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Beach Erosion and Preventive Countermeasure at Kangnan Coast, Taiwan

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ABSTRACT

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Kangnan Coast has suffered from beach erosion since the extension of breakwaters and two groins of Hsinchu Fishing Harbor was completed. This is a typical example of human impact on coastal erosion in Taiwan. The aim of this article is to explore the erosion at Kangnan Coast using several analyses, such as shoreline revolution detected from satellite images, planform description of depth variation, volumetric change of bathymetry, and variations in the trends of volumetric changes of the sea bottom. Beach erosion at Kangnan Coast in response to structural effects was quantitatively determined. A suggested countermeasure using submerged detached breakwaters, developed through a 3-year study, is proposed to mitigate beach erosion.

ADDITIONAL INDEX WORDS: *Shoreline evolution, bathymetric variation, sediment transport, groin effect.*

INTRODUCTION

Coastal erosion sometimes happens around the island of Taiwan. Human interventions, especially the construction of coastal structures, have contributed significantly to erosion in more recent times (Hsu, Lin, and Tseng, 2007). The placement of structures on the beach frequently induces morphological changes in the coastal zone because such structures alter the nearshore currents and then disturb the natural balance of supply and loss of littoral material. The longshore sediment transport on the beaches manifests itself whenever this natural movement of sediment is blocked by the construction of jetties, breakwaters, or groins. Such structures act as a dam, holding back upstream sediment and causing a buildup of the beach on the up-drift side and simultaneous erosion in the down-drift direction. Kangnan Coast has also suffered from beach erosion for more than 10 years since the construction of a fishing harbor.

Kangnan Coast lies to the northwest of Hsinchu, located in the northwest of Taiwan. Kangnan Coast is close to Hsinchu Crematory and Hsinchu Fishing Harbor northwards, and neighbors to the estuary of the Keya River southwards (Figure 1). Before 1988, Kangnan Coast was a beach in a state of accretion because of lots of sand supplied from the Touchien River (Wu and Wu, 2003). Figure 2 and Table 1 show the positions and the corresponding construction time, respectively, of extended breakwaters of Hsinchu Fishing Harbor. After extension of the breakwaters and construction of two groins were accomplished, Kangnan Coast suffered from beach erosion due to sand trapped by the long breakwaters of Hsinchu Fishing Harbor in the north (Figure 3a). A temporary treatment to protect against beach erosion was set on the shoreline using a porous breakwater armored only with concrete blocks weighing 8 tons each (Figure 3b). The breakwater was two layers high and 1300 m long. These blocks protected the coast behind them but induced extra erosion problems, such as terminal scour and the toe scouring in front of the blocks. Terminal scour, also called flanking, removes support from the end of the structure and leads to undermining at the end of the wall. It is common to observe an area of increased erosion at the ends of seawalls (French, 2001). The terminal scour observed at Kangnan Coast is shown in Figure 3c. The mechanics of terminal scour is diagrammatically demonstrated in Figure 4. The down-drift end of the seawall is marked by increased erosion, causing a stepped appearance to the shoreline and landward movements.

A sketched figure showing the process of coastal erosion—how a structure causes up-drift accumulation and down-drift erosion—is illustrated by Uda and Ishikawa (2005) in Figure 5. After a period of accretion against one of the breakwaters, littoral transport of material starts to bypass the head of breakwaters and deposits at the entrance of a harbor. The breakwater sometimes causes channel silting at the entrance of the harbor and erosion augmentation in the down-drift. An analysis of bathymetric changes over a series of bathymetric measurements is commonly used to evaluate beach erosion.

Traditional topographical measurement by an altazimuth or a real-time kinematic Global Positioning System (GPS) method is a quantitative way of evaluating beach changes.

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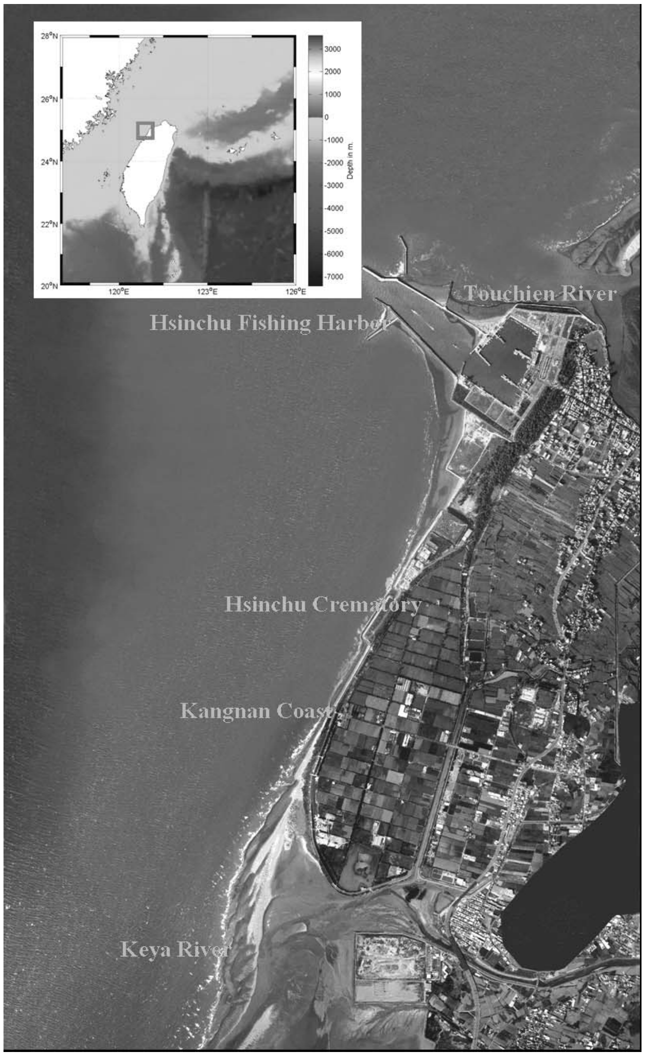

Figure 1. Location map for Kangnan Coast. **For a color version of this figure, see page 395.**

Due to the high cost of manpower or the requirement for measurement accuracy, such field observations are generally carried out for a small area. For qualitative evaluation of the beach change of a large area, a photographic comparison in different years at the same place is sometimes applied for practical uses. Recently satellite images have been widely available from many scientific satellites. Moreover the resolution of these satellite images is also improved for engineering uses. Therefore, some studies on the applications of satellite imagery and aerial photographs have appeared in the literature, such as Asano *et al.* (2000) and Kurosawa and Tanaka (2001). Gardel and Gratiot (2005) developed a method for monitoring mud bank migration rates since 1986 between the coastal cities of Cayenne and Kourou by Système Probatoire d'Observation de la Terre (SPOT) and Landsat images. Ryu, Won, and Min (2002) noted that bands of thermal-infrared rays, near-infrared rays (NIR), and short-wave infrared rays are, in that order, effective for extracting waterline while ebb tides are in progress. The effect of turbid water on NIR can be reduced by a ratio of multibands of satellite imagery. Wu and Wu (2003) used multitemporal remote sensing data to analyze the change of the western coast in Taiwan. Their results showed that Kangnan Coast was one of the most serious erosion areas on the western coast.

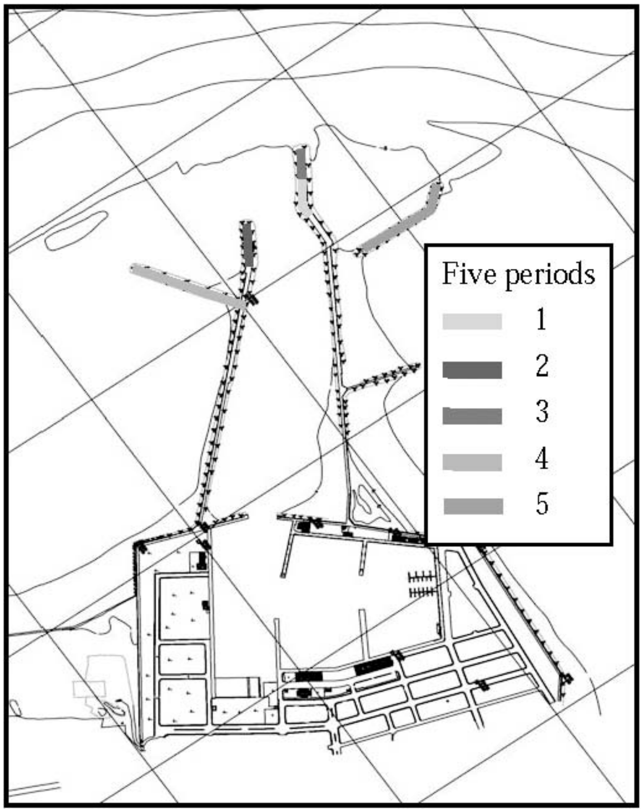

Figure 2. Location of extended breakwaters of Hsinchu Fishing Harbor during five periods of construction time. **For a color version of this figure, see page 395.**

The aim of this paper is to investigate the long-term shoreline evolution in the south of Hsinchu Fishing Harbor using

Table 1. *Construction time of extended breakwaters of Hsinchu Fishing Harbor during five periods.*

Period	Start Date	Finish Date	Content
1	March 1995	December 1995	The extension of the 100-m north breakwater
2	October 1995	July 1996	The extension of the 115-m south breakwater
3	October 1996	May 1999	The extension of the 75-m north breakwater
4	September 1996	August 1997	The construction of the 300-m south groin
5	March 1998	December 1998	The construction of the 300-m north groin

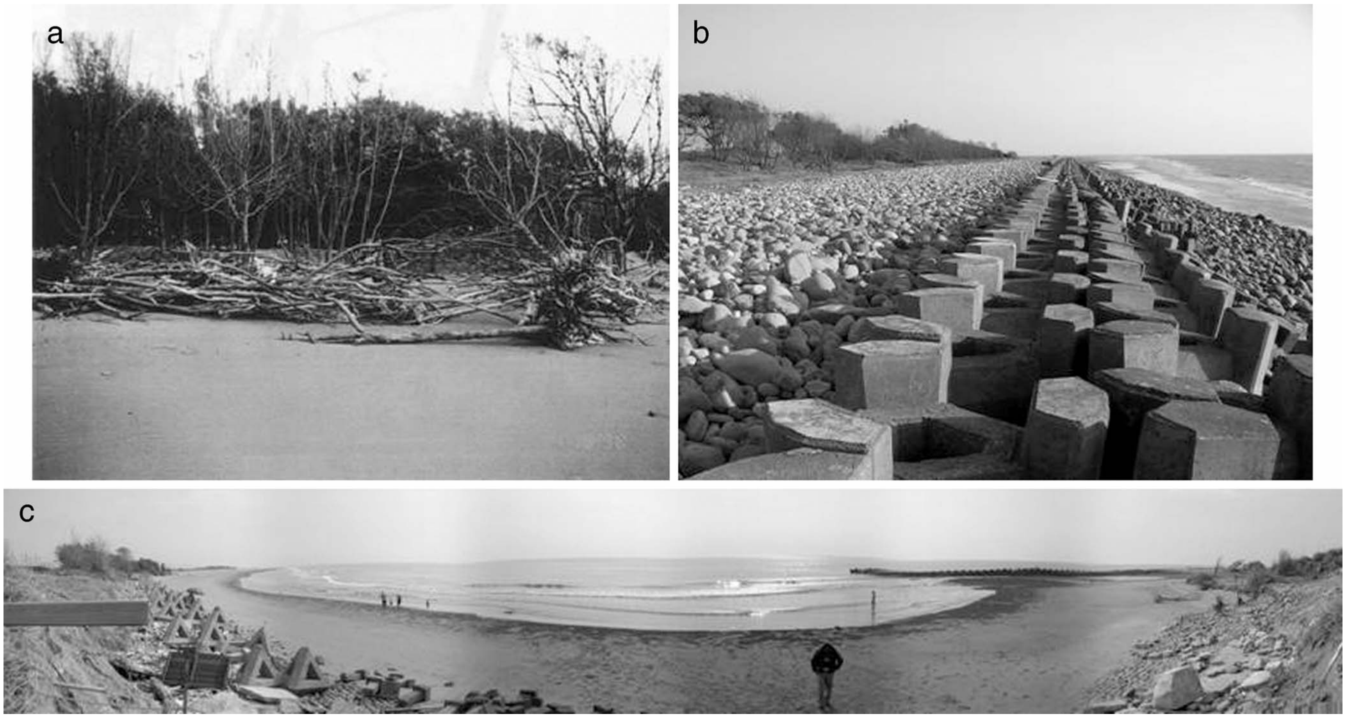

Figure 3. Photos showing the beach erosion at Kangnan Coast (a) before the construction of the breakwater (1998) and (b) after the construction of the breakwater (2000); (c) terminal scour at the end of the constructed breakwater (2005). **For a color version of this figure, see page 397.**

both satellite images and bathymetric measurements. Quantitative expression from 1998 to 2006 is shown in a color map for variation of bathymetry. The change in bathymetric volume and the corresponding change in bottom elevation are quantitatively assessed to explain the beach erosion of Kangnan Coast.

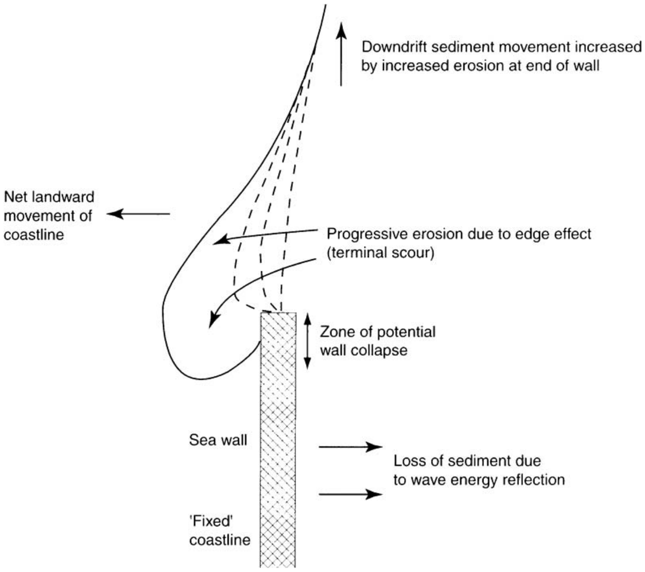

Figure 4. Typical end effects (terminal scour) at the end of a seawall (French, 2001).

SHORELINE EVOLUTION

Long-term shoreline change can be visibly determined using satellite images at different times (Gardel and Gratiot, 2005). In the present study, four SPOT images were collected from 1994 to 2007 (Figure 6), chosen for the clearness of imagery and for time periods before and after groin construction in Hsinchu Fishing Harbor. Bright histograms were calculated and congregated in different ranges from a target region selected from the collected images. Histogram equalization is a useful and common method for manifesting image contrast enhancement, which is used to efficiently recognize the characteristics of some brighter or darker imagery through transformations of the bright scale in each image (Gonzalez, Woods, and Eddins, 2004). Image adjustment that emphasizes the bright range of the boundary zone is a good and necessary skill of extracting edge detection. Thus both histogram equalization and image adjustment were used for preliminary treatment.

The earliest image collected for Kangnan Coast was from 1994 (Figure 6a). Therefore 1994 was taken as a base time of measuring the shoreline of Kangnan Coast. Before 1994 neither the north nor south groins of Hsinchu Fishing Harbor were yet constructed to trap sand from longshore sediments. The south groin was constructed in 1997, so that it is present in Figure 6b but absent in Figure 6a. A comparison of the

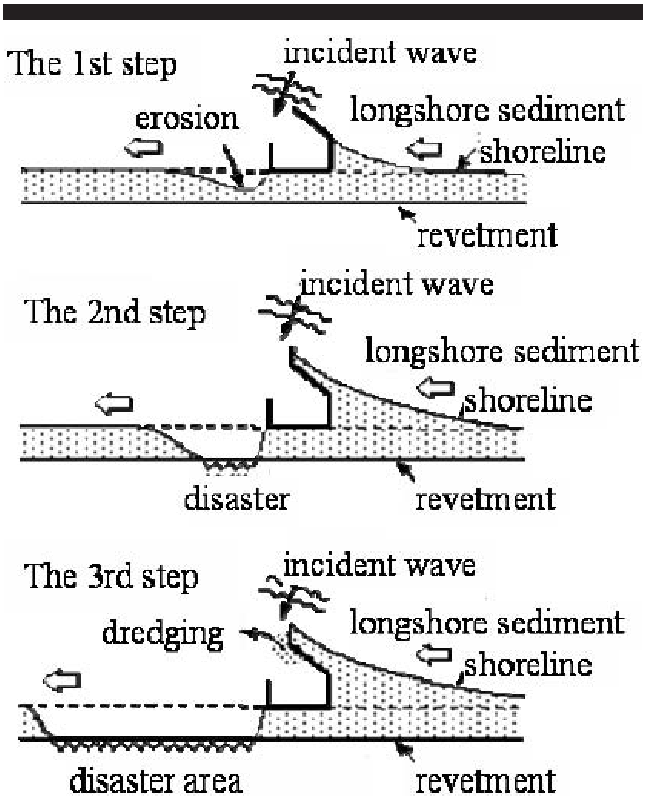

Figure 5. Process of coastal erosion (Uda and Ishikawa, 2005).

shoreline of Kangnan Coast between Figures 6a and 6b showed slight sand accretion at the neighboring beach to the south breakwaters of Hsinchu Fishing Harbor. However, both Figures 6c and 6d compared with Figures 6a and 6b showed that the whole shoreline retreated and that, in particular, much of the sandbank at the estuary of the Keya River vanished.

To estimate the change in shoreline, the positions of shorelines can be detected from satellite images in different years. Proper edge detection techniques will enhance the most important desirable features of an image while removing unwanted information. Thus the process can reduce the storage of a large amount of data in an image. The Canny algorithm is a good, common way of detecting edges due to its high efficiency of filtering out white noise from an image (Semmlow, 2004). Therefore, in this paper the Canny algorithm was chosen to figure out the shoreline of Kangnan Coast as an edge. Some unwanted features of the originally detected edges, such as ripples in the sea surface and offshore islands, were removed using Geographic Information System (GIS) software with an erasing function. Detected edges were recorded as many pixels in binary code. Skeletonization is the necessary skill of making the originally detected edges thinner so that the modified edge retains important information about the shape of the original edge without surplus pixels. The shorelines of Kangnan Coast for Figures 6a–d detected through this process are illustrated in Figure 7. The positive x-axis denotes the alongshore distance from the origin and the positive y-axis indicates the offshore distance. The origin was chosen at a point located at about the estuary of the Keya River. The alongshore distance of Figure 7 is also shown in the corresponding map in order to clearly describe the location.

Figure 8 shows the shoreline change, indicated by the subtraction of the original position in the base year, 1994, from the shoreline position in subsequent years. The x-axis of Figure 8 also denotes longshore distance; the y-axis shows shoreline movement, where the positive y-axis denotes beach accretion and the negative y-axis shows beach erosion. Figure 8a shows shoreline change from 1994 to 1998, indicating that the shoreline moved seawards at segments $x = 800$–2000 m and $x = 3500$–4800 m but that the shoreline moved slightly landwards at the segment $x = 2000$–3500 m. The result shows that beach accretion occurred at the estuary of the Keya River and the coast neighboring the south breakwater of Hsinchu Fishing Harbor and slight beach erosion happened at Kangnan Coast during that 3.5-year period. The effect of the south groin on beach accretion/erosion was gradually evident. Some sand had been trapped continuously by the groins so that longshore sediment was reduced. Figure 8b (1994–2000) indicates that significant beach erosion occurred at the segment $x = 1500$–3000 m, that is, Kangnan Coast. The shoreline change between March 1994 and March 2007 is shown in Figure 8c. A comparison of Figure 8c with Figure 8b shows that the whole coast was eroded severely, especially at the segment $x = 1000$–3000 m. Furthermore, the shoreline at Kangnan Coast moved landwards, illustrating that the beach was eroded at the segment $x = 1700$–4000 m.

BATHYMETRIC VARIATION

The distance between the Touchien River and the Keya River was divided into six areas (A–F) in consideration of possible interception of longshore sediment by structures. The critical depth was determined by the following expression, proposed by Sato and Tanaka (1966):

$$\frac{H_o}{L_o} = A\left(\frac{D_{50}}{L_o}\right)^{1/3}\left[\sinh\left(\frac{2\pi d}{L}\right)\right]\left(\frac{H_o}{H}\right) \tag{1}$$

where H_0 and L_0 are the wave height and wave length in deep water, respectively; D_{50} is the mean diameter of sand; d is the local water depth; H and L are the corresponding wave height and wave length at such local water depth, respectively; and A is an empirical coefficient depending on the type of sand movement. The required data for Equation (1) were collected. The wave height and period are 1.27 m and 5.28 s, respectively, determined through statistical analysis on wave data from January 1998 to May 2005 measured by the Central Weather Bureau in Taiwan. The median diameter of sand is 0.2 mm. A value of $A = 1.35$ is commonly suggested. Using these data, a critical depth of 5.36 m was obtained. The common plot for isocontours of water depth is taken as an integer. Thus a water depth of 5 m was considered to be a critical depth to separate the beach into the offshore zone and nearshore zone.

The divided regions are shown in Figure 9a. Areas A and B are divided by the Touchien River and are located in the north of Hsinchu Fishing Harbor. Area C neighbors the south breakwater of Hsinchu Fishing Harbor. Area D runs along the revetment of Hsinchu Crematory. Areas E and F run along Kangnan Coast. Subscripts 1 and 2 denote the region of nearshore and offshore, respectively.

Planform Description of Bathymetric Variation

Bathymetric planform variation between the Touchien River and the Keya River is shown in Figures 9b-d. Bathymetric planform variation from September 1998 to August 1999 is shown in Figure 9b. According to this figure, a little deposited sand appeared at the entrance of Hsinchu Fishing Harbor. A comparison of Figure 9c with Figure 9d shows that the deposited area increased visibly at the entrance of Hsinchu Fishing Harbor and in the offshore zone of the Touchien River from 2002 to 2006. Only some littoral sediment transport occurred through the entrance of Hsinchu Fishing Harbor, so that the offshore zone of Kangnan Coast was accreted but the nearshore zone of Kangnan Coast was eroded.

Volumetric Change of Bathymetry

Eight periods of bathymetric observation were carried out sequentially from 1988 to 2006. Generally, field measurements on bathymetry were done twice per year. One measurement was in April or May, and the other one was in September or October. The purpose of these two measurements was to study the change in sediment under the action of summer waves or winter waves. Evaluation of volumetric change of bathymetry was based on the original bathymetry measured in September 1998. The volumetric change of bathymetry was defined as the volume of the original bathymetry in September 1998, subtracted from the bathymetry in one sequential measurement. The results are shown in Table 2. The second column of Table 2, denoted by areas A–B, indicates the volumetric change of bathymetry in the region of the northern breakwater of Hsinchu Fishing Harbor. The third column of Table 2, denoted by areas C–F, shows the volumetric change of bathymetry in the region of the southern breakwater of Hsinchu Fishing Harbor.

From September 1998 to September 2006, bathymetry in areas A–B was gradually accreted. The total amount of sand accretion in these regions was 863×10^4 m^3 during these 8 years. The rate of accretion was thus 108×10^4 m^3/y. For areas C–F the sea bottom suffered from erosion by an amount of 261×10^4 m^3 in 8 years, indicating that the rate of erosion was 33×10^4 m^3/y. Thus the sea bottom was in a state of accretion in the whole region by an amount of 75×10^4 m^3. According to Water Resources Agency Ministry of Economic Affairs (1992–2003), the total river sediment transport of the Touchien River was 490×10^4 m^3 from 1992 to 2003, indicating that the rate of river sediment transport was 41×10^4 m^3/y; the value was the same order as the net sediment of the whole region. The result shows that river sediment transport was one of the key factors of bathymetric change along this coast.

An alternative expression for accretion/erosion of bathymetry is the variation of average elevation of sea bottom, defined by the volumetric change of bathymetry divided by the corresponding area. The average elevation of sea bottom is important for navigation of fishing boats and determining wave properties, such as breaking wave height, which is generally connected to water depth.

Figure 10a shows the variation of average elevation of each nearshore region for different measurements. The average elevation of areas E1 and F1 visibly and monotonically decreased. Area E1 had the most severe erosion: a drop in average elevation of 1.99 m from September 1998 to September 2006. The breakwater with concrete blocks on the shoreline at Kangnan Coast was built up during 2000. The toe scour occurred after the construction of the breakwater and was continuously deepened to an equilibrium state until 2002. Only one strong typhoon, Toraji (2001), passed by Hsinchu from 1999 to 2003. However, after 2003 some strong typhoons passed through Hsinchu, causing large waves: Mindulle (2004), Aere (2004) and Haitang (2005). These large, high-energy waves induced deeper toe scour in front of the breakwater than ordinary waves, so that the sea bottom in areas E1 and F1 had a fast drop during 2005 and 2006.

From August 1998 to September 1999, area D1 descended by an average elevation of 0.38 m and then reversely ascended from September 1999 to April 2001. After the impact of summer waves on this area during 2001 and 2002, the sea bottom of area D1 had a slight drop, comparing the second line legend with the third and the fourth with the fifth. Under the action of winter waves, the average sea bottom in area D1 uplifted, indicating sand deposition, from a comparison of the third line legend with the fourth and the fifth with the sixth (Figure 10a). The results showed that the northeast winter waves induced longshore sediment transport from north to south, of which some passed by the entrance of Hsinchu Fishing Harbor and some deposited in this area. However, some large typhoon waves in the summer eroded the beach in this area to move sand to the offshore. The sea bottom of area D1 in 2006 was restored to the original average elevation in 1998. Thus the bathymetry of area D1 had a seasonal variation and remained in equilibrium.

Area C1 had small variation of bathymetry, less than 0.6 m. This result was caused by the sheltering effect of the south breakwaters of Hsinchu Fishing Harbor, forming local circulation so that net sediment transport was almost scanty, having little average accretion. Area B1 had little erosion in the first 2 years. Because of some sand trapped by the north groin, the sea bottom of area B1 gradually deposited up to the highest elevation by 0.91 m. The bathymetry of area A1 had an increasing trend with a terminal value up to 0.55 m in 2006.

The variation of average elevation in each area in the offshore zone is shown in Figure 10b. The average elevation of the sea bottom in area F2 decreased with little variation down to -0.75 m until 2006. The average elevation of the sea bottom in area E2 varied within a small range of -0.16 to approximately -1.78 m, with a mean of -0.89 m. Comparing Figures 10a and 10b for areas E and F shows that the eroded sand in the nearshore zone moved to the offshore zone until 2001, and then the sea bottom in areas E2 and F2 became gradually stable.

Area D2 had the lowest elevation by -0.86 m for October

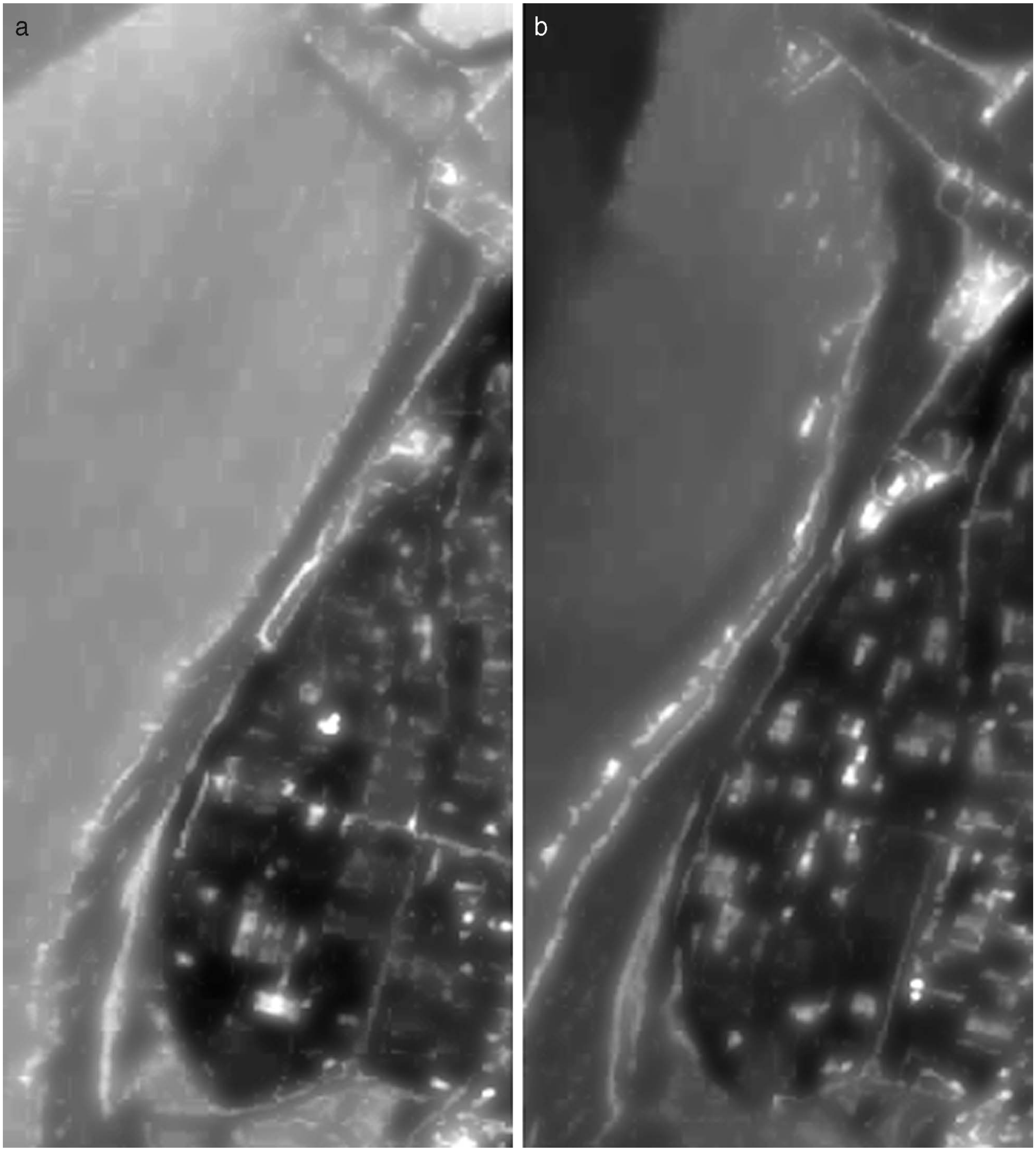

Figure 6. Four SPOT images of Kangnan Coast. (a) March 4, 1994; (b) November 11, 1998; (c) July 25, 2000; (d) March 30, 2007.

2002 and a small variation of sea bottom within a range of −0.36 to approximately 0.04 m. The average elevation of the sea bottom in area C2 gradually increased and reached an equilibrium state with a value up to 1.10 m in 2006. The sea bottom in areas A2 and B2 fast increased up to 2.43 m and 3.08 m, respectively, due to plentiful sand supplied from the Touchien River and sand trapped by the north breakwater and groin of Hsinchu Fishing Harbor.

Variation Trends of Volumetric Change

The trend of volumetric change in each area was investigated to determine whether the accretion or erosion of each

Figure 6. Continued.

area reached a new balance or not after the groins of Hsinchu Fishing Harbor were constructed. The results are shown in Figure 11. Solid circles and hollow circles in Figure 11 denote the volumetric changes in the nearshore zone and the offshore zone, respectively. Both kinds of data for these circles were expressed by the best-fitting curve in a quadratic form. A best-fitting curve with a positive slope indicates that the sand in the region deposited on the sea bottom. In contrast, when the best-fitting curve has a negative slope, the sea bottom in the region suffered from erosion. When the best-fitting curve approaches a horizontal line, the sea bottom in the region hardly varied.

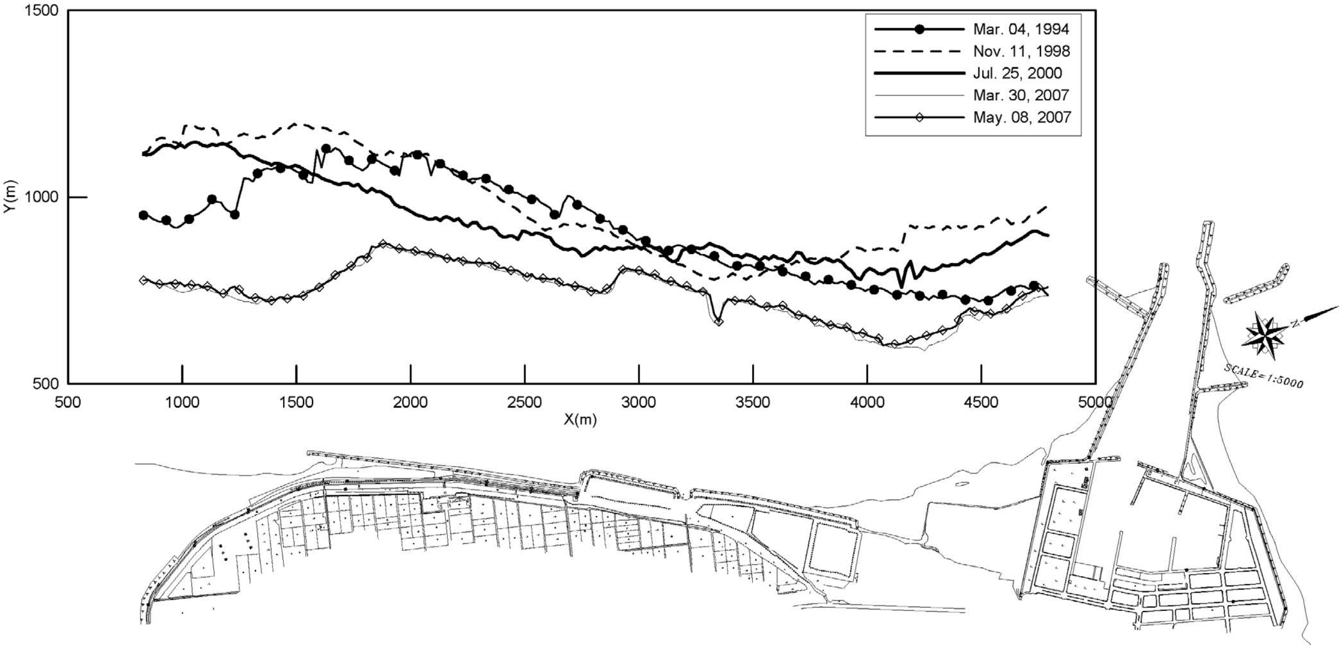

Figure 7. The position of detected shorelines from satellite images.

Figures 11a and 11b show that both areas A and B were in a state of sand deposition on the sea bottom, especially in the offshore region. A large amount of sand supplied from the Touchien River and sand trapped by the north groin of Hsinchu Fishing Harbor were the keys to sand deposition in these regions. The average rate of volumetric change of bathymetry in each region is listed in Table 3. The average rate was computed for three time periods: from 1999 to 2003, from 2003 to 2007, and from 1999 to 2007. For offshore area A2, the rate of volumetric change of bathymetry began slow but suddenly became fast by an average rate of 111.9 × 10^4 m^3/y after 2003. An average rate of volumetric change of bathymetry from 1999 to 2007 was 66.3 × 10^4 m^3/y. For nearshore area A1, the average rate of volumetric change of bathymetry was 16.6 × 10^4 m^3/y for the whole period, showing a slower increase than offshore area A2. For areas B1 and B2, the increased rates of both areas were approximated by an average value of 22.8 × 10^4 m^3/y, as shown in Figure 10b and Table 3. The results in Figure 9c show that the sand accumulation by the north breakwater and groin of Hsinchu Fishing Harbor reached to the entrance of the harbor after 2003 and then started to bypass materials already deposited at the end of the breakwater.

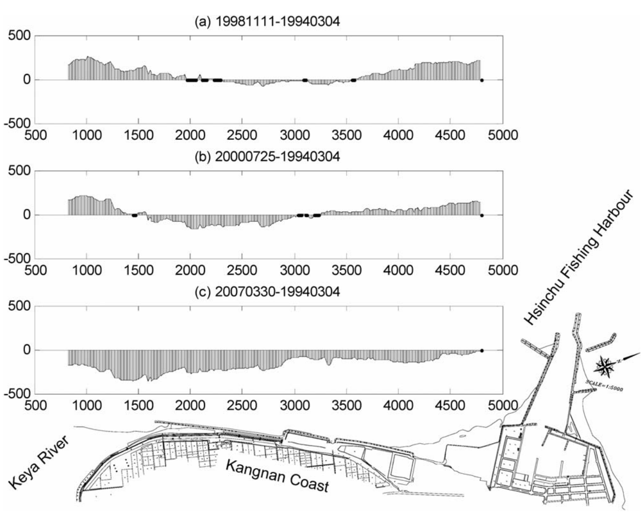

Figure 8. Shoreline change at Kangnan Coast (a) from 1994 to 1998; (b) from 1994 to 2000; (c) from 1994 to 2007.

In Figure 11c both best-fitting curves are close and had a slight increase in rate of volumetric change of bathymetry by 12.2–17.7 × 10^4 m^3/y from 1999 to 2003. After 2003, both curves are approximately horizontal, showing that the net longshore sediment transport maintained equilibrium in these areas. For areas D1 and D2, the average rate of volumetric change of bathymetry first decreased before 2003 and then slightly increased after 2003. The sheltering effect of the long south breakwater of Hsinchu Fishing Harbor on sediment transport made a blocked region, including areas C and D, so that the sediment in these areas was in a closed system. The dashed curves of Figure 11e for offshore area E2, with the average rate of volumetric change of bathymetry being -1.1 × 10^4 m^3/y, seemed extremely horizontal, showing that the sea bottom in the offshore region was invariant. However, volumetric change of bathymetry in nearshore area E1 continuously decreased at a fast rate by -14.2 × 10^4 m^3/y before

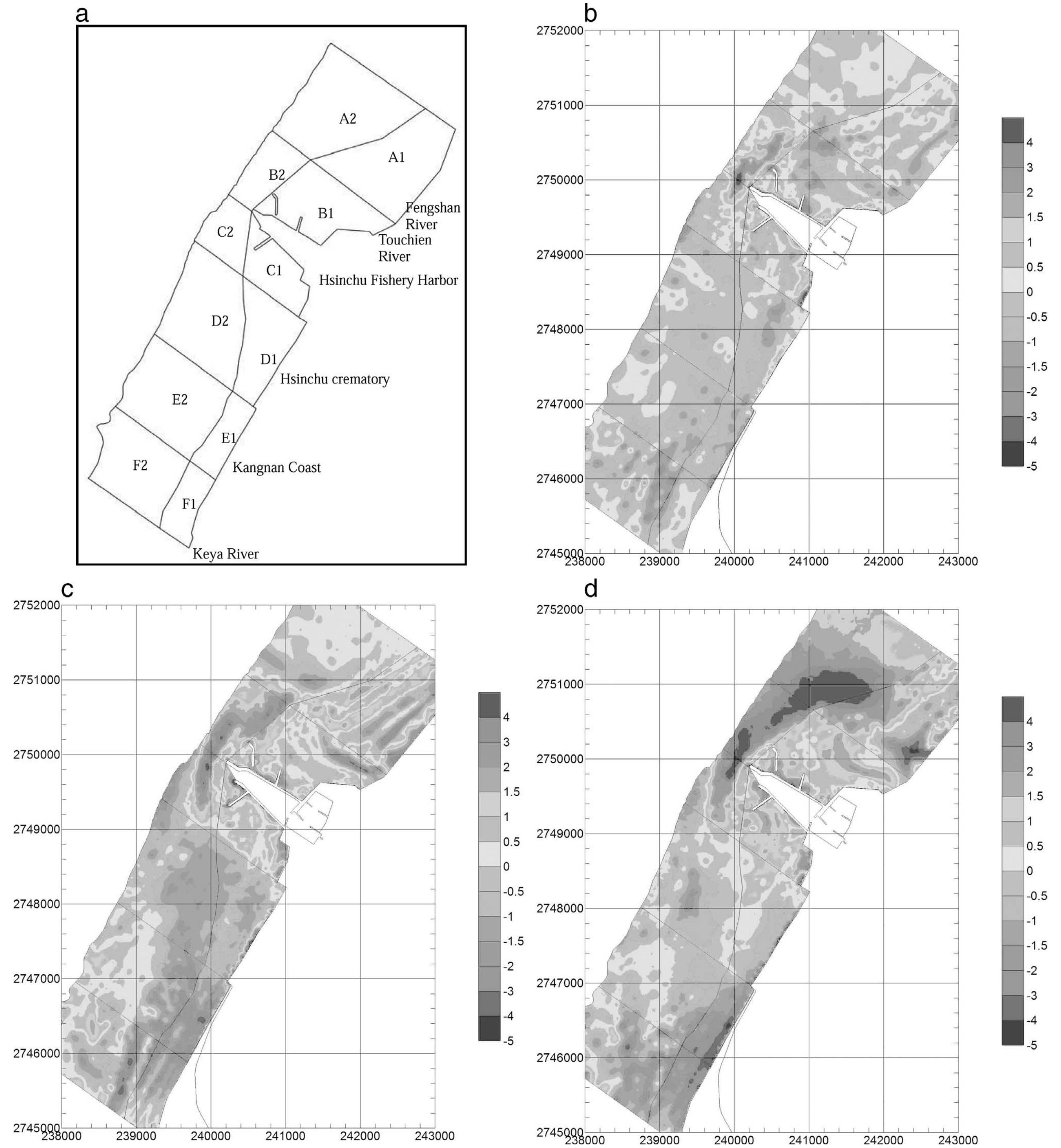

Figure 9. Bathymetrical planform variation in each area. (a) Definition sketch of separated areas; (b) Period from September 1998 to August 1999; (c) Period from September 1998 to October 2002; (d) Period from September 1998 to September 2006. **For a color version of this figure, see page 396.**

2003 and at a slow rate by -5.3×10^4 m^3/y after 2003. In the early period, area F1 had more severe erosion than area F2 by about two times. However, both areas had an equivalent decrease in rate of change of bathymetry from 2003 to 2007.

Table 3 shows that the average rate of volumetric change of bathymetry at Kangnan Coast reduced slightly. The isodepth contour of 5 m in Figure 9 at the entrance of Hsinchu Fishing Harbor dropped rapidly toward the nearshore zone of Kangnan Coast, indicating that more sand was transported

Table 2. *Volumetric changes of bathymetry in each region (unit: 10^4 m^3). A positive value indicates sand accretion, while a negative value indicates sand erosion.*

Date of Measurement	Areas A–B	Areas C–F	Areas A–F
September 1998–August 1999	−13	−240	−253
September 1998–April 2001	23	38	61
September 1998–October 2001	40	−278	−237
September 1998–March 2002	216	−181	34
September 1998–October 2002	173	−371	−198
September 1998–April 2005	539	−193	346
September 1998–September 2006	863	−261	602

Table 3. *The average rate of volumetric change of bathymetry in each region (unit: 104 m^3).*

Area	Time Period		
	1999–2003	2003–2007	1999–2007
A1	13.9	12.1	16.6
A2	10.3	111.9	66.3
B1	16.5	27.6	24.9
B2	26.5	21.1	20.8
C1	17.7	7.0	9.9
C2	12.3	9.4	6.8
D1	−6.0	13.2	2.8
D2	−23.5	28.2	−2.3
E1	−14.2	−5.3	−9.2
E2	−2.5	3.7	−1.1
F1	−12.4	−11.7	−11.5
F2	−6.7	−11.4	−6.3

via the north-to-south sediment drift to the nearshore zone rather than to the offshore zone. When trapped sand in the north of Hsinchu Fishing Harbor was much enough to bypass the entrance of Hsinchu Fishing Harbor into the nearshore zone at Kangnan Coast. This explains the gradual mitigation of beach erosion at Kangnan Coast.

A SUGGESTED STRATEGY TO MITIGATE EROSION

The Second River Management Office of the Water Resources Agency, Ministry of Economic Affairs of Taiwan is in charge of costal affairs in northwestern Taiwan. The office took account of the beach erosion at Kangnan Coast. The office provided sequential funds for bathymetric measurements from 1998 to 2006 and a 3-year research project for mitigating erosion at Kangnan Coast. CECI Engineering Consultants, Inc., in association with some researchers took the project to solve the problem of beach erosion. Kangnan Coast was a wide beach in the past and served as a bathing beach from 1984 to 1990. A promenade park is located behind the coast to serve recreational and ecological functions. When severe beach erosion occurred, the bathing beach was closed in 1991, and then few people came to enjoy the beach.

The team workers set three guidelines for planning countermeasures to mitigate the beach erosion. The first guideline was coastal protection for preventing further beach erosion. The second was to provide a rich ecological environment. The third was to restore the recreational functions. The original 1300-m-long line of armored blocks was set on the shoreline to protect the coast. High blocks created a bad view and prevented people from going to the beach. Under these guidelines, a suggested countermeasure was proposed to set four submerged offshore breakwaters at a mean water depth of about 3–4 m. The position was about 100–180 m from the shoreline. Each breakwater was 200 m long, and the gap between two breakwaters was 100 m. When these breakwaters, associated with applicable artificial nourishment, are carried out, the beach forms salients behind them. The predicted salients were determined by the theory of McCormick (1993). The design sketch is shown in Figure 12.

The blocks of the original breakwaters on the shoreline were moved to offshore breakwaters as recycled materials. People on Kangnan Coast will not see concrete blocks on the sea any more since the submerged offshore breakwaters are settled. The detached breakwaters can protect the beach from wave impact and furthermore provide a good habitat for fish and marine algae. The water between breakwaters and salients became calm but still flowed with small speeds due to

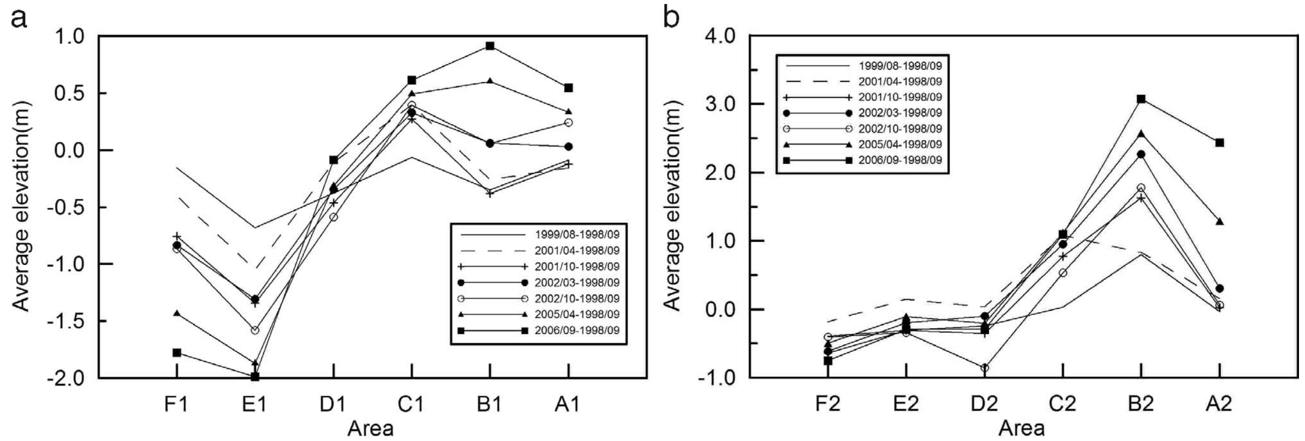

Figure 10. Variation of average elevation of the sea bottom in each region (a) nearshore and (b) offshore.

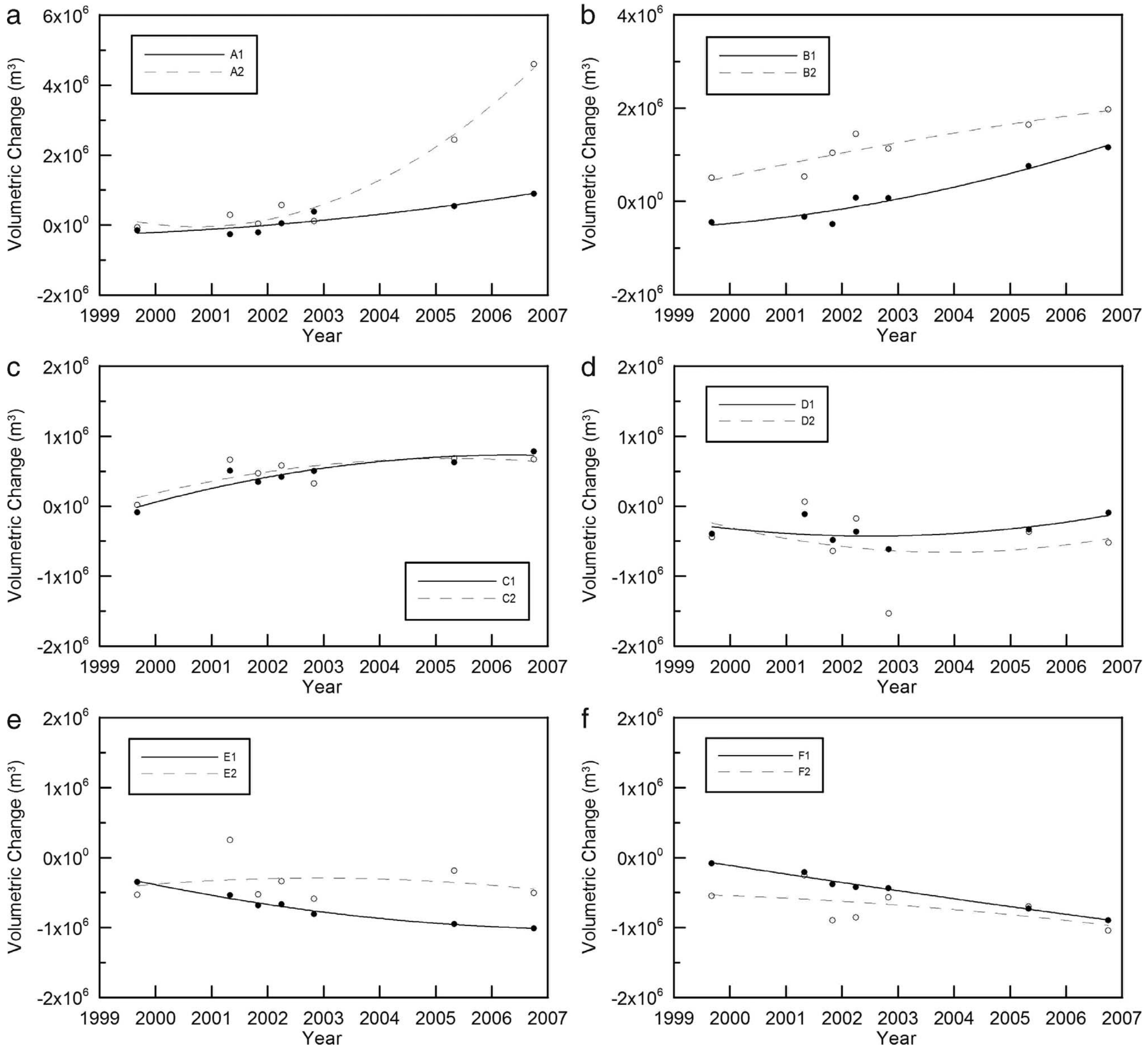

Figure 11. Volumetric changes in each cell. (a) Area A; (b) Area B; (c) Area C; (d) Area D; (e) Area E; (f) Area F.

the driving force of waves. Thus the predicted salients maintained the equilibrium for a long time. These salients widened the eroded beach and provided a good and safe place for recreational activity, such as strolling and swimming. The proposed shore protection simultaneously had multiple functions to conform to established guidelines.

CONCLUSIONS

This paper presented the shoreline evolution and bathymetrical variation at Kangnan Coast and investigated the possible structural effect of Hsinchu Fishing Harbor on beach erosion. Using the technique of edge detection from satellite images to subtract the shoreline from 1994 to 2007, the shoreline position in different years between Hsinchu Fishing Harbor and the Keya River indicated that the shoreline moved landwards at Kangnan Coast, indicating the beach was eroded there. Furthermore, using bathymetric measurements, bathymetric planform variation was studied quantitatively to show which area eroded or deposited. An alternative expression of average elevation of the sea bottom in distinct areas was used to determine the fact that Kangnan Coast has been in a state of beach erosion in the nearshore zone up to now. Through an analysis of volumetric change in a divided area, the beach erosion in the southern region of Hsinchu Fishing Harbor was found. That resulted from northern sand trapped by the long breakwater of Hsinchu

Figure 12. The design sketch. **For a color version of this figure, see page 395.**

Fishing Harbor. Sand was trapped in the north of Hsinchu Fishing Harbor until 2003. It was then transported past the entrance of the harbor into the nearshore zone at Kangnan Coast, causing beach erosion along Kangnan Coast. The structural effect of Hsinchu Fishing Harbor on beach erosion at Kangnan Coast was considerable.

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