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A historical perspective of river basin management in the Pearl River Delta of China

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Abstract

Three innovations in water and soil conservancy technology in the Pearl River Delta of South China, i.e., dike building, land reclamation, and dike–pond systems, were examined from a historical perspective. They were found to best reflect local farmers' efforts to cope with the challenges of various water disasters and to build a harmonious relationship with the changed environment. These technologies were critical to the agricultural success and sustainability over the past 2000 years, and reflected local farmers' wisdom in balancing land use and environmental conservation. Imprudent use of a new agricultural technology could damage the environment, and could disturb the human–environment relationship, as evidenced by the more frequent flooding that followed inappropriate dike building and premature reclamation. It is suggested that as the urbanization and industrialization process in the delta region continues, the kind of thinking that made the water and soil conservancy sustainable needs to be incorporated into the design of similar technologies for water use and river basin management today.

Keywords: Water and soil conservation technology; River basin management; Human–environment interactions; Land use; Pearl River Delta

1. Introduction

The Pearl River ("Zhujiang" in Chinese) Delta, China, is located between latitudes 21°40′N and 23°N, and longitudes 112°E and 113°20′E (Fig. 1). It is the third largest river delta in the nation (next to the Yangtze and Yellow River Deltas), with an area of 17,200 km^2. The delta has a subtropical climate with an average annual temperature between 21 and 23 °C, and an average precipitation from 1600 to 2600 mm. Because of the impact of the East Asian Moonsoonal circulation, about 80% of the rainfall comes in the period of April–September with a concentration in the months of May–July, when flooding is prone to occur (Ditu Chubanshe, 1977). Another hazard is typhoons, which occur most frequently from June to October. Since 1978, when the economic reform and open-door policy was implemented, a dramatic social, economic, and spatial transformation has occurred in China. This is particularly true in the coastal regions such as the Pearl River Delta, where economic growth has exhibited a two-digit rate over the past two decades and which has appeared as one of the most advanced regions in the nation (Xu and Li, 1990; Lin, 1997; Weng, 1998). The urbanization process has been speeded up due to accelerated economic development. Massive parcels of agricultural land are disappearing each year for urban or related uses. Because of the lack of appropriate land use planning and measures for sustainable development, rampant urban growth has created severe environmental consequences (Weng, 2001a, b, 2002). The field surveys the author conducted in the summers of 1998 and 2001, sponsored by the National Geographic Society, witnessed the deteriorating environment. Fieldworks were carried out in different parts of the delta to provide "ground truth" data on current land use and land cover, and first-hand data on environmental changes induced by urbanization. Interviews with city planning officers, visits to contaminated sites, and literature and document surveys were also conducted.

Nothing was more important than water in shaping the civilization in the delta over the past 2000 years. The fertile alluvial deposits, the subtropical climate, and millenniums

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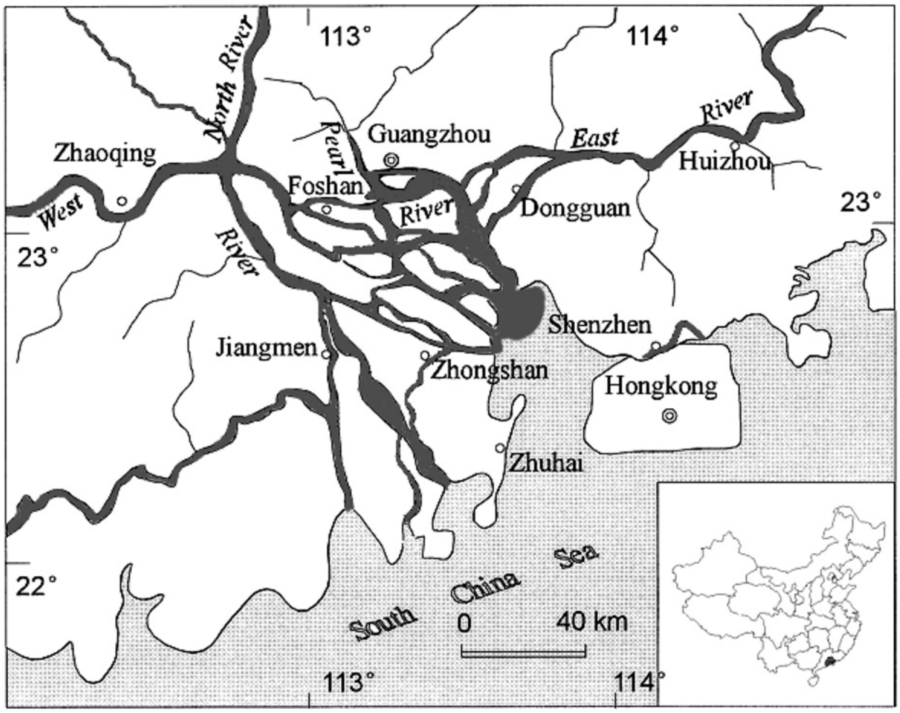

Fig. 1. Study area—Pearl River Delta of the southern China (after Zhu et al., 2002).

of exploitation have nurtured the region into one of the most diversified agricultural areas in China. Its paddy cultivation, sugarcane and fruit horticulture, and dike–pond agriculture–aquaculture have long been known to the nation and to the world. Innovations in water and soil conservation technology were crucial to these agricultural accomplishments. Recent environmental, socioeconomic, and demographic changes in the delta region urge us to re-examine the significance of these technological innovations from a historical perspective, in order to understand better the emerging relationship between the people and the environment.

The objective of this paper is to examine the history of the formation and development of three water and soil conservancy technologies, namely, dike building, land reclamation, and dike–pond systems, and their impacts on the delta's evolution in the Holocene period. Field survey data were applied in addition to the literature and documents in government gazetteers (*di fang zhi*), archeological discovery, agricultural history, geology, and geography. These data and materials were analyzed to demonstrate that the innovation of dike building, land reclamation, and dike–pond agriculture–aquaculture systems was a result of the dynamics of people and the environment and their interplay in the Holocene era. A major argument is that these water and soil conservation technologies were elegant in that they showed a great understanding of the people–environment interactions, and provided a good lesson for today's water resources and river basin management in the delta as well as in other areas of similar settings in the world.

2. The geomorphological setting and drainage system

Geomorphologically, the delta consists of three subdeltas: the West River (Xijiang in Chinese), North River (Beijiang in Chinese), and East River (Dongjiang in Chinese) Deltas. These subdeltas were formed by sediments, which originated approximately 40 thousand years ago (Department of Geography, Zhongshan University, 1988). There are hills surrounding the delta to the east, west, and north that have an average of 500 m above mean sea level (m.s.l.). Inside the delta itself, there are over 160 hills and terraces located at heights between 100 and 300 m above m.s.l. (Huang et al., 1982). They occupy one fifth of the total area, and are remnants of former islands. The hills are concentrated in the south, and are erosional remains of granitic rock intruded during the Yenshanian Orogeny. The terraces of 20–40 m in height are located in the north, extending from Panyu to Guangzhou, and are the results of river dissection. The plains of the delta can be categorized into four types based on their formation, height, and age: high plain, low plain, waterlogged land, and dike–pond land (Huang et al., 1982). Located in the central and northern part of the delta, the high plain is the oldest, and has a normal elevation of 0.5–0.9 m above m.s.l. The low plain is a more recently reclaimed plain in the coastal areas with an elevation between 0.7 and 0.9 m below m.s.l. The two types of plains combine to account for 60.8% of the total area. The waterlogged land is restricted to the northwestern part at the confluence of the West River and the North River, and has an average height of 0.4–0.7 m below m.s.l. Also located in this area is the dike–pond land, an artificially reclaimed flood-prone low-lying land. The two types of low-lying land occupy 4.8% and 14.4% of the area.

The drainage system is well-developed because of abundant rainfall. The subtropical location of the delta and the monsoonal circulation of Eastern China give rise to a total annual mean runoff of 341.2 billion m^3. The West River contributes the most (72.10%), followed by the North River (14.13%) and the East River (9.14%). The annual mean discharge for the West River ranges from 848 to 48,800 m^3/s, for the North River, from 139 to 14,900 m^3/s, and for the East River, from 31.4 to 12,800 m^3/s (Department of Geography, Zhongshan University, 1988). The load discharge of the river system is large with an annual silt discharge of 83.36 million tons, of which the West River is the major contributor (87%) (Huang et al., 1982). Of the total silt discharge, 20% is deposited in the delta proper while 80% enters the sea, thus causing seaward extension in the mouth region of the Pearl River at a rate of 40 m per year (Gong and Chen, 1964). The rivers of the system arrive at the South China Sea through eight estuaries ("gates" in Chinese), namely, Humen, Jiaomen, Hongqili, Hengmen, Modaomen, Jitimen, Hutiaomen, and Yamen from north to south. Perhaps the most distinguishing characteristic of the river system is its numerous tributaries. There are over 100 main branches, with a total length of over 1700 km. The drainage density in the West-North River Delta is 0.81 km/sq. km, compared to 0.88 km/sq. km in the East River Delta. The average channel width–depth ratio is 1.8–11.5. However, 68% of the channels in the Pearl River Delta have a ratio of less than 6.0, which indicates that most river channels are stable. The average channel gradient of the major rivers is low: 0.0023% in the West River, 0.0037% in the North River, and 0.026% in the East River.

Geologically, the delta region was originally part of the ancient Cathaysian massif in southeastern China, which is the western remnant of a massif raised by folding in the Sinian and existed throughout the Paleozoic (Zhao, 1994). Several granitic intrusions and a batholith were emplaced in the Mesozoic era. Later, a basin was formed in the northern and central part of the present delta as a result of faulting. The basin was then filled with a series of continental deposits, which is the so-called Red Rock system. The rock system was eroded throughout the Tertiary Period into a peneplain, leaving behind only some residual granitic hills (Department of Geography, Zhongshan University, 1988). At the end of the Tertiary Period, subsidence of the coastline in South China resulted in the formation of a funnel-shaped Pearl River estuary (Department of Geography, Zhongshan University, 1988). During the Quaternary, a large amount of silt was deposited in the mouths of the West, North, and East Rivers. These eventually coalesced to form the composite Pearl River Delta. The NE–SW, NW–SE, and E–W faults intersected to form the characteristics of the geomorphologic feature. The geological structural units were arranged into a chessboard pattern (Department of Geography, Zhongshan University, 1988).

The coastline was dynamic in the Holocene and had a general trend of extending southeastward in the West and North River Deltas and westward in the East River Delta (Huang et al., 1982) (Fig. 2). In the Middle Neolithic Age (6500–5200 years B.P.), the vast majority of the delta region was submerged under the ocean. At an early stage of the Late Neolithic Age (5200–4200 years B.P.), there was a substantial decline in the sea level (Li et al., 1991). The coastline of the West and North River Deltas was located along the line that linked Huangpu, Guangzhou, Shijie, Foshan, Xiqiao, and Jiujiang, while in the East River Delta it extended between Shilong and Dongguan. During the Qin (221–207 BC) and Han Dynasties (207 BC–220 AD), there was a substantial fall in sea level (by as much as 4–5 m), and the areal extent of the delta became larger. The coastline in the West and North River Deltas moved southeast to Chenchun, Daliang, and Xingtan of central Shunde County, whereas the coastline in the East River Delta moved to near Guangcheng of Dongguan County. During the Sui (581–618 AD) and Tang (618–907 AD) Dynasties, the coastline further advanced to the southern Shunde County and to the west of Guangcheng. From the Song (960–1279 AD) to Yuan (1279–1368 AD) Dynasties, a large number of swamps were filled by sand and loam. Many islands were joined with the mainland, conducive to an accelerated extension. The coastline extended to a line linking Miaotou, Tanzhou, Xiaolan, and Lile in the West and North River Deltas, and to Daojiao and Houjie in the East River Delta (Fig. 2). During the Ming Dynasty (1368–1644 AD), both coastlines continued to extend, reaching the farthest south at Shiqi of Zhongshan County in the West and North River Deltas and reaching the farthest west at Machong in the East River Delta. During the Qing Dynasty (1644–1911 AD), the rate of sand accumulation increased, so that the tributaries were completely silted up, and the Shiziyang Ocean became narrower. The coastline extended to Tanzhou in the West and North River Deltas and to the west of Zhangpeng in the East River Delta. By the end of the Qing Dynasty, the eight major estuaries were formed. The delta's seaward extension seemed to have gained momentum in the Holocene period (Table 1) (Huang et al., 1982). The West River Delta grew more rapidly than the North River Delta, while the East River Delta grew more slowly. Over the past 100 years, the delta continued to extend seaward, most prominently at Wanqingsha region in the east and Denglongsha in the south of the West and North River Deltas. The most recent (in the 1980s and 1990s) seaward extension rate exceeds 100 m per annum (Li et al., 2002). Although factors such as the size of and the land cover of the catchment area may explain some of the differences in the extension rate, these extensions can be better perceived with regard to human activities, especially to dike building and land reclamation activities.

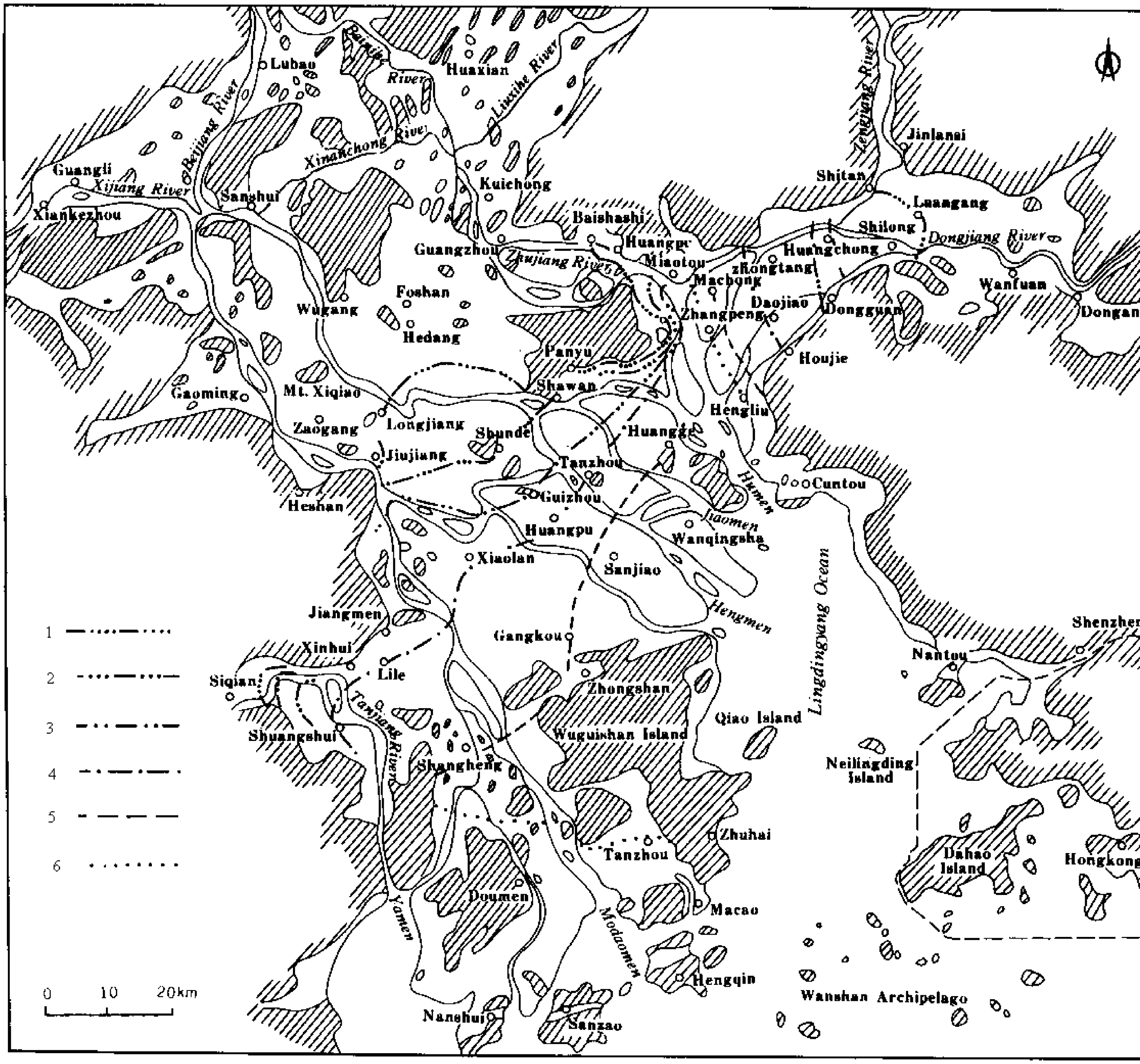

Fig. 2. Coastline evolution in the Holocene (after Weng, 2000; *source*: Huang et al., 1982).

3. Dike building and delta evolution

3.1. Increased flooding and dike building

Agricultural development in the delta region was strongly associated with dike building technology. The dikes were initially built to prevent low-lying lands from being flooded. Excess water could be drained from the enclosed fields by using waterwheels (for example), thus improving water conservancy and agricultural productivity. The first dike was built during the Tang Dynasty (Zeng and Huang, 1987), in response to a sharp increase in flood frequency. Statistics of flood frequency during different dynasties are shown in Table 2.

Prior to the Tang Dynasty, the population was sparse, so people were able to select higher ground for agricultural development. However, the population density increased rapidly by the end of the Tang Dynasty because of accelerating southward population migration. Rapid population expansion made it impossible for the higher grounds alone to produce sufficient food. The low-lying delta had to be brought under cultivation. Dike building thus became necessary. As more dikes were built, enclosed fields grew. River channels became longer. With the reduction in channel gradients, rivers silted up quickly. Draining off floodwater required a longer time. The human activities had apparently altered the people–environment relationship (Weng, 2000).

Table 1
Estimated extension rates of the three sub-deltas in the Pearl River Delta (*source*: Huang et al., 1982)

Time period	Number of years	North River Delta		West River main stream		East River Delta	
		Total extension length (km)	Average extension rate (m/a)	Total extension length (km)	Average extension rate (m/a)	Total extension length (km)	Average extension rate (m/a)
Neolithic to Qin-han Dynasties	3800	33.0	8.7	—	—	23.0	6.1
Qin-han to early Tang Dynasty	837	8.5	10.2	—	—	7.0	8.4
Tang to Song early dynasty	342	6.4	18.7	23.5	68.7	5.0	14.6
Song to early Ming Dynasty	408	8.0	19.6	18.5	45.3	8.0	19.6
Ming to early Qing Dynasty	276	7.2	26.9	12.6	45.7	4.2	15.2
Qing Dynasty to 1960 AD	316	13.6	43.0	16.0	50.6	2.6	8.2

Table 2
A statistics of floods in the Pearl River Delta (*source*: Yuan, 1992)

County	Song dynasty (960–1279)	Yuan dynasty (1279–1368)	Ming dynasty (1368–1644)	Qing dynasty (1644–1911)	Republic of China (1911–1949)	P.R. China (1949–)	Data period
Baoan 1981	—	—	—	2	1	4	1660–1981
Dongguan 1987	1	3	18	20	16	12	812–1987
Guangzhou 1983	—	—	5	9	3	7	975–1983
Heshan 1983	—	—	11	31	5	5	1422–1983
Nanhai	—	—	26	56	16	12	810–1985
Panyu	—	—	3	12	5	6	996–1985
Sanshui 1915	—	—	12	18	2	—	1535–1915
Shunde 1983	—	—	16	11	36	11	1448–1983
Xinhui 1985	—	—	2	7	9	8	1516–1985
Zhongshan 1987	—	1	9	5	8	6	1199–1987

The Song and the Yuan Dynasties mark an era when people launched large-scale dike building projects. A total of 28 dikes were built during the Song Dynasty, with a total length of 220 km, which can safeguard fields up to 162,145 ha (Zhujiang Delta Agricultural History Committee (ZAHC), 1976). During the Yuan Dynasty, 34 dikes were built, which extended 168 km in length and safeguarded a total area of 15,547 ha (Zhujiang Delta Agricultural History Committee (ZAHC), 1976). These dikes were distributed along the banks of the lower West, North, and East Rivers and their branches (Fig. 3). Because river channels were relatively wide and floods were moderate, the dikes built during this period of time were low (usually 1–1.7 m), and were made of mainly dirt rather than stones. The dikes were rarely linked together.

From the Ming to the mid-Qing Dynasty, the activities of dike building and land reclamation intensified as the population grew. Increased use of marshes along riverbanks and islets in the estuaries caused the river channels to prolong and narrow. River channels were silted easily, so that the size of floods became larger and the duration longer. Consequently, there was a notable increase in flooding frequency in the Ming Dynasty. Gaoyao County in the lower reaches of the West River was an extreme case. There were 41 floods during 276 years of the Ming Dynasty, averaging 1 flood per 6.73 years (Weng, 1994). For the whole delta, 44 floods were recorded to have inundated at least 3 counties, averaging 1 flood every 6.27 years (Zhujiang Water Conservancy Committee (ZWCC), 1990). During the Qing Dynasty, flooding became even more frequent. From 1736 to 1839 AD, there were 30 floods in 103 years, averaging 1 flood per 3.43 years (Zhujiang Water Conservancy Committee (ZWCC), 1990). The impacts of these floods were not constrained to the main streams in the central delta but also reached the tributaries in the estuaries. To protect the land from flooding and to ensure high agricultural productivity, 181 dikes were built during the Ming Dynasty. These dikes produced a total length of 735 km, twice as long as those built in both the Song and Yuan Dynasties. The Ming's dikes were found mainly in the following three locations (Fig. 4): (1) along the main stream of the West River below Sanrong and its tributaries (including Xinxing, Hungdongsui, and Gaoming Rivers); (2) along the main stream of the North River below the Feilai Gorge and its tributaries (including Suijiang, Lubaochong, and Xinanchong Rivers); and (3) in the intersectional area of the Xisui and Beisui Rivers and in the central and western parts of the delta below Sixianjiao. In contrast, few dikes were built in the East River Delta during this period. The trend of massive construction of dikes continued in the Qing Dynasty, when 190 dikes were built with a total length of 774 km. Diking

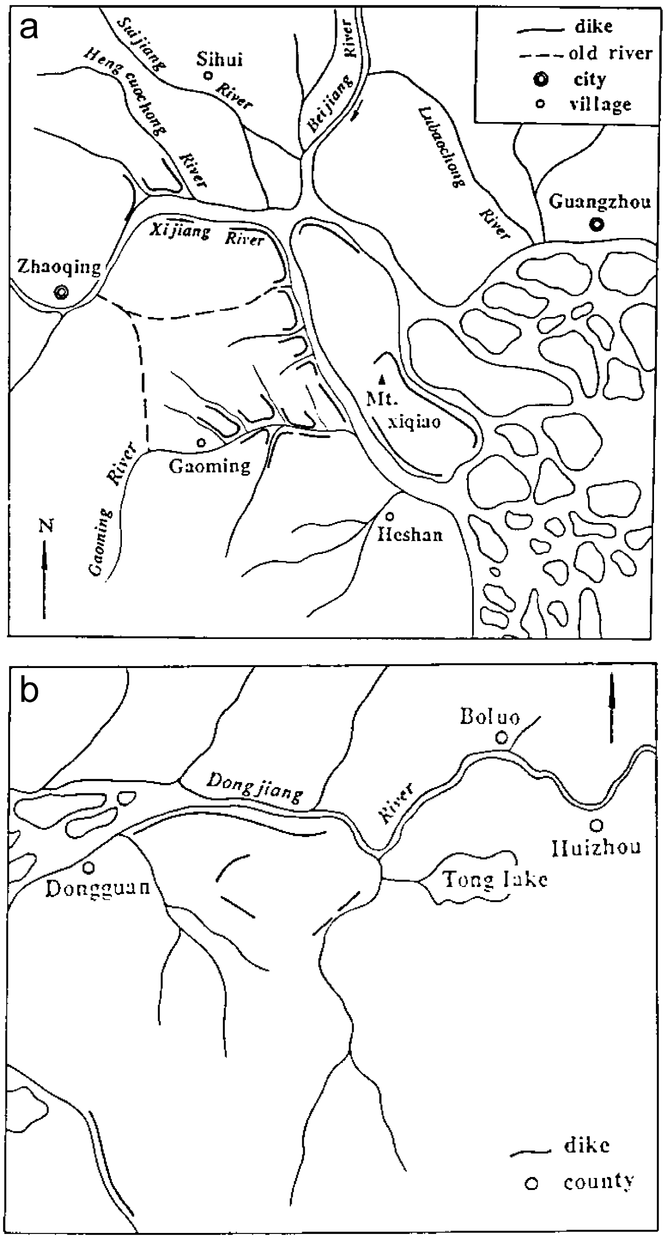

Fig. 3. Distribution of dikes built in the Song and Yuan Dynasties (after Weng, 2000; *source*: Zhujiang Water Conservancy Committee, 1990). (a) In the West and North River Deltas; and (b) in the East River Delta.

activities continued to spread southward in the West and North River Deltas, approaching the estuaries area. Dikes also appeared sporadically in the lower reaches of the East River Delta above Shilong.

The period from the late Qing Dynasty to 1948 witnessed the most frequent and the most serious flooding in history. Not only did the population explosion and economic growth demand more farmlands, but also the landlords' greed for more profit contributed to premature land reclamation and diking (Situ, 1986). The lack of governmental rules and carelessness with regard to the environmental consequences of farmland development and land utilization led to a vicious circle in the relationship between dike building and flooding. As more dikes were built, more floods occurred. Therefore, many old dikes needed to be reinforced, raised, and linked together. The dikes built during this period were concentrated in the waterway area, largely in the counties of Shunde, Xinhui, Zhongshan, Dongguan, and their coastal areas (Fig. 5). Dikes were further built in the coastal area of Panyu County and near Modaomen and Hengmen Gates. Indeed, by the end of this period, dikes could be found everywhere in the delta except for a few places such as the Tan River Delta, southern Panyu, and western Dong River Delta, where fields were irrigated with tidewater.

3.2. *Environmental impacts of dike building*

Dike building was a response to local farmers' acceptance of living in a wetland environment with frequent water disasters. However, this technology facilitated the evolution of an aqueous environment to a terrestrial one, and raised the elevation of the delta. Furthermore, dike building speeded up the process of sedimentation, leading to the formation of a modern drainage system and the land's seaward extension.

A major impact of dike building is the fastening of the river channels. Due to the nature of the composite delta and abundant rainfall, the Pearl River Delta is characterized by multiple river convergence and numerous tributaries. The major rivers tended to bifurcate and meandered after arriving at the delta proper owing to a reduced gradient. Many estuaries were created but constantly changed their positions. Small and isolated shoals and islets in the estuaries continued to emerge above the water. The building of dikes not only fastened the river channels, but also simplified the drainage system by silting up small tributaries and consolidating large ones. The drainage density thus decreased. These observations are verified by the fact that there were fewer river channels in the upper reach of the West and North River, while more in the lower reach. The upper reach has a longer history of dike building than the lower reach does. The majority of dikes in the lower reach were constructed after the Qing Dynasty. The process of bifurcation and meandering is still dominant today in some lower reach areas.

Dike building also promotes the seaward extension of the delta. Because river channels were positioned after building dikes, less silt discharge was deposited in the delta proper while more entered the sea. The sedimentation process in the estuaries was therefore speeded up, and more and more shoals and islets emerged above the water and were linked together. All of these geologic processes helped to move the coastline forward. Table 1 shows that the extension rate dramatically increased since the Tang Dynasty. The extension rate was 10 m per year before the Tang Dynasty, while it was 20 m after the Song and Ming Dynasties in all the subdeltas. This sharp contrast may be considered to be the result of sealevel decline from the Qin to the Tang Dynasty (Li et al., 1991), since a lower sea level

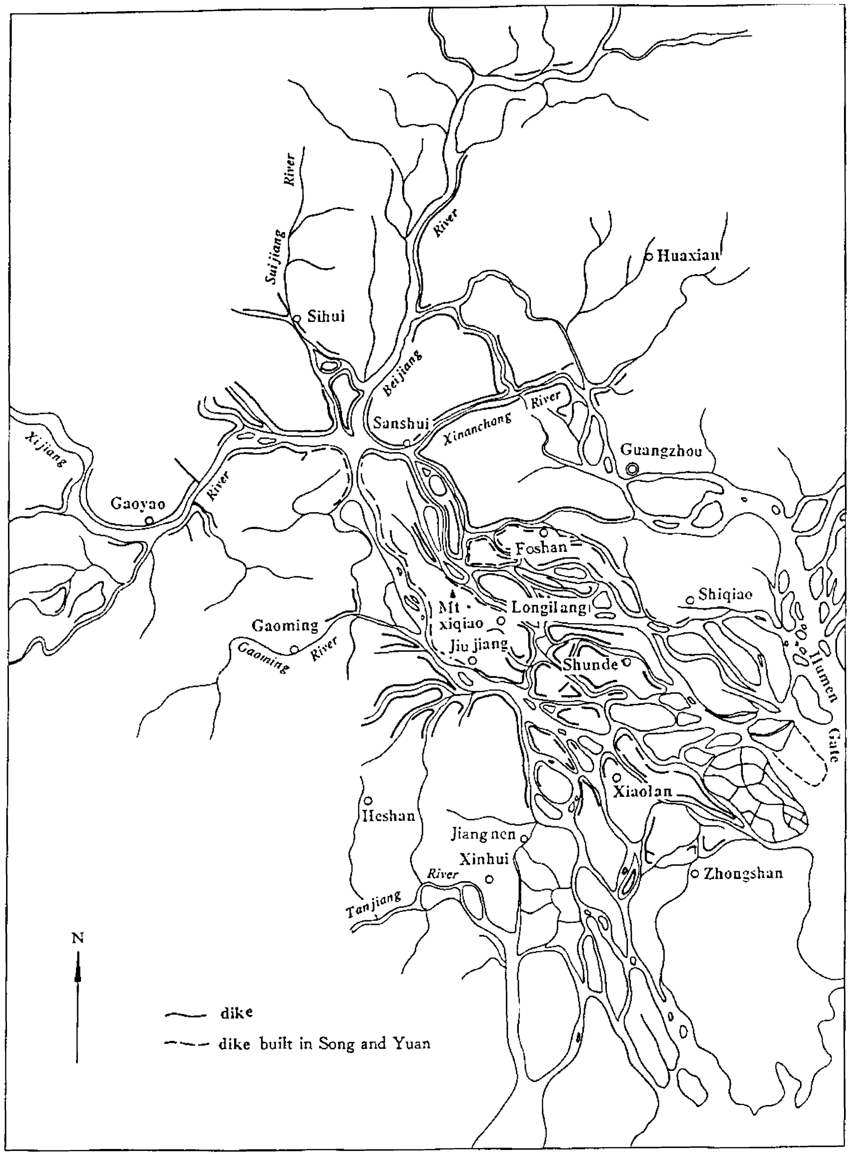

Fig. 4. Distribution of dikes built between the Ming and mid-Qing Dynasties in the West and North River Deltas (after Weng, 2000; *source*: Zhujiang Water Conservancy Committee, 1990).

tends to promote fluvial erosion and to slow down the seaward extension. However, the most important factor in the accelerated extension during the Song and the Yuan Dynasties was the large-scale dike building projects. The delta extended 33.3 m per year in the West and North River Delta and 19.6 m in the East River Delta, 2–4 times faster than that in the Tang Dynasty.

The human impact on the seaward extension is illustrated vividly at Wanqingsha in the Lingding Bay. The Lingding Bay was initially part of a sea bay in the Middle Holocene Period, but it is getting shallower due to the large amount of silt from the West and North Rivers. It is estimated that 40% of its water surface has been silted up, and will be completely silted up and be changed into a river channel after 700 years (Li et al., 1991). Fig. 6 shows the coastline positions at different times. The average rate of extension can be calculated for each period according to these positions. The results indicate that the rate was 55.6 m per year from AD 1830 to 1883. This rate had increased to 60.3 m from AD 1883 to 1936 and further to 91.2 m from AD 1950 to 1956.

Rice cultivation, in particular, could not succeed without dike building technology. Dike building facilitated the formation of paddy fields, and thus laid the foundation for propagation of rice cultivation technology. Furthermore, dike building changed the water, heat, and soil conditions through controlling the ground water table. The changes in the physical environment improved farming conditions, which, in turn, made it possible to gradually improve farming methods. The cropping pattern was one crop per year before dike building. Slash-and-burn agriculture was practiced on the high grounds, while the method of fire and

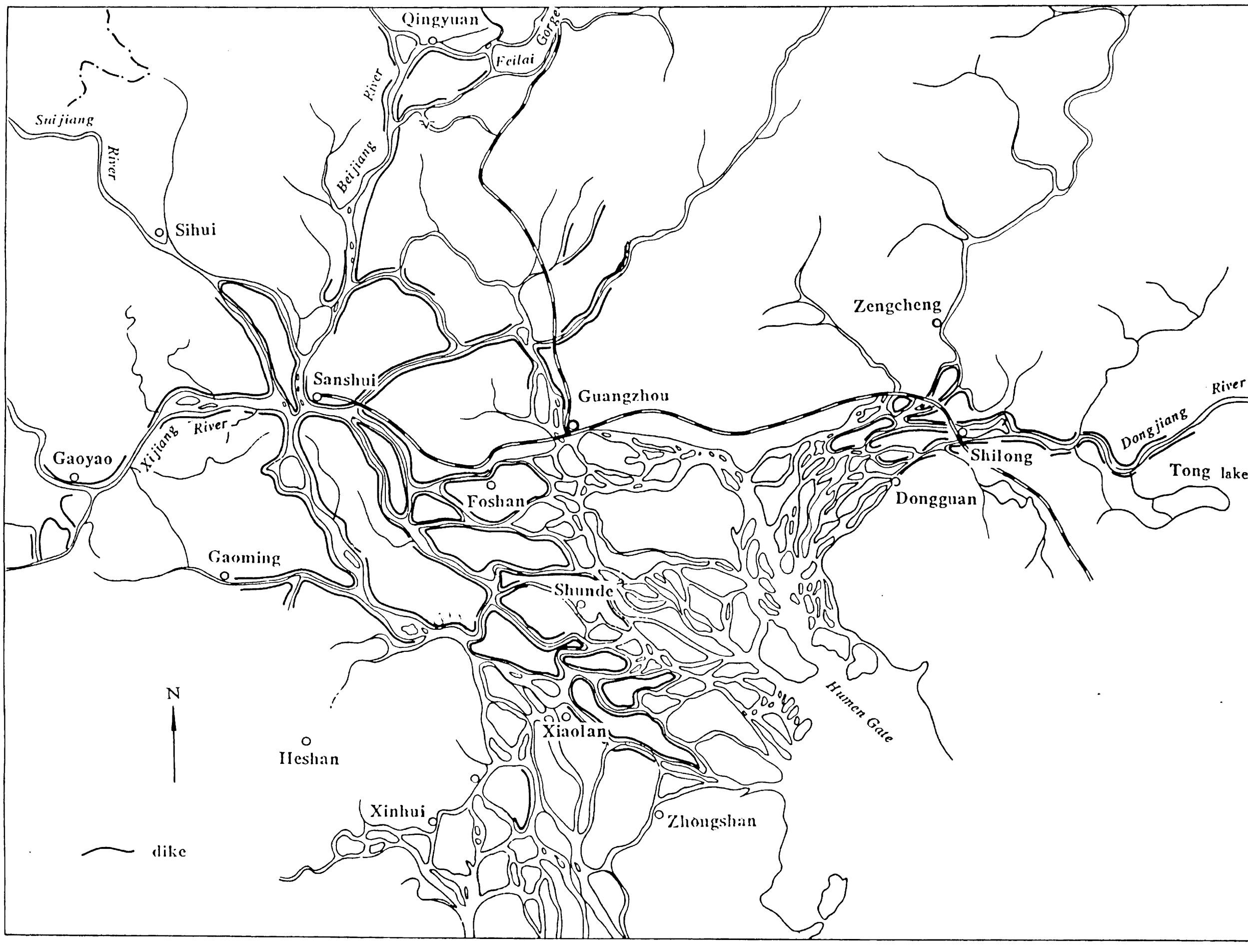

Fig. 5. Distribution of dikes in AD 1948 (after Weng, 2000. *source*: Zhujiang Water Conservancy Committee (ZWCC), 1990).

water farming ("*huo geng shui ru*") was used in wetland environments (Yu, 1988). Rice cultivation required eliminating the grass with fire before sowing seeds, and killing the weeds by flooding the fields. This low productivity but labor-saving method was popular in southern China, because it was suited to the wetland environments (Peng, 1987). The single-cropping system continued in some parts of Guangzhou, Panyu, Shunde, Xinhui, and Zhongshan until the early Qing Dynasty. This cropping system was particularly popular in the sand fields, where water conservancy facilities were poorly developed. Only after dikes had been built could a double-cropping system be established. By the dawn of the twentieth century, a variety of triple-cropping patterns had been developed. The predominant pattern was two crops of rice and a dry food/cash crop in the winter such as vegetable, fruit, sugar cane, or other cash crops (Zhujiang Delta Agricultural History Committee (ZAHC), 1976). It should be noted that the cropping patterns in the delta have undergone a great change since 1978. The increased commercialization of agriculture resulted in the production of less grains but more economic and cash crops. All-season, high-profit agricultural products, including vegetables, fruit, flowers, seafood, and poultry, are grown on a large scale.

A major negative impact of dike building is a sharp increase in flood frequency. As more dikes were built, enclosed fields grew. River channels became longer and shallower. With the reduction in channel gradients, rivers became easily silted up. Draining off floodwater slowed down, and the water table rose. Clearly, human activities have adversely altered the environment. For the 320 years of the Song Dynasty, 9 floods were recorded, yielding a frequency of 36 years (Zhujiang Delta Agricultural History Committee (ZAHC), 1976). The flood frequency drastically increased to every 6 years during the Yuan Dynasty, every 2 years in the Ming and early Qing Dynasties, and to every other year in the late Qing Dynasty (Zhujiang Delta Agricultural History Committee (ZAHC), 1976). Since the foundation of the People's Republic of China in 1949, there has been flooding every year. Table 2 breaks down the statistics of floods by county by dynasty. Although these figures (derived from *di fang zhi*) are not as accurate as expected, an increasing trend of flood frequency can be seen. Two recent floods, occurring in June 1994 and June 1998, were both characterized as nearly 100-year floods and brought about great economic loss (Wang et al., 2005; Qian, 2005).

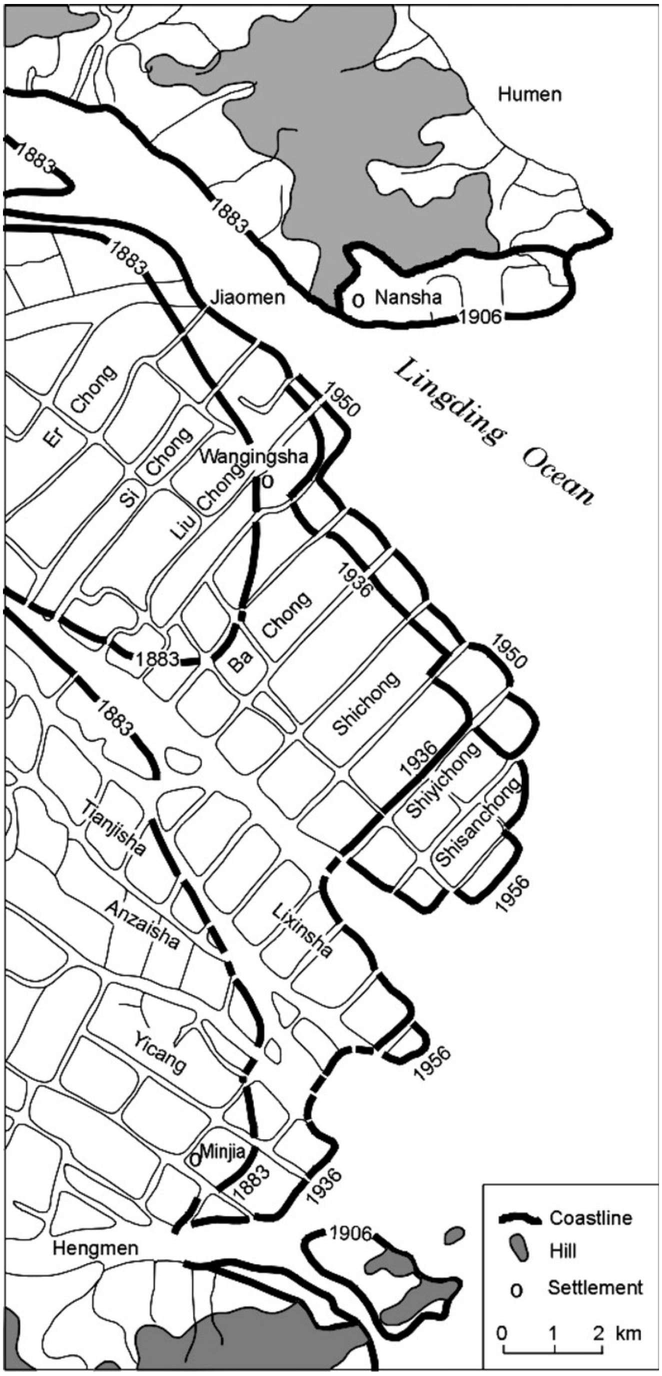

Fig. 6. Coastline positions in *Wanqingsha* in different times (*source*: Zeng and Huang, 1987).

The water table rose gradually, especially in the estuary areas, as a result of dike building. The water table of the delta had a notable rise in the 1970s, but became stable in the 1980s (He, 1986). The average level of the water table in the wet season in the 1970s was higher than that in the 1960s by 10–15 cm in the West River estuaries, by 3–12 cm in the North River estuaries, and by 5–8 cm in the East River estuaries. The differences were smaller in the dry season. Between the 1960s and the 1970s, the difference was 6–20, 2–8, and 2–5 cm in the three estuary areas, respectively. These rises may be attributed to dike linking and dam building projects, which were launched in the 1950s and peaked in the 1960s and 1970s (He, 1986). Although the water table showed signs of becoming stable after the 1980s, it could rise further if dike building and land reclamation activities continue. Because of the rise in the water table, many areas now suffer water logging every year. Our 1998 field survey (in June) observed a 100-year flood and water logging up to one foot in the city streets of Zhongshan during a storm. The June 1994 flood caused an economic loss of about 94 million US dollars in the Zhongshun area alone (Wang et al., 2005)

4. Land reclamation and seaward extension

4.1. History of land reclamation

Sandy fields, located between the coast and the inland, are a special type of farmland that was reclaimed from sea beaches or river marshes. In the West and North River Deltas, sandy fields are distributed near the line linking Huangpu, Shiqiao, Longjiang, and Jiangmen. The formation of sandy fields is closely related to two factors: the extension of the delta by the deposition of sediments, and the development of land reclamation technology.

From the Ming to Qing Dynasties, the delta region experienced a population increase as a consequence of the southward shift of the national economic center. The average population density jumped from 5 persons/km^2 in the Ming Dynasty to 50–200 persons/km^2 in the Qing Dynasty (Zhujiang Delta Agricultural History Committee (ZAHC), 1976). As more migrants arrived, deforestation in the upper and middle reaches of the West, North, and East Rivers accelerated. Increased soil erosion hastened sedimentation in the rivers and the extension of the coastline. Most tributaries of the West and North Rivers became silted, and a large amount of sand accumulated in the southern Panyu, northern Zhongshan, and eastern Xinhui, with the coastline extending nearly to today's Modao Gate. Many islands, including Wuguishan, Huangyangshan, Zugaoling, and Nansha Islands, were joined with the mainland. The East River Delta had basically formed. Numerous beaches began to emerge along the coast in Panyu, Shunde, Dongguan, Xinhui, and Xianshan Counties (i.e., today's Zhongshan, Doumen, and Zhuhai). The hope for reclaiming land from the sea attracted even more settlers. Not only did the population explosion and economic growth increase the demand for farmland, but also the landlords' greed for more profit and local governments' interest favored land reclamation from the sea (Weng, 2000).

During the Ming Dynasty, land reclamation was largely concentrated in southern Panyu County, southeastern Shunde County, northern Xianshan County, southeastern Xinhui County, as well as in some estuary areas of southwestern Dongguan County. Two distinct stages can be identified based on the type of beach reclaimed. While the reclamation during the early Ming used mostly older beaches, during the middle and late Ming reclamation started to make use of newly formed beaches (Zhujiang Water Conservancy Committee (ZWCC), 1990). Such measures as planting reeds and throwing larger numbers of stones and boulders into water to slow the velocity of water flow were widely used to promote the deposition of sediments and formation of beaches. The most prominent example was in Xianshan County, where local farmers turned the entire Shiqi Bay into cultivated land through reclamation. The total reclaimed area was over 10,000 *qing* (66,667 ha) in the Ming Dynasty (Zhujiang Water Conservancy Committee (ZWCC), 1990).

The Qing Dynasty was a period of great development of land reclamation. With continued and accelerated sediment accumulation, more beaches emerged. The majority of land reclamation took place in the river mouths and along the coast near Modaomen, Jiaomen, and Hengmen. A new technique developed in this period was the exploitation and reclamation of pre-emerging beaches. Measures to trap silt and sand such as planting reeds and throwing stones and boulders into the shallow water became a common practice in the reclamation. Due to concern that unregulated reclamation of land would lead to a complete silting up of navigation channels at sea and flooding of the delta proper, the central government issued several bans on reclaiming in the river mouths. However, the yearning for more agricultural land always outweighed these bans. Between 1753 and 1874 AD (a period in the Qing Dynasty), at least 13,000 *qing* (86,667 ha) of land was reclaimed in Guangdong Province, most of which occurred in the Pearl River Delta (Zhujiang Water Conservancy Committee (ZWCC), 1990). The intensity of land reclamation activity was well illustrated in the Wanqingsha region, where some 600 *qing* (4000 ha) of land were reclaimed in 100 years (Fig. 6).

4.2. Environmental implications of land reclamation

The success of extensive land reclamation from marshes and sea beaches relied on the proper use of water conservancy technologies. Local farmers developed two reclamation methods through experimentation: One was cultivation before building dikes, and the other was building dikes before cultivation. The first approach was designed to reclaim recently emerged sand bars, shoals, or river islands, followed by irrigating the fields with de-salted tidewater. This approach had one disadvantage, i.e., the inability to protect crops from the damage of flooding. The second approach was more popular and environmentally conservative. The entire three-stage reclamation process took approximately 4–10 years (Zhujiang Delta Agricultural History Committee (ZAHC), 1976; Zhujiang Water Conservancy Committee (ZWCC), 1990): (1) the rock-deposit stage, when the water was about 0.2–0.3 m deep; (2) the grass-growing stage taking place 1–5 years later, when reeds were planted to speed up trapping of sediments; and (3) the solid-dirt dike building stage, 3–5 years after the second stage, when the land was more frequently exposed. This approach to reclamation reflects local farmer's awareness of environmental conservation in agricultural land uses.

No matter which method of land reclamation was adopted, the importance of identifying four stages of sedimentation was emphasized, which would eventually lead to the formation of fields. They were: (1) the "fish-swimming" stage, when the depth of water was 2–3 m deep at low tide; (2) the "scull-touching bottom" stage, when water depth was 1–1.5 m deep; (3) the "crane-standing" stage, when water further deceased to about 0.2–0.3 m; and (4) the "grass-spreading" stage, when most of the beaches were exposed at low tide and waterweeds start to grow. Figs. 7–9 show different stages of the reclamation process at Wanqingsha region. These observations indicate that local farmers became aware of the significance of environmental protection (Lo, 1996).

Sandy fields are a result of land reclamation, and have unique environmental characteristics and agricultural uses.

Fig. 7. The fish swimming/scull touching bottom stage of the reclamation.

Fig. 8. The crane standing/grass spreading stage of the reclamation.

Fig. 9. Sugar cane cultivation in the newly reclaimed land.

These fields are normally flat and weaved with a dense network of waterways. The drainage density in the West and North River Deltas is 0.81, and 0.88 km/sq. km in the East River Delta (Huang et al., 1982). Most sandy fields may be irrigated with tidewater. Local farmers customarily classify the sandy fields into three types, according to elevation with respect to the sea level and irrigation conditions. The high sandy fields, with an elevation of 0.7 m above m.s.l., are irrigated by tidewater less than 12 days per month. The medium sandy fields with an elevation between −0.2 and 0.7 m have 12–20 irrigation days per month. The low sandy fields, with an elevation between −0.8 and 0.2 m, are irrigated for at least 20 days by tidewater. The soils in low sandy fields tend to have a high ground water table, and are much less useful for agriculture than those in high and medium sandy fields.

Reclaiming land prematurely results in a longer period of water logging and unusable farmland, and thus increases the likelihood of flooding. On the other hand, postponing reclamation time could harm farming because over-accumulation of sediments would make self-irrigation by tidewater difficult. A thorough understanding of these technologies is critical in keeping the ecological balance of the natural environment while pursuing economic goods. Over-reclamation in the Pearl River estuary has caused many severe environmental problems (Li et al., 2002; Chen et al., 2005; Qian, 2005; Wang et al., 2005). Chen et al. (2005) indicate that the Pearl River estuary was continuously reclaimed from 1978 to 1998, resulting in decline of deep-water channels and bays. The rate of reclamation in the 1990s was 1.18 times faster than in the 1980s. The rapid shrinkage of Lingding Bay is due to reclamation of shoals and beaches and loss of waterways, which is often done by silting up lateral waterways that connect deep-water channels (Li et al., 2002). These activities have had a destructive impact on the delta's aquatic ecosystem and have raised the water table of Guangzhou–Huangpu port, which could lead to greater flooding in the delta (Chen et al., 2005). In addition, prolonged river channels and bifurcation can reduce the carrying capacity for water and silt discharge, leading to silting up of the river channels and raising of the water table. These changes in drainage network and hydraulic conditions present a great threat to flood prevention, water logging discharge, irrigation, and coastal ecosystems (Xu, 2002).

5. The dike–pond landscape

5.1. Origin and development of the dike–pond landscape

In the low-lying central delta, there were originally numerous waterways, and flooding and tide disasters were frequent. Waterways began to silt up one after another since dikes were built in the Tang and Song Dynasties. Silt from the upper reaches can only be deposited outside the dikes and the cofferdams. In time, a unique landscape was created, where the fields inside dikes and cofferdams were lower than the water surface of rivers outside the dikes and cofferdams. When a flood, a torrential rain, or a long-duration rainstorm occurred, draining became a big problem and disasters often followed. This is extremely dangerous, since water logging broke out usually between June and September, the critical period for both early-season and late-season rice. In addition, a great increment in population after the Ming Dynasty created an urgent need for acquiring new lands and improving productivity of the existing land. In an attempt to solve the problems of increased water disasters and lack of new land, local farmers excavated low-lying lands inside the dikes and cofferdams to form ponds. Other farmers erected dams around small rivers that had been silted up so as to form ponds. The mud from excavation was placed on top of dikes and used to grow a variety of plants. Depending upon what kind of plant they grew, different names were given to the landscapes. For example, if mulberry trees were planted, a mulberry-dike-fish-pond landscape was created. Other types of dike systems include fruit-dike, sugar cane-dike, flower-dike, and so on. The ponds were used to raise fishes, especially four major species of carp, namely grass carp (*Ctenopharyngodon idellus*), big head carp (*Aristichthys nobilis*), silver carp (*Hypophthalmichthys molitrix*), and mud carp (*Cirihinus molitorella*) (Zhujiang Delta Agricultural History Committee (ZAHC), 1976; Lo, 1990). Because the dike–pond landscape was so well adapted to the delta's flood-prone low-lying areas, it eventually developed into a unique type of cultivation that integrated agriculture and aquaculture (Zhong et al., 1993).

When the dike–pond system was first introduced in Jiujiang of Nanhai County in the early Ming Dynasty, the interactive nature between fish ponds and dikes was little appreciated. Typical crops grown on the dikes were fruit trees such as litchi (*Litchi chinensis*), longan, and mulberry trees. Pond fish was used mostly for a household's own consumption. The increased commercialization of agriculture since the mid-Ming Dynasty, however, stimulated local farmers' interest in raising pond fish and fruit. The fish-pond–fruit-dike system spread rapidly to the eastern part of the delta. By AD 1581, the total area of fish ponds reached 160,000 *mu* (10,672 ha). These were distributed in the counties of Nanhai, Shunde, Panyu, Xinhui, Sanshui, Gaoming, Xin'an, and Dongguan (Zhujiang Water Conservancy Committee (ZWCC), 1990). At least half of these fish ponds were concentrated in Nanhai (48,326 *mu*, or 3223 ha) and Shunde (40084 *mu*, or 2674 ha), where the towns of Jiujiang, Shatou, Longshan, and Longjiang were known for specialization in dike–pond cultivation (Zhujiang Delta Agricultural History Committee (ZAHC), 1976).

A commercial silk industry flourished during AD 1757–1839. Fruit trees were thus replaced by mulberry trees on the dikes. After the central government shut down the seaports in Jiangsu, Zhejiang, and Fujian Provinces and left Guangzhou the only open seaport, the price of silk rocketed in Guangdong. These changes in political and economic settings led to the rapidest development of mulberry-dike–fish-pond systems in the delta's history. Such systems were found to be capable of maximizing silk and fish production by fully utilizing the wastes generated by the two components in a mutually supported system (Zhong et al., 1993). Mulberry leaves were fed to silkworms, and in turn, the droppings from silkworms were fed to the fish. The organically enriched mud at the bottom of the pond was dredged regularly to prevent the pond from becoming anaerobic, and the mud was used to fertilize the dike soils for growing the mulberry trees (Zhong et al., 1993). This delicate agro-ecosystem was maintained to ensure high productivity in fish, mulberry, and silk. Since rice cultivation alone cannot match such high productivity and profit, many farmers abandoned rice cultivation and shifted to dike–pond cultivation. The mulberry-dike–fish-pond system spread rapidly as silk prices soared in the world market. Jiujiang, Longshan, and Longjiang towns grew into pure production centers of mulberry-dike–fish-pond systems. By the end of the Qing Dynasty, the total area of land devoted to mulberry-dike–fish-pond systems had reached 1 million *mu* (66,700 ha) (Zhujiang Delta Agricultural History Committee (ZAHC), 1976). Fig. 10 shows the distribution of mulberry-dike–fish-pond systems in the West and North River Deltas.

5.2. Environmental implications of the dike–pond systems

Research in China has shown that the dike–pond system is a scientific and environmentally conservative approach to agricultural production in a flood-prone low-lying area such as the Pearl River Delta (Ruddle and Zhong, 1988; Zhong et al., 1993). The dike–pond systems not only improve the capability of storing floodwater and lower the groundwater table, but also optimize agricultural production efficiency and increase profits. The danger of flooding

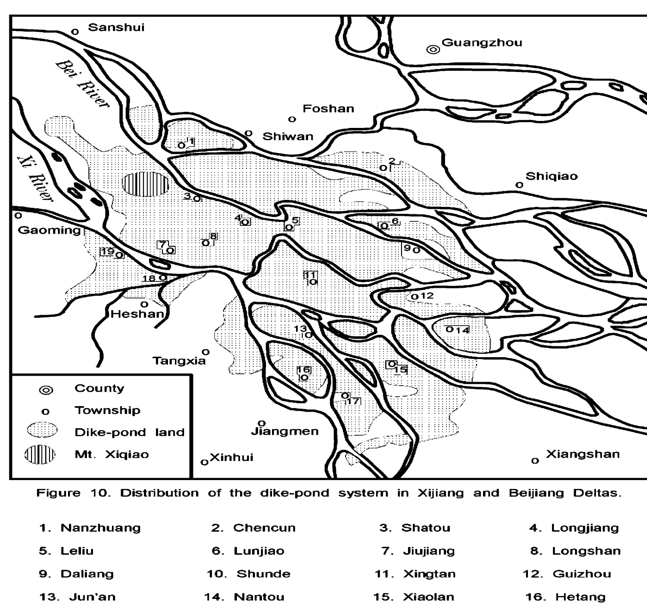

Fig. 10. Distribution of the mulberry-dike–fish-pond system by the end of Qing Dynasty (*source*: Zhujiang Delta Agricultural History Committee, 1976).

is lessened, while drought can also be accommodated. However, dike–pond cultivation is labor intensive, and requires cheap water transport to market for its products (fish and silk), in addition to abundant fish fry (Zhong et al., 1993). Diverse types of crops, such as fruit, mulberry, vegetables, sugar cane, and flowers, grown on the dikes reflect the advancement in cultivation technology. High temperatures and plentiful rainfall in the delta region favor their growth. Mulberry bushes, for example, can grow throughout the year, and their leaves can be harvested 7–8 times a year.

The operation of a dike–pond system can be understood in terms of energy flow within the system (Ruddle and Zhong, 1988; Zhong et al., 1993). Two major components of energy input are solar energy (photo-synthetically active radiation) and other subsystems in the form of feeds, while the outputs are economic product energy and wasted energy. A productive dike–pond system should maximize energy input and minimize energy waste. Organic wastes produced in one system can be recycled and reused within the same or another system.

Because individual components of a dike–pond system interact and function as one ecosystem, the proportional ratio of pond (water) and dike (land) is significant in balancing energy input and output between the two components. To raise more fish, more crops should be planted, necessitating a larger dike area. The typical ratio of land to water area is 4–6, i.e., 40% dike and 60% pond. The usual size of such an integrated dike–pond system is about 0.41 ha, or about 1 acre. The high degree of commercialization in agriculture in the delta region implies that profit is the only motivation for agricultural innovations (Zhong et al., 1993). The profitability of the mulberry-dike–fish-pond systems in the Qing Dynasty lay in the high price of commercial silk in the world market. When the price dropped in 1929, mulberry trees were replaced by sugar cane on the dikes. Mulberry trees have continuously declined in the twentieth century, and a great variety of crops have been grown on the dikes and new species of fish introduced to the ponds (Zhujiang Delta Agricultural History Committee (ZAHC), 1976; Zhong et al., 1993). Especially after 1978 when the Chinese government initiated economic reform and the open-door policy, the mulberry-dike–fish-pond systems declined drastically. When conducting fieldwork in the delta during the summer of 1998, our research team was told that the mulberry-dike–fish-pond systems had completely vanished years ago. Jun'an Township of Shunde County was building a live museum of a mulberry-dike–fish-pond system for the purpose of educating new generations and attracting more tourists. Apparently, the delta is facing great challenges in conserving the environment in the context of rapid economic development.

6. Discussion

While the Pearl River Delta appeared as one of the most rapidly advanced economic regions in the nation after 1978 and has now become known as the world's workshop, a series of environmental problems have emerged, including continued shrinkage of agricultural land, upstream deforestation and soil erosion, silting up of river channels, flooding, and the decline of water surface in the estuaries. Although it is one of the wettest regions, water crises have occurred in such cities as Guangzhou, Shenzhen, and Zhuhai primarily due to water pollution. All these problems prompt us to re-think the issues of river basin management and sustainable development in this unique aquatic environment under the new conditions. Lessons learned from history may enlighten solutions for many of the problems we face today.

Over-reclamation of shoals and beaches and loss of waterways have threatened the delta's coastal environment and agricultural production, due to greater problems in flooding prevention, water logging, and irrigation. Moreover, increased dam building and water extraction and changed land uses and covers have affected the surface runoff pattern. In addition, unregulated sediment mining has changed the longitudinal profiles of river channels, which affect flood discharge and may cause the penetration of saline water (Qian, 2005; Wang et al., 2005). Saline flows have been reported to have penetrated far into the delta proper, contaminating tap water near Macao (Wehrfritz, 2006). Similarly, with growing marketization in agriculture and desire for high productivity, the non-point source pollution due to the use of chemical fertilizers and pesticides has become increasingly serious in the fruit/flower-dike–pond systems since the late 1980s. The accumulation of organics and heavy metals in the systems has polluted different species of fishes in fish ponds. Kong et al. (2005) found that the level of DDTs in more than 30% of the fishes they sampled exceeded the limit for human consumption recommended by US EPA in 2000. In fact, water pollution has become a major environmental problem in the Pearl River Delta. The main pollution sources include industrial wastewater, domestic sewage, chemical fertilizers and pesticides, and oil pollution of the rivers, and the major pollutants include dissolved oxygen, permanganate, biochemical oxygen demand, nonionic ammonia, and oils (Zhu et al., 2002). Among the 19 rivers surveyed by Zhu et al. (2002), six were found to belong to the highly and extremely polluted classes, according to the Chinese National Standard for Surface Water Quality (GB3838-88), while four belonged to the class of average pollution and the remaining nine to the classes of clean and slightly polluted.

To combat the environmental degradation and sustain future development, coordinated development of physical, economic, and social subsystems and regional cooperation have been advocated (Zhu et al., 2002; Weng and Yang, 2003). The environmental issues in the delta are fairly complex, and involve scientific and engineering problems, and have important social, legal, economic, and political ramifications. The only way to deal with such complex problems is to consider them as an integrated watershed management issue, and to bring together all participants—planners, engineers, landscape architects, scientists, social scientists, local officials, and others at all watershed scales, for the common good. At present, a scaled-down experimental model, covering 30,000 m^2, for management of the delta has been built in Nanhai, where the dike–pond landscape prevails, and historically it has had severe flooding and now all sorts of environmental problems.

7. Conclusions

Water is one of the most important natural forces that have shaped the material cultural landscapes of the Pearl River Delta. The changing relationships between people and the physical environment have led to innovations in water and soil conservation technology. Three innovations in water and soil conservancy, i.e., dike building, land reclamation, and dike–pond systems, have been examined in this paper from a historical perspective. These technologies were found to best reflect local farmers' efforts to cope with the challenges of various water disasters and to build a harmonious relationship with the changed environment. The dike-building technology was developed to protect the enclosed fields from flooding, whereas the land reclamation technology was called for when additional agricultural land was needed. The dike–pond system was designed to solve flooding and water logging problems in a low-lying wetland environment.

These technological innovations contain millennium-long wisdom of local farmers in balancing land use and environmental conservation. Dike building promoted the process of sedimentation, the formation of a modern drainage system, and the seaward extension of the delta. These environmental evolutions were important in altering a quasi-aqueous delta into a terrestrial one. A triple-cropping pattern was created when population pressure increased, and the technology of water and soil conservancy and farming improved. The significance of the four stages of sedimentation and three-stage implementation of reclamation is that they conserve the ecosystem through the combined uses of biological and engineering measures. The dike–pond system optimizes agricultural outputs by recycling wastes and efficiently transmitting energy, and is particularly suited for densely populated deltaic environments.

Imprudent use of a new technology could bring about negative impacts on the environment and damage the human–environment relationship, as evidenced by the frequent flooding that followed inappropriate dike building and premature reclamation activities. The rapid seaward extension provided the foundation for unregulated reclamation for agriculture. The failure to keep a balance between agricultural land use and conservation could lead to severe environmental deterioration, such as deforestation, soil erosion, silting up of river channels, flooding, and water logging. The demise of the mulberry-dike–fish-ponds and continuous degradation of other agro-ecosystems in recent years have threatened the long-established harmony between the environment and the inhabitants. As urbanization and industrialization processes continue, the kind of thinking that made water and soil conservancy sustainable needs to be incorporated into the design of similar technologies for water use today (Shunde City Water Conservancy Society, 1996; Xu, 1998).

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