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Modern geomorphological environment research during rapid urbanization in Shenzhen east coastal zone

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Abstract: The geomorphological environment is one of the most fundamental variables affecting the development of human society. The mission of geomorphological environment research is to explore the most basic environment and features of our Earth's surface morphology. The results can be applied to resource evaluation, environmental protection and reducing and preventing geological disasters. Thus, it can serve to help achieve sustainable development. This paper examines the Shenzhen east coastal zone as a case strongly influenced by urban expansion. We use modern geomorphological theory and methods, along with GIS and RS techniques, to reveal key characteristics of the geomorphological environment and landform classification. Furthermore, coastal ecosystem evaluation and regional resources sustainable utilization should be considered relative to the corresponding geomorphological environment. Based on this study, we conclude that modern geomorphological theory and methods, supported by "3S" techniques including GIS, RS and GPS, can play an important role in resolving the environment, resources and population problems as well as sustainable development challenges facing humankind at present.

Keywords: Shenzhen; geomorphological environment; geographic information system; remote sensing; sustainable development

1 Introduction

The problems of population, resources and environment are becoming more and more serious all over the world. And, achieving sustainable development has become one of the most significant challenges (Wang and Niu, 2004). Sustainable development seeks the overall

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improvement of society on the basis of the sustainable utilization of resources, the protection of ecological integrity and the continual development of the economy. Among the environmental problems which human beings face, the geomorphological environment occupies an important position, because it is the most fundamental environment which sustains the human and societal development (Goudie, 2002; Gao, 2006; Murray *et al.*, 2009; Slaymaker, 2009).

The research regarding theories and methods of the geomorphological environment has been steadily improving with the development of society and technology (Walsh *et al.*, 1998; Vallega, 2005). For example, the analysis and application of digitalization of geomorphological elements, three-dimensional visualization of the geomorphological environment and of the digital elevation model have become major components of modern research on the geomorphological environment (Tempfli, 1998; Arnaud and Bernard, 1999; Losa *et al.*, 1999; Walsh *et al.*, 2003; Jude *et al.*, 2006; Saadat *et al*., 2008). Many geologists use 3S (GIS, RS, GPS) techniques to study the geomorphological characteristics, landform processes and evolution mechanisms (Fyfe, 1997; Alberotanza *et al.*, 1999; Wang *et al.*, 2000; Mohan, 2002; Zhang *et al.*, 2006; Rashed, 2008). The research about regional geomorphological environments has received more attention with the appearance of the sustainable development theory. For instance, the relief amplitude is used as an important factor regarding the natural environment to calculate the regional development costs. And the results of geomorphological environment research can be applied to resource evaluation, environmental protection and reducing and preventing the geological disasters. Thus it can support the realization of sustainable development (Kamal and Midorikawa, 2004; Bonachea *et al.*, 2005; Rivas *et al.*, 2006; Gumell and Lee, 2007; Westen *et al.*, 2008; Kamp *et al.*, 2008).

The research of regional sustainable development needs new ideas, techniques and methods. Urban fringes are in the transition zone between urban and non-urban areas, including various geomorphical elements and processes which are strongly influenced by natural forces and human activities (Werner and McNamara, 2007). Thus, they are vulnerable ecotones in the geomorphological environment. This paper uses the Shenzhen east coastal zone as a case study which is strongly influenced by urban expansion. Using modern geomorphological theories and methods, along with the GIS and RS techniques, the characteristics of the geomorphological environment can be revealed and a landform classification can be determined. Furthermore, coastal ecosystem evaluation and regional resources sustainable utilization can be completed relative to the corresponding geomorphological environment. The research results can thus provide a scientific basis for regional sustainable development and planning.

2 Study area

Shenzhen is situated in the eastern part of the Pearl River Estuary and has an area of 2296 km^2. The coastline, 256 km long, can be classified into two major types: a coastal plain in the west from the Lingdingyang Estuary to the Shenzhen River Mouth, and a coastal bedrock embayment in the east, including Dapeng Bay and Daya Bay (Wang and Aubrey, 1987; Wang and Zhu, 1994) (Figure 1). The Shenzhen east coastal zone covers an area of 361.5 km^2 with a total population of 274,070 including Yantian District (72.36 km^2) and the three

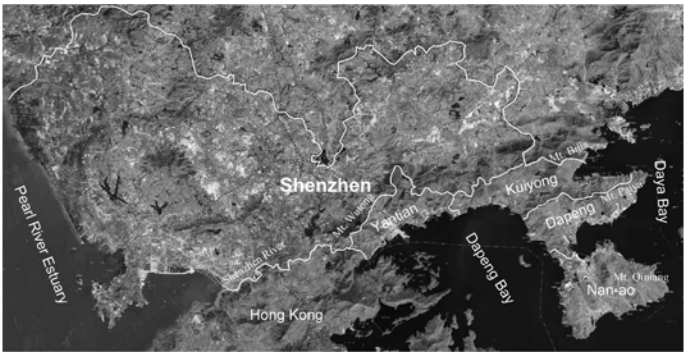


Figure 1 Map of the research area in the Shenzhen east coastal zone

towns of Kuiyong (98.86 km^2), Dapeng (76.24 km^2) and Nanao (114.04 km^2). And the urban construction land in the towns of Kuiyong, Dapeng and Nanao are 4.71 km^2, 7.63 km^2 and 1.32 km^2, respectively.

3 Methodology of modern geomorphology based on GIS and RS techniques

3.1 Field investigation and laboratory analysis

Field investigation, survey and sampling are the basic steps of geomorphological research. Modern geomorphology can not use overall computer simulation without field investigation and laboratory analysis. The field investigation in the Shenzhen east coastal zone includes aspects of coastal geomorphology, marine hydrology, marine sedimentary dynamics and marine ecology. The geomorphological map was plotted and created in the field. The surface samples from the sand beach were collected at the tops of the modern beach, the areas where inflow reaches, the beach ridges, the middle parts of tidal zones and the breaker zones. The slopes and aspects of sand beaches were measured by compass. Photos of sand beaches were taken. The positions of the samples were recorded by GPS. The sediment grain sizes were analyzed in the laboratory using Mastersize 2000.

3.2 Extraction of geomorphological characteristic and landform profiles

The basic work of geomorphology is to acquire the landform characteristics, geomorphological composition and spatial distribution in order to prepare a geomorphical classification and map. GIS and RS techniques have great value in analysis of macro-geomorphic characteristics, extraction of geomorphic factors and quantitative evaluation. Pretreatments of geographic information of the study include processing of the ETM image of the Shenzhen area in 2001 regarding registration, enhancement and band combination using satellite image software of Erdas8.5. The coastal digital elevation model (DEM) was created by ArcGIS. Geomorphic factors such as elevation, slope, NDVI, length of coastline and area of basins, were extracted using spatial analysis. Furthermore, we overlay the satellite images on digital elevation model with the same spatial reference. Thus, a three dimensional virtual geomorphical environment was produced which provides a scientific basis for extraction of a geomorphical composite profile and geomorphological classification.

3.3 Geomorphic classification and sustainable evaluation of ecosystem

The characteristics and geomorphical environment of the Earth's underlying surface is closely related to the evolution and development of different ecosystems. Different landscape environments are also one of the indicators in an ecosystem classification system. And this paper provides a new method of coastal ecosystem evaluation, which starts with the quantitative evaluation of geomorphical characteristic factors. The utilization prospect of the resources and the protection of the coastal ecosystem were evaluated according to the adaptability, vulnerability and restoring ability of the geomorphical environment.

4 Research of the geomorphological characteristics of the east coastal area

4.1 Regional tectonics

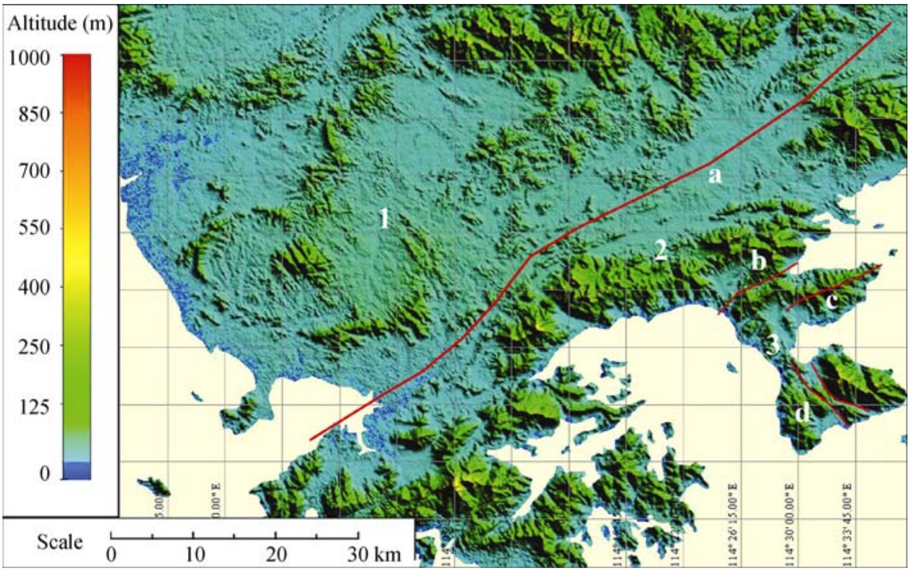
Tectonics controls the geomorphic pattern of the eastern areas. The Shenzhen Fault is the main fault which divides Shenzhen City into two parts: the southeast area of the fault is mainly low mountains and high hills; the northwest area is mainly low hills, terraces and valleys (Huang and Li, 1983; Wang and Zhu, 1994) (Figure 2). The NE-trending Wangmu fault group (Paiyashan Fault and Wuniyong Fault) approximately parallels the Shenzhen Fault. It cuts through Dapeng Ao and Dapeng Bay, dividing the southeast area of Shenzen into two geomorphological units: a coastal mountain geomorphological zone, and a peninsula-bay geomorphological zone. The demarcation of the coastal mountains and the Dapeng Peninsula is the southern boundary of the Kuiyong Basin and Beigang Bay. The NE-trending fault results in the remarkable geomorphological differentiation in this area. Three geomorphologic units were formed from the southeast to the northwest: peninsula and coastal embayment, and coastal mountains, low hills and valleys.

Geological structure determines the NE orientation of the eastern mountains. It is consistent with the major tectonic direction. Among the five low mountains in the east, Wutong Mountain, Meisha Tip, Bijia Mountain and Paiya Mountain extend NE, which is the same direction of the Shenzhen Fault and the Wangmu Fault. The Qiniang Mountain with a NW orientation is at the south of the peninsula. Its formation is connected with the Shuitou-Xichong Fault.

4.2 Extraction of regional geomorphological factors based on GIS/RS

(1) Elevation: The landforms of the east coastal area are complex, where mountains, hills and plains are distributed. The highest mountain is the Wutong Mountain, with an elevation of 943.7 m. Secondly are the Qiniang Mountain, Paiya Mountain and Bijia Mountain which are 897.6 m, 707.5 m and 717 m high, respectively. As a whole, the north and south mountains are higher than the middle. Four basins also exist: Shatoujiao, Yantian, Kuiyong and Dapeng.

(2) Slope: The eastern mountains are mainly composed of granites with steep slopes. The slopes of the mountains are 15°–45° according to DEM (Figure 3a). Wutongshan and Qiniangshan, at the south of the peninsula, are composed of volcanic rocks with high hard-



1. Low hills and valleys 2. Coastal mountains 3. Peninsula and coastal embayment
a. Shenzhen fault b. Wuniyong fault c. Paiyashan fault d. Xichong fault

Figure 2 Geomorphological zones controlled by geological structure in Shenzhen

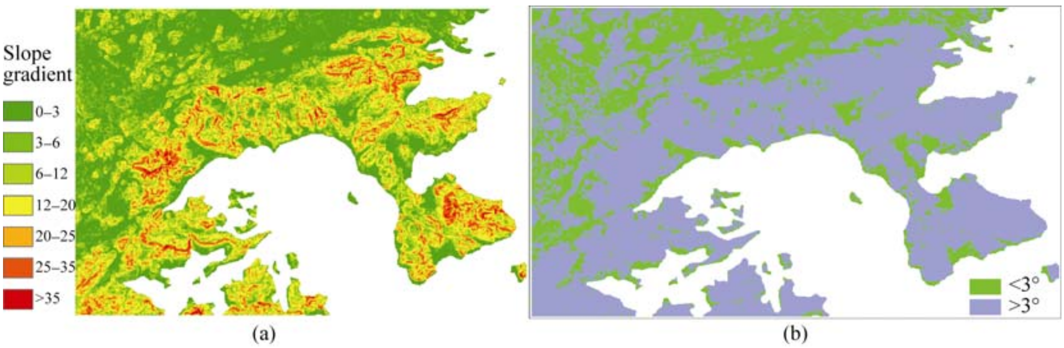


Figure 3 Slope map of Shenzhen east coastal zone (a); and plains in east coast (slope < 3°) (b)

ness, strong weathering resistance and steep slopes. The slopes which are higher than 35° account for 85%. The flat plot (slope<3°) mostly is found in Shatou Tip, Yantian, Dameisha, Xiaomeisha, Kuiyong Town, Dapeng Town, Nanao Town, Xichong and Baguang. The area is small and scattered (Figure 3b).

(3) Vegetation index: The vegetation index is an indirect index to reflect the vegetation growth, coverage and biomass conditions as well as the vegetation species. It is calculated according to vegetation reflection bands. The normalized difference vegetation index (NDVI) is an optimum indicator for the vegetation growth condition and coverage. The NDVI of the east coastal area was calculated using ETM near-infrared and infrared wavebands and was further normalized to calculate the vegetation coverage (F). The formula for the calculation is as follows (Aronoff, 2005):

$$NDVI = (IR - R)/(IR + R)$$

$$F = (NDVI - NDVI_{min}) / (NDVI_{max} - NDVI_{min})$$

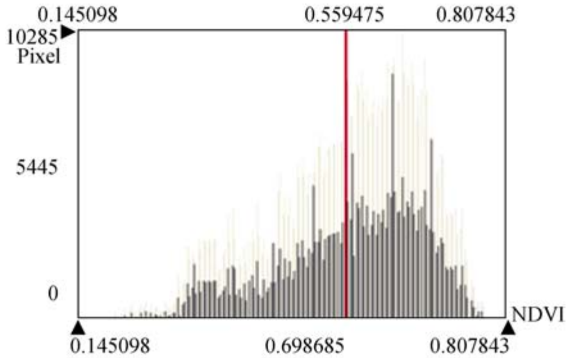


Figure 4 NDVI spectral histogram of the Shenzhen east coastal area

The average vegetation coverage of the east coastal areas is 55.9%, according to the NDVI spectral histogram of the Shenzhen east coastal zone (Figure 4).

(4) Coastline resources: Based on the ETM imagine in 2001 and a topographical map of 1:10,000, the total length of coastline of the Shenzhen east coastal zone is 156.46 km, including 31.12 km for Kuiyong, 40.84 km for Dapeng, 65 km for Nanao and 19.5 km for Yantian (8.5 km for Meisha, 8.3 km for Yantian and 2.7 km for Shatoujiao).

According to field investigation, the utilization of the east coastlines concentrates on the area from Shatoujiao in Dapengwan to Nanao and the nuclear power plant at Daya Bay. The coastline utilization is scattered because of the natural landforms. Classified by coastline utilization types, there are industrial, port, tourism, aquicultural, domestic and natural coastlines (Table 1).

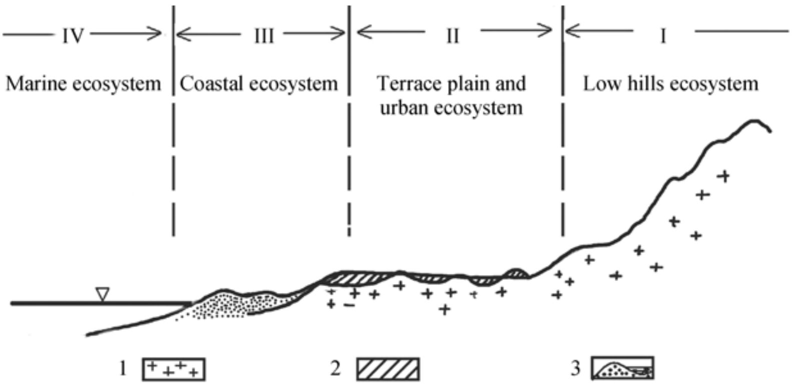
Table 1 The present status of coastline utilization in Shenzhen

Utilization type	Scale(km)	Percentage (%)	Distribution
Industrial coastline	14.8	9.5	Shangdong, Guanhu, Diefu and the nuclear power station
Port coastline	20.88	13.3	Yantian, Xiadong, Kuiyong and Nanao
Tourism coastline	5.3	3.4	Meisha, Xiasha and Xiyong
Aquicultural coastline	8.1	5.2	Baguang, Nanao and Dapengao
Domestic coastline	3.8	2.4	Shatoujiao and Shuitousha
Natural coastline	103.58	66.2	The area around Dapeng Peninsula

4.3 3D visualization and application of geomorphical comprehensive profile

3D imitation of east coastal geomorphology is created by overlying satellite images on a digital elevation model (Figure 5). Its application is to provide a basis for a comprehensive geomorphological profile extraction and classification. Based on field investigation, a geomorphological comprehensive profile of the east coastal area can be extracted from the geomorphic simulation (Figure 6). It is divided into five geomorphological units from land to ocean: low hills→foot hill plain→coastal barrier→lagoon→submarine slope. The corresponding coastal ecosystem includes a low hills ecosystem, terrace-plain town and farmland urban ecosystem, coastal zone ecosystem, and marine ecosystem. The comprehensive

Figure 5 3D visualization of geomorphological simulation in the Dapeng Peninsula



1. Bedrock 2. Fluvial deposits 3. Barrier-lagoon deposit

Figure 6 Comprehensive geomorphological profile in the Shenzhen east coastal zone

geomorphological map provides a scientific basis for locating regional industrial sites and spatial planning according to the characteristics of underlying surface of different ecosystems.

5 Geomorphological environment and evaluation of sustainable development of regional ecosystems

The diversified landforms were formed due to a combination of geomorphological characteristics such as elevation, slope, aspect, relative height, orientation etc. They play a leading role in the ecosystem environment, distribution of resources, and utilization patterns. According to the characteristics of different landforms and environments, the protection and utilization prospects were evaluated from the perspectives of geomorphological environmental vulnerability, adaptability and restoring ability using the theory of sustainable development.

I. Low hills ecosystem

Slope is one of the important terrain factors. It not only directly affects soil development and vegetation distribution but also controls eco-environmental patterns as well as exploitation and utilization modes. The slopes of the eastern coastal hills are about 15°–45°. The mountains have many fragments affected by fault structure. 80% of the soil types are granitic red soil which is thin and easily eroded. The mountains are now covered by artificial and secondary forest, shrub and artificial masson pine. The average vegetation coverage rate reaches 55%, indicating a good quality ecosystem environment. However, the fragile ecosystem is difficult to restore once deteriorated. The rocks will be exposed if the vegetation is destroyed because of the steep slopes and thin soils. Special efforts should be made to maintain good vegetation coverage here. Quarry, house construction and road construction should be prevented. Slope protection and greening are strongly suggested.

II. Terrace-plain town and farmland ecosystem

Eastern towns are located on the terrace-plain area where human activities have the strongest influence on the environment. Faced with the rapid growth of population and cities, the construction of the eastern towns extended into the foothills. Mountain excavation leads to possible geological disasters such as rock fall, landslide and debris flow in the eastern areas. Analyzed by remote sensing interpretation and a slope map, flatlands are few and scattered in the eastern areas. As a result, the development cost is high and the development capacity is low. The east Dapeng Peninsula is inappropriate for large-scale construction, according to the environmental suitability analysis. The construction scale should be therefore controlled reasonably.

III. Coastal ecosystem

The coastline of eastern Shenzhen, with more than 20 sand beaches and bays, is very long and alternates between promontories and bays. The east coastal geomorphology has a common feature: coastal sand beaches deposited between rocks and promontories. 1–3 coastal bars are parallel at the inner beaches. Inside are lagoon plains. The above three parts compose the eastern coastal zone ecosystem.

(1) Evaluation and protection of beach resources

The sands of the beaches at eastern Shenzhen are mainly medium-coarse sands. The sand fraction of 0.063–2 mm accounts for more than 90%. The high quality beach resource is the basis of 3S coastal tourism. More than 20 bays and beaches have great potential.

According to coastal dynamic geomorphology (King, 1972; Wang and Zhu, 1994), the development of sand beaches is mainly controlled by waves. The inflow and backflow created by waves breaking have shaped the beaches during thousands of years. In the case of natural beaches, when a wave breaks, the inflow climbs across the top of the beach and filters through the sands while backflow returns to the sea along the beaches (Figure 7a). The wave energy is thus dissipated. As a result, the sands will not be scoured and removed. However, if the breakwaters and houses are built at the beaches or above the high tide line, waves can not normally cross the constructions (Figure 7b). The remaining water energy brought the sands away from the beaches and resulted in scouring. Eventually, the foot of the breakwaters was eroded and the breakwaters collapsed. The irrational permanent constructions above the high tide line led to the erosion of the beaches. It is hard to restore them artificially once they have been destroyed (Figure 7c). The protection of beaches should be in accordance with the rules of coastal dynamic geomorphology. Construction of permanent structures above the high tide line should be prevented. Spaces should be left between the high tide line and land. Setbacks should be used to protect the coastal beach resources (Clark, 1995).

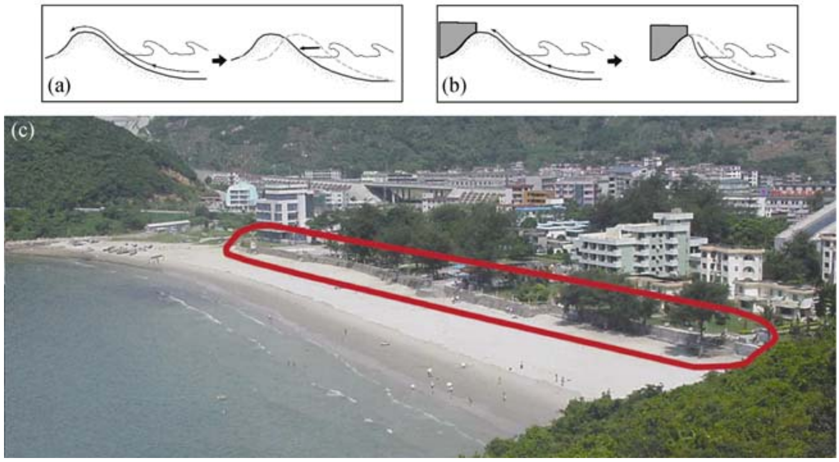
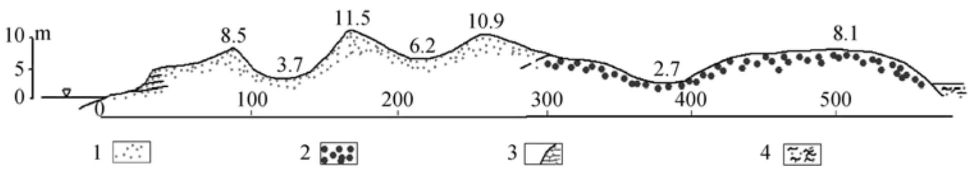


Figure 7 Beach dynamic process and destructive engineering in the Shenzhen east coastal zone

(2) Sand bar-lagoon coastal geomorphological analysis

The major coastal geomorphological type of eastern Shenzhen is the coastal sand bar and lagoon. The geomorphological character is that the sand bars developed between the promontories. One or several bars parallel with the coast deposited inside the bay. At the back of the bars is the lagoon plain. The rivers flow into the plain and then cross the bars to go into the ocean. There are 34 large lagoon plains in eastern Shenzhen, such as Yantian, Dameisha, Xiaomeisha, Xiyong, Shangdong, Guanhu, Xichong, and Dongchong. The most typical and largest is the Xichong coast (Figure 8). From land to sea, three sand bars are located in a bird shape. The first seaward bar is 8.5 m high, composed of shallow yellow-white medium-fine sands. The second and third bars are higher (11.5 m and 10.9 m), composed of medium sands. The color turns darker landward (yellowish white–orange yellow–orange red). The cementation degree gets higher, demonstrating that the ages of the three bars are older seaward. The first was formed in the late Holocene, about 2170±85a before present, according to ^{14}C dating (Huang and Li, 1983). The inner old sand was formed in the middle Holocene. The medial side of the bars is the lagoon plain with an area of 1.57 km^2.



1. Yellow-white loose medium-fine sand; 2. Red and yellow cement-sand; 3. Beachrock; 4. Lagoon plains

Figure 8 Geomorphological profile of the coastal sand bar and barrier lagoon in Xichong Bay

From sea to land, the coastal bar-lagoon system includes submarine slope, sand beaches, coastal bars, lagoons, foothills and mountains. In a natural state, rivers flow from the mountains across the lagoons, sand bars and beaches and finally into the ocean. Multi-layer geomorphological landscapes form, with beautiful scenery and a good ecological environment. However, the existing shrubs and green lands were destroyed in order to construct leisure parks after the tourism areas were developed. For instance, many restaurants were built along the coastal area of Dameisha. The natural rivers were canalized by cement and stones.

However, artificial canals can not transport the pollutants. Moreover, mouth bars are often formed at the estuary, open only in the flood seasons and contact with sea. Moss lands appear between the bars. Polluted water is enclosed from the foothill to the sea. The ecosystem restoration of this area should connect the lagoons with the open sea. Excavating the shoals at the estuary is recommended. In order to prevent wave breaking at estuaries and to avoid estuary shoals, a leading dike should be built from the estuary to the deep water area (water depth is –5 m) to connect the water from the rivers and lagoons with the water in the open sea (Yan, 1996). The beds and banks of the rivers across Dameisha Town should be restored to natural status. The measure is appropriate for the east sand bars-lagoons area.

IV. Marine ecosystem

(1) Submarine geomorphological characteristics

Dapeng Bay is a semi-enclosed bay with an opening in the southeast. The opening is 9.26 km wide and 18 km deep with an area of 335 km^2. The water depth is 18 m. The eastern area is higher than the western area of the sulciform bottom of the bay. The water depth increases from the top of the bay to the estuary (8–10 m at the top, 18 m at the middle, 22–24 m at the estuary).

(2) Marine dynamics

Dapeng Bay is controlled by tides. According to the formula of the tidal type index: $N_f=(H_{o1}+H_{k1})/(H_{M2}+H_{S2})$, the correlation of tidal types N_f is between 0.82–1.3 which indicates an irregular semidiurnal mixed tidal type (Defant, 1958). The tidal range increases from bay mouth to bay head with the average of 1 m. The tide current velocity is small with an average of 0.1 m/s, the max of 0.2 m/s and 0.05 m/s at bay head and offshore area. Water exchange is slow. Few large rivers flow to the long shore area. The marine ecosystem mainly relies on a tidal prism. In addition, red tides bio-species of dinoflagellates as the dominant planktons of the bay lead to frequent red tides in Dapeng Bay. Red tides appeared 49 times during 1981–2001, according to statistics which indicate the fragile ecological environment.

(3) Analysis on quality of sea water and sediments

A comprehensive pollution index of the sea area is used to evaluate the sea pollution. The formula is as follows (Lu, 1999):

$$P = \frac{\sum C_{ij}/C_{io}}{n} \tag{1}$$

where P is average value of comprehensive pollution indexes of section j; C_{ij} is annual average value of i types of pollutants at section i; C_{io} is standards of evaluation on i types of pollutants

According to the monitoring data of the eastern sea area (SEPB, 2001), the values of inorganic nitrogen, available phosphate and oils all exceeded standards with a large increasing margin (Table 2). The monitoring data of five sites for the eastern area show that annual average value of available phosphate, inorganic nitrogen and coliform group for the Shatoujiao bay mouth exceeded the standard of the second class and reached the fourth class. The annual average value of other areas all reached the second class. The monitoring results of sediments for the eastern long shore areas indicate that the sedimentary environment was good even though a few environmental indexes such as lead exceeded standards. Wuniwan was subject to light pollution from heavy metals and oils.

Table 2 Main contamination in east marine time between 1995 and 2000 in Shenzhen (mg/l)

Year	Inorganic nitrogen	Available phosphate	Oils	COD	Suspended matter	P (average value of comprehensive pollution indexes)
1995	0.039	0.005	0.02	1.13	5.5	0.23
2000	0.146	0.009	0.04	1.03	2.4	0.3
Rising range (%)	274	80	50	–8.8	–56	

The result indicated that the marine environment of Dapeng Bay is good at present. The water quality is between the first and the second class, except for some local areas. However, the areas around Yantian and Shangtong suffered from oil pollution. Waste water discharging from small illegal dye houses led to the pollution of sea water and beaches. Lead content of sea water went beyond the standard greatly due to the industrial discharge of batteries from eco-industrial parks at Aolongqi Bay which also affected the offshore marine aquaculture greatly. The bay mouth of Dapeng Bay is small and the currents there are weak. Due to the limited capacity of environment, avoiding industrial waste discharge and promoting municipal waste water to meet the discharge standards are important measures to protect marine ecological environment.

6 Conclusions and discussion

The geomorphological environment is closely related to regional sustainable development. It not only provides an underlying surface basis for the formation and development of urbanization but also controls the distribution, development and landscape pattern of towns. The geomorphological environment is complicated and the economy is poorly developed in the eastern areas of Shenzhen. The enormous development difference between the eastern and western areas leads to the main rationale for accelerating the development of eastern areas. Affected by urban expansion and spread of industry to the urban margin of Shenzhen, a series of plans to accelerate industrial development and industrial parks construction were put forward for three east towns in 2008. What is the rational development direction for the eastern area and how much is environmental carrying capacity facing the challenge of large-scale development? Using the theory and methods of modern geomorphology, this paper has evaluated the regional development and protection comprehensively regarding the aspect of geomorphological environment, relying on 3S technology for quantitative evaluation. Comparative advantages of regional development options were studied, and a regional sustainable development strategy and industrial development direction were proposed. Practice shows that such research concepts and methods can provide a scientific basis for resource evaluation, environmental protection, land use and urban planning, as well as creating a regional sustainable development strategy.

Based on the research of coastal geomorphological environment of the eastern Shenzhen, conclusions and suggestions for regional sustainable development and a scientific plan in the future include:

(1) According to the analysis of vulnerability of the geomorphological environment, most of the eastern low mountains are granite with steep slopes. Many valleys and fragments formed with thin weathering crusts due to the fault structures. They are easily eroded which can lead to soil and water loss, even geological disasters.

(2) According to the analysis of restoring ability, the red soil of the eastern granite areas is thin and the mountains are steep. High covered vegetation is crucial to soil and water conservation. If vegetation is destroyed, it is difficult to restore and it will accelerate water and soil loss of east areas. The successive landscapes of high quality beaches, plain coast lagoons and low mountains are the most precious resources of the eastern areas and should be protected as a whole.

(3) According to the analysis of adaptability, large-scale development, especially industry, should be avoided in the eastern areas. From the perspective of sustainable development, the unique geological and geomorphological resources along Dapeng Bay should be used as urban ecological buffer zone. Geological parks and natural protected areas should be established. Coastal ecological tourism of high quality should be developed. As an international garden city, in the city expansion process, to maintain the natural pattern of eastern coastal geomorphology and the integrity of the ecosystems are important measures not only for maintaining the city ecology integrity but also for enhancing city quality and promoting regional sustainable development.

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