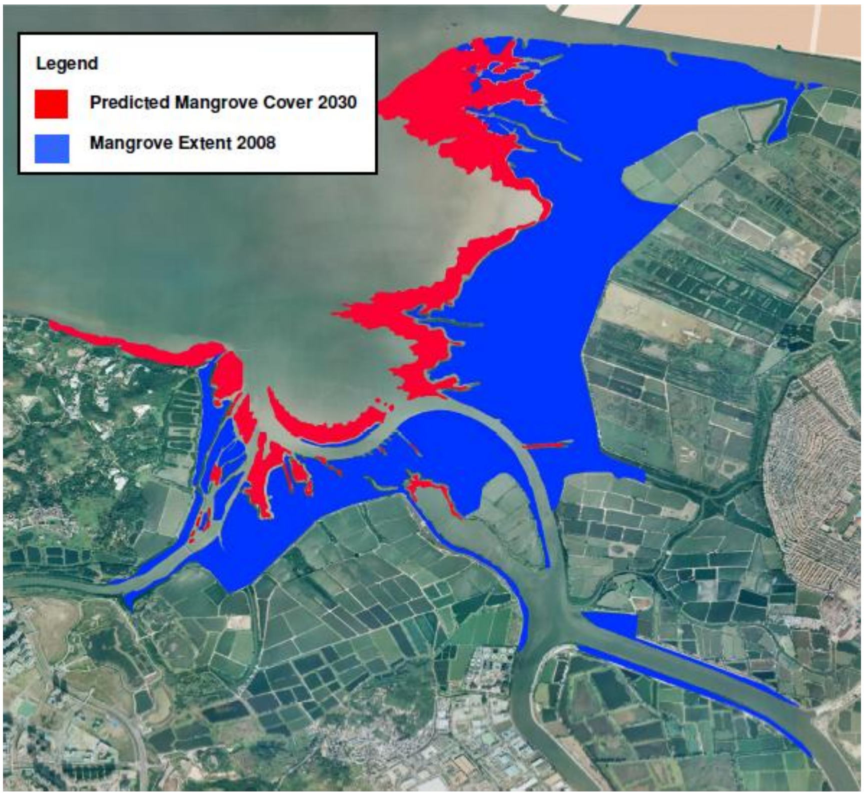


Figure 4 **Predicted mangrove distribution map for Inner Deep Bay in 2030 (mangrove extent in 2008 highlighted in blue)**

Hydraulic analysis of mangrove in estuaries of inland rivers

Mangrove can be regarded as a kind of surface roughness which reduces the capacity of the drainage system. Depending on the water level and the height of the mangrove, the flow phenomena for vegetation completely submerged in water or partially submerged are different. The results of the field measurements of vegetation parameters can be converted into an appropriate description of vegetation resistance (roughness) – the Chézy factor *C*, according to well-established analytical equations (see Baptist et al., 2007).

For partially submerged (non-submerged) vegetation, the equation is as follows:-

$$C = \sqrt{\frac{2g}{C_D mDh}} \qquad (1)$$

For submerged condition, the equation is as follows:-

$$C = \sqrt{\frac{2g}{C_D mDk}} + 2\sqrt{g}\ln\left(\frac{h}{k}\right) \qquad (2)$$

where: C = Chézy factor $[m^{0.5}s^{-1}]$;

C_D = drag coefficient;

m = stem density [m^{-2}];

D = stem diameter [m];

k = vegetation height [m];

h = water depth [m]; and

g = acceleration due to gravity on Earth, [ms^{-2}].

To assess the hydraulic impacts arising from the mangroves in Deep Bay, vegetation roughness values were derived from actual field measurements of mangrove tree density and mean stem circumference at four different heights (0, 50, 100 and 150 cm) above the sediment surface, collected in a series of random (triplicate) plots at 5 locations (A through E) at various locations in the estuaries (see **Figure 5**).

Figure 5 Mangrove survey areas

According to equations (1) and (2), the Chézy factor will also depend on the drag coefficient which is not directly measured from the physical properties of the mangrove. A sensitivity test on drag coefficients ranging from 1 to 4 was carried out using a SOBEK 2D model covering the river and urban drainage network in Yuen Long and Tin Shui Wai areas with a 2-dimensional ground layer established under the Project "Review of Drainage Master Plans in Yuen Long and North Districts – Feasibility Study" to compare the computed and the 2008 surveyed water levels along Kam Tin River, Shan Pui River, Navigation Channel and Tin Shui Wai Main Drainage Channel. The results indicated that a drag coefficient approaching 1.0 was appropriate to derive the mangrove tree roughness of the channels in question.

Figure 6 presents the calculated Chézy factor (in $m^{0.5}s^{-1}$) for the 5 locations (A through E) as a function of the water level (i.e. height above the sediment surface), based on the field data and the drag coefficient of 1.0. A higher Chézy value corresponds with a lower hydraulic resistance. As can be seen clearly in the figure, the Chézy factor varies significantly depending on water level, with values ranging between 12 - 19 $m^{0.5}s^{-1}$ at 150 cm above the sediment, and 21 - 28 $m^{0.5}s^{-1}$ at 50 cm above the sediment surface. Greatest hydraulic resistance occurs at location A and D (estuary of Kam Tin and Shan Pui Rivers), while the lowest resistance occurs at location E (estuary of Shenzhen River).

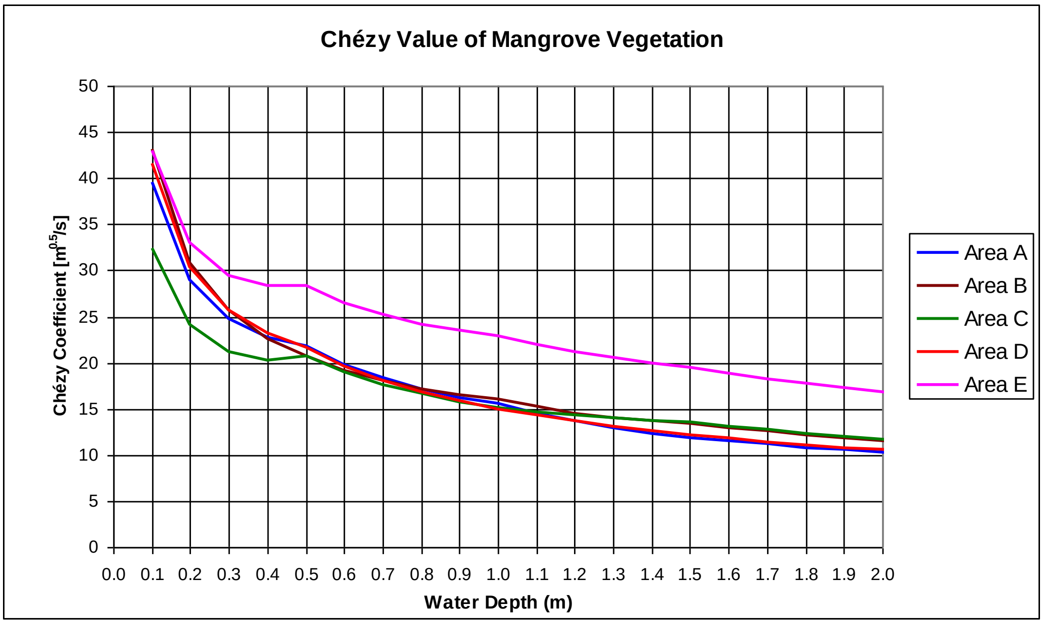


Figure 6 Chézy Value for mangrove areas

In order to predict the possible changes in future density and circumference of the mangrove vegetation due to the age of the mangrove tree - and therefore in their roughness – data from a detailed vegetation study (September 1993) along a transect at Mai Po by Duke & Khan (1999) were re-analysed. The study by Duke & Khan (1999) described the mangrove vegetation (including tree densities and diameters by species) in a series of plots (1-20) running along a transect from land to sea, with plot 1 representing the oldest (most landward) mangrove stand and plots 19-20 representing the youngest (most seaward) mangrove stands (**Figure 7**). Additional field surveys were also carried out under this assessment (in Year 2009) to provide valuable data for calculating the Chézy roughness of mangrove undergrowth (smaller-sized plants) along the edges of forests and banks of tidal creeks or mangrove areas which are likely to proliferate after cutting or pruning. These roughness values, together with the mangrove tree roughness values, were accordingly incorporated into the model to reflect the interaction between vegetation and flows in the hydraulic modelling analyses.

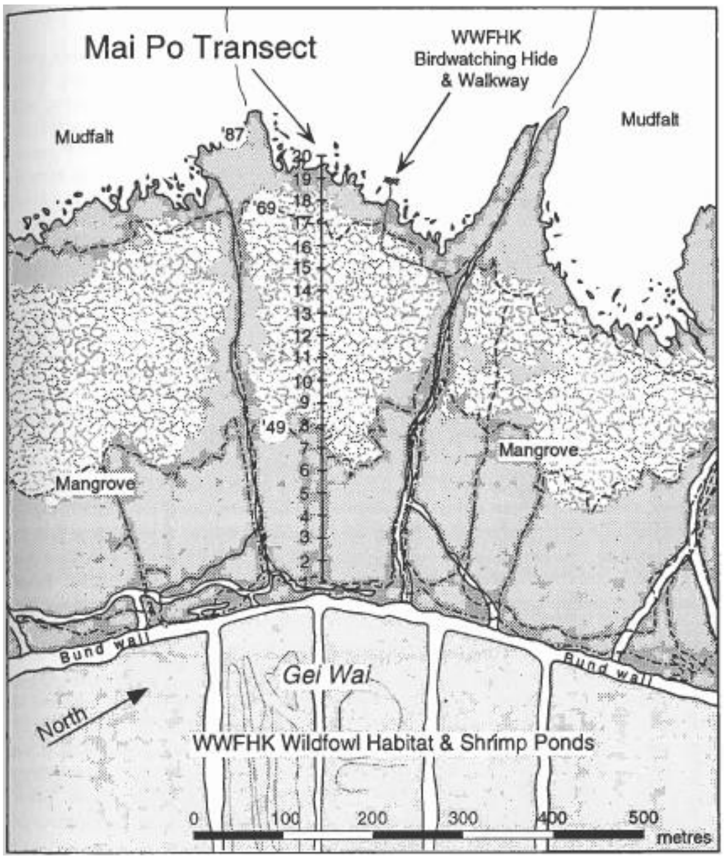


Figure 7 **The 'Mai Po transect' of the September 1993 vegetation study by Duke & Khan (1999) across the fringing mangroves of Inner Deep Bay, with plot 1 representing the oldest (most landward) mangrove stand and plots 19-20 representing the youngest (most seaward) mangrove stands**

The analysis of the data based on vegetation data from the study by Duke & Khan (1999) consisted of adding and averaging the data of all mangrove tree species together, the results of which are shown in **Figure 8**. Clearly, tree density (in red) is highest in the youngest mangrove stand and decreases with aging of the forest, while stem diameter (in blue) is lowest in the youngest forest stand and increases with aging of the forest.

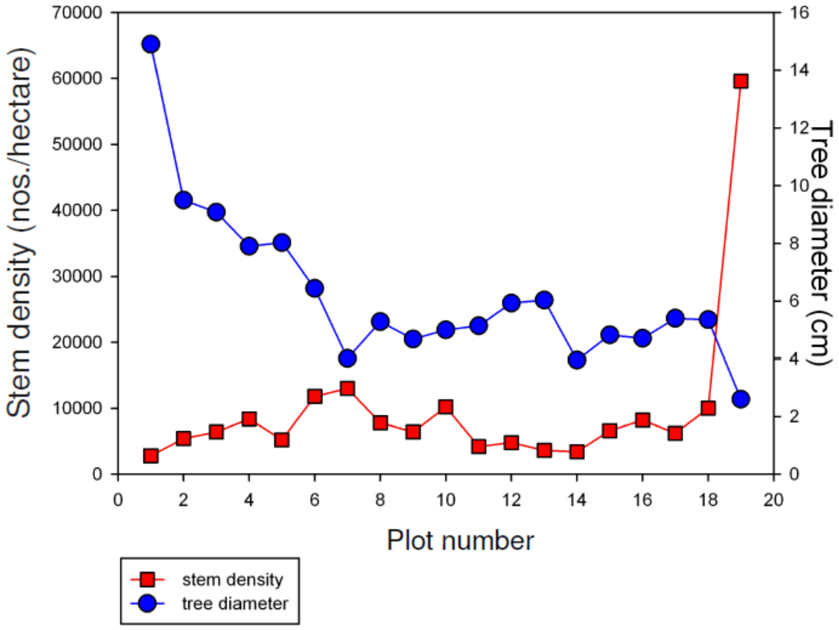


Figure 8 **Stem density (in red) and tree diameter (in blue) of all mangrove trees in plots 1 to 20 along a transect at Mai Po, based on vegetation data from study by Duke & Khan (1999)**

Chézy values subsequently calculated using this data on tree density and diameter were lowest in the dense young forest stands (plots 18-20), implying greater resistance to water flows (**Figure 9**). Chézy values increased with initial aging of the mangroves (i.e. reducing tree density and gradual increase in tree diameter) up to plot 14, after which Chézy values steadily declined until about plot 7, after which the Chézy values more or less stabilised (**Figure 9**).

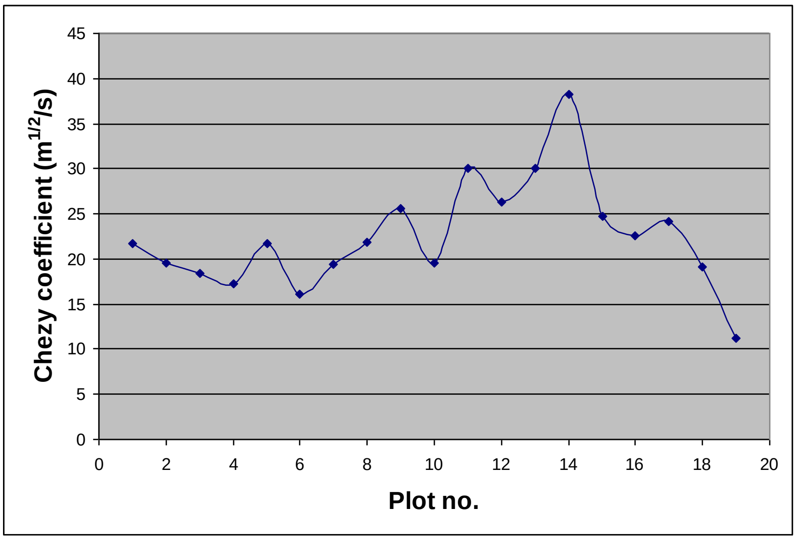


Figure 9 **Chézy coefficient ($m^{1/2}/s$) for mangrove vegetation at water level of 1.0 m for the different plots along the 'Mai Po transect' by Duke & Khan (1999)**

The Chézy coefficient shows an inverse exponential relationship with the 'biomass' of the vegetation (here represented by 'density * diameter' of stems as a proxy), as shown in **Figure 10**.

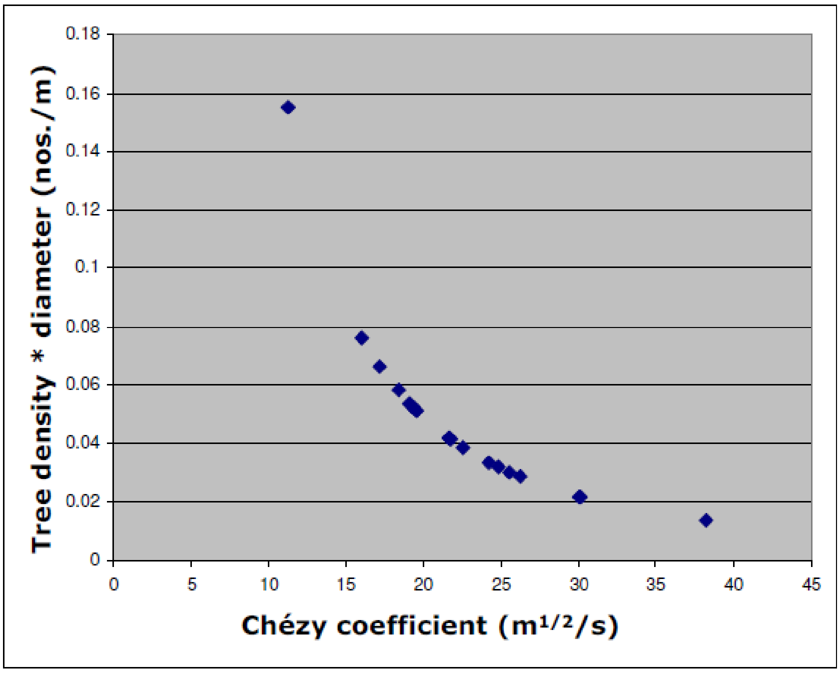


Figure 10 Relationship between Chézy coefficient ($m^{1/2}/s$) and biomass (density * diameter) of mangrove trees, based on the data from Deep Bay (Duke & Khan, 1999)

Different mangrove management options

There is a range of possible management options that can be considered to address the issue of increased flood risk due to the growth of mangrove vegetation in Inner Deep Bay. In total, nine modelling scenarios, representing the various mangrove management options ranging from "do nothing" (autonomous development) to "restored back to original design channel conditions" (removal of all above- and below-ground vegetation plus full dredging at the estuaries of Shan Pui River and Tin Shui Wai Main Drainage Channel) were analyzed.

For each scenario, four combinations of rainfall-dominated or tide-dominated events under return periods of 50 and 200 years were simulated by SOBEK 2D model. The results of the calibrated hydraulic modelling analyses indicated that management measures as extensive as completely removing the mangrove vegetation from the outlets of the Tin Shui Wai Main Drainage Channel and Shan Pui River would result in a relatively "not-as-significant" improvement in the hydraulic conveyance (i.e. a maximum reduction in water levels in the order of 9 cm in the estuarine outlets, and less than 5 cm further inland).

Additional dredging of the lower sections of the Tin Shui Wai Main Drainage Channel outlet to its channel level (i.e. dredging to approximately 1 m lower than the ground level of mangrove forest) and at the Shan Pui River outlet to by-pass level (dredging to approximately 1 m deep and 3 m deep respectively) would allow some additional improvement to the hydraulic conveyance (the maximum reduction in water levels would be in the order of 19-28 cm in the estuarine outlets depending on the dredging extents, and less than 10 cm further inland). While hydraulic conveyance would be enhanced by additional dredging, dredging of such extent is not desirable due to its impacts on the sedimentation dynamics of Inner Deep Bay, and the substantial environmental impacts such as water quality, ecology and disposal of potential contaminated mud of such an operation on the estuaries and parts of Inner Deep Bay.

In the absence of any vegetation management, thus allowing for the continued expansion of the mangrove vegetation in Inner Deep Bay, however, the hydraulic conveyance in the area will further decrease, with water levels increasing by about 9 cm in the outlets by year 2030.

Large scale removal of mangrove vegetations at the estuaries of Kam Tin River, Shan Pui River and Tin Shui Wai Main Drainage Channel for flood control will be costly and induces substantial ecological impacts to the environment. On the contrary, the adoption of “do nothing” mangrove management will have negative drainage impacts to the existing drainage systems and is unacceptable from a flood alleviation point of view. A balanced approach is therefore needed.

Choice of mangrove management option

Remove a small portion of above- and below-ground vegetation in the estuary of Tin Shui Wai Main Drainage Channel and restrict further expansion and thickening of mangrove vegetation to the 2008 extent at the outlet of the estuaries to maintain the existing hydraulic performance is considered as the most preferred mangrove management option because it strikes an optimal balance between flood control and environmental considerations. It is also cost effective because it is a relatively low-effort approach to mangrove management. The current extent of mangrove forests in the estuaries is allowed to remain intact except for a small portion of mangrove vegetation at the Tin Shui Wai Main Drainage Channel (about 1.5 ha, see **Figure 11**) which will be removed to mitigate the adverse effects of the hydraulic resistance due to continuous growth of the mangrove trees.

Annual removal of seedlings and regular maintenance (selective thinning and trimming) will be required on the existing forest fringe bordering the mudflats and creeks in the estuarine outlets to prevent further expansion and thickening of the mangrove vegetation. The above-ground vegetation and the below-ground (i.e. the roots of the mangrove plants) portions of vegetation will be removed at the designated areas with extent similar to the mangrove area in 2008. This management option serves the dual purposes of compensating for the increased in hydraulic resistance due to the mangrove vegetation as well as minimizing environmental impacts on Inner Deep Bay.

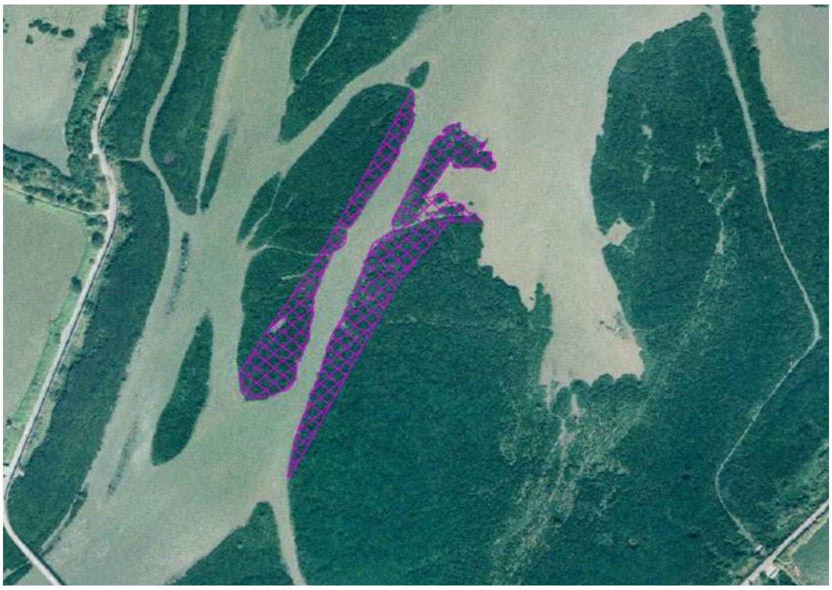


Figure 11 **Extent of mangrove areas to be removed at Tin Shui Wai Main Drainage Channel outlet**

Conclusion

In recent years, Inner Deep Bay has witnessed a substantial expansion of mangrove vegetation (in the order of 200 ha). This expansion of intertidal mangrove vegetation is of major significance for the ecology and conservation of Inner Deep Bay. On the other hand, however, the rapid mangrove expansion may have adverse consequences on the drainage capacity and increasing the flooding risk in parts of the New Territories.

Field measurements were made of mangrove vegetation characteristics (tree density, stem diameter, vegetation height, etc.) in a series of plots at 5 different sites and 4 different heights in the study area, which were used to calculate specific parameters that describe the additional roughness due to the vegetation. These (spatially varying) roughness values were then used as site-specific input in a 2D part of the SOBEK hydraulic model of the mangrove area in which the effects of different management scenarios (involving mangrove removal and dredging) were evaluated.

Large scale removal of mangroves at the estuaries of Kam Tin River, Shan Pui River and Tin Shui Wai Main Drainage Channel for flood control would definitely induce significant ecological impacts to the environment. On the other hand, the adoption of “do nothing” mangrove management option would have negative impacts on the capacity of the existing drainage system and hence be unacceptable from a flood management point of view. In order to satisfy both environmental and flood control requirements, mangrove management option “remove a small portion of above- and below-ground vegetation in the estuary of Tin Shui Wai Main Drainage Channel and restrict further expansion and thickening of mangrove vegetation to the 2008 extent at the outlet of the estuaries" is recommended. This constitutes a low-effort approach to mangrove management in which the current extent of mangrove vegetation in the two estuaries is allowed to remain intact except for a small portion of mangrove at Tin Shui Wai Main Drainage Channel (about 1.5 ha) which will be removed to mitigate the adverse hydraulic resistance due to the rapid expansion of mangrove vegetation in the area.

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