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NARRATIVE

Environmental remediation promotes the restoration of biodiversity in the Shenzhen Bay Estuary, South China

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ABSTRACT

Background: Rapid urbanization has greatly changed land-use patterns in many estuarine areas around the world, including the Guangdong–Hong Kong–Macao Greater Bay Area (GBA) resulting in serious water pollution and ecosystem degradation. Shenzhen City has conducted comprehensive ecological management and restoration in the Shenzhen Bay since 2007. The natural vegetation consisting of mangroves, semi-mangroves, wetland plants, and terrestrial plants were restored from the bund to the inner bank of the Fengtang River. Rain and sewage flow diversion systems were established. The non-point source and point-source sewage are now treated in municipal sewage treatment plants, then naturally flow through the constructed wetland, and then through a natural wetland, restored natural embankment, and finally through mangrove communities substantially improving water quality.

Result: The restoration of the wetland has increased animal and microbial diversity and has supported the establishment of a complex and stable food web. With water purification and habitat restoration, the number of alien invasive plants in the estuarine ecosystem has decreased, and the diversity of native species of birds, fish, macrobenthos, amphibians, and reptiles has increased.

Conclusion: These improvements indicate that human beings and nature can coexist in support of the sustainable development of Shenzhen City.

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Coast was characterized by natural areas and rich biodiversity. As a sea–land transitional zone, however, the coastal areas are vulnerable to natural and anthropogenic disturbances (Ren et al. 2011). This transition zone plays an important role in the transport of polluted water from rivers that traverse dense human settlements such as cities (Schlacher et al. 2020). The studies on environmental remediation in these transition zones can help formulate effective methods for biodiversity restoration in light of the human pollution of waterways. Recently, many countries have launched ecological restoration projects to safeguard the sensitive ecosystem from excessive human disturbance and pollution in coast regions (Fan, Li, and Pavao-Zuckerman 2021). Therefore, there is no doubt that the experience and lessons of the completed projects have important reference value for ecological restoration in other regions.

The Shenzhen Bay is located on the east coast of the Pearl River Estuary in South China, between Shenzhen and Hong Kong, which are the two economic centers of the Guangdong–Hong Kong–Macao Greater Bay Area (GBA). Eight rivers, including the Fengtang River, flow into Shenzhen Bay. Because of rapid population growth and urbanization, beach reclamation (Figure 1), tidal flat reclamation, and sewage discharge in the early development of Shenzhen City, the coastal zone has experienced a series of ecological problems. The problems include the serious pollution of the river water, habitat degradation, and the destruction of natural vegetation; resulting in a dramatic reduction in regional biodiversity (Ren et al. 2011).

Photographer: Tian-Zhu Ning.

In response to the growing environmental challenges, Shenzhen City (113°46′ E – 114°37′E, 22°24′ – 22°52′N) intensified the habitat management of the Shenzhen Bay Coastal Zone with the aims of reducing coastal river pollution and restoring the health of the estuarine ecosystem in 2007 (Ren et al. 2011). Shenzhen municipal government successively invested and constructed the “Fengtang estuary ecological restoration project,” “Xiaosha estuary coastal mangrove restoration project,” and the “Shenzhen Bay coastal mangrove restoration project” in the Shenzhen Bay between

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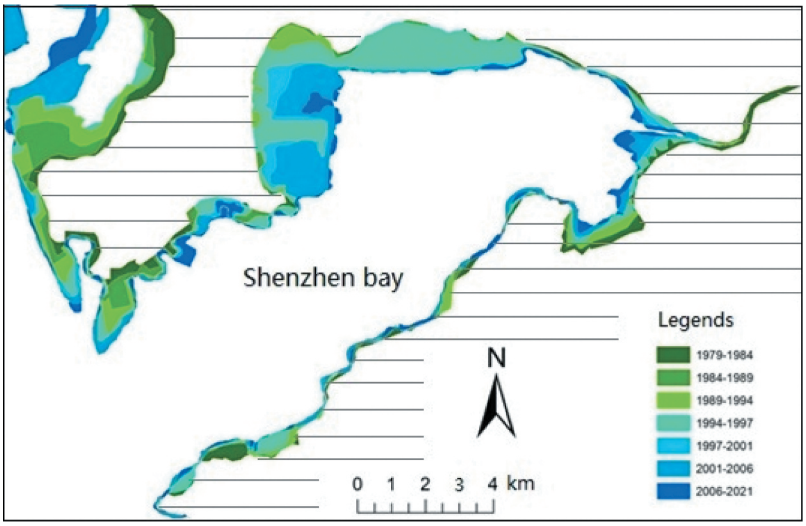

Figure 1. Shoreline changes and beach reclamation in Shenzhen Bay from 1978 to 2021.

2007 to 2015, with a total investment of 50 million US $. These projects aimed to improve the self-recovery ability of the ecosystems in the bay. To achieve this, the city built rainwater and sewage diversion systems that have substantially increased the quality of water that flows into the bay. The engineering design and study team embodied the characteristics of interdisciplinary integration drawing on expertise from water pollution control, constructed wetlands, mangroves, aquatic animals, and ecological restoration. Given the deterioration of river water quality, the degradation of freshwater wetlands and mangroves, and the reduction of biodiversity in the bay, the team designed the whole chain of biological and engineering measures of " initial rainwater interception →initial rainwater purification →brackish water wetland vegetation restoration →watershed water ecosystem restoration," to promote the restoration of the biodiversity through water purification and ecological restoration (Figure 2). The project focuses on the integration of engineering and biological measures. For example, the river slope is replaced by an ecological slope protection system instead of the original concrete bank, which has the functions of flood control and planting plants. We implemented a long-term monitoring project on changes in water quality and biodiversity from 2007 to 2019. The research methods are shown in the references of the relevant parts.

After the sewage is processed in the municipal sewage treatment plants, the treated water is transported to the estuary and is further purified by passage through newly built constructed wetlands, natural wetlands, a restored natural embankment, and restored mangroves (Photo 1). With the resulting improvement in water quality, alien invasive species decreased and native biodiversity in the estuary gradually increased (Huang, Luo, and Hu 2020). Using water pollution control and ecological restoration

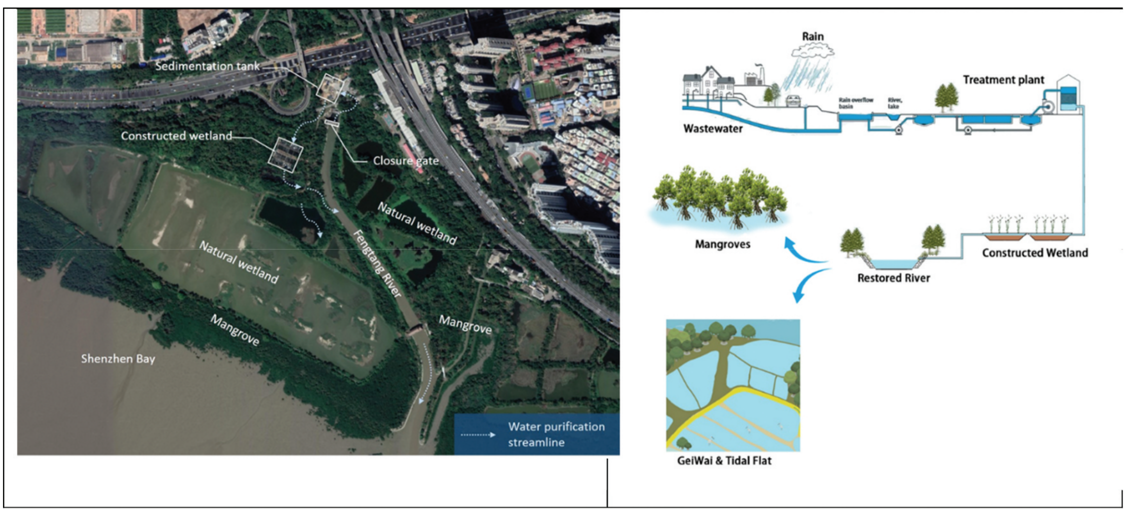

Figure 2. The whole chain of biological and engineering measures of environmental remediation projects. Aerial view (left), Drawn illustration (right). Photographer: Tian-Zhu Ning & Ke Liu.

Photo 1. The water purification process in Shenzhen Bay. Photographer: Tian-Zhu Ning.

in the Fengtang River estuary in Shenzhen Bay as an example, here we provide a framework of how ecological restoration can be achieved in other urban estuaries along the Southern China coast.

Control and primary treatment of surface runoff pollution

By measuring the quantity and quality of rainfall and runoff in five estuaries in the Shenzhen Bay Drainage Basin (estuaries of the Fengtang, Futian, Xinzhou, Baimang, and Xiaosha rivers), we found that during a rainfall event, at least 80% of the pollution load was carried by the first 30% of the surface runoff (Huang, Luo, and Hu 2020). Therefore, the runoff during the first 30 minutes of rainfall (which accounted for 30–40% of the runoff) was intercepted and treated to reduce the non-point-source pollution effectively and economically; this required the construction of additional pipelines in 2007. Although a pipe network system of rainwater and sewage flow diversion had been built in the basin before 2005, the pipelines added after 2006 also made it possible to harvest point-source pollution (urban domestic sewage) in the dry season and to direct the material to a treatment plant. With this treatment of both non-point-source and point-source pollution, the quality of the water leaving the plant has been substantially improved (Table 1).

After flowing through a sedimentation tank, the water treated by the sewage treatment plant then enters a constructed wetland for further treatment. The constructed wetland is filled with oyster shells and is planted with *Brassia caudata, Cyperus papyru, Miscanthus sinensis, Phragmites australis*, and other selected plant species with a strong ability to absorb water pollutants (Photo 2). Oyster shells have a large specific surface area and porosity and are therefore able to adsorb, micro-precipitate, and filter pollutants. The microbial community and plants attached to the oyster shells also improve the water quality (Photo 3). The water then moves from the constructed wetland to the natural wetland, which further increases the water quality before the water moves to the river and then to the bay.

Table 1. Inlet and outlet water quality of the Fengtang River sewage treatment plant (15 October 2012, shenzhen futian district environmental protection monitoring station).

Variable	COD_{cr} (mg/L)	BOD_5 (mg/L)	TN (mg/L)	SS (mg/L)	TP (mg/L)
Inlet water	94.7	28.5	20.3	31.0	1.03
Outlet water	17.4	5.2	2.7	7.0	0.92
Level A standard GB18918-2002*	50	10	15	10	0.5

Note: Chemical oxygen demand chromium (CODcr), biochemical oxygen demand (BOD5), total nitrogen (TN), suspended solids (SS), and total phosphorus (TP).

*Discharge standard of pollutants for the municipal wastewater treatment plant. The State Environmental Protection Administration of China, 2002. Level A is used for clean water that can be drunk after simple treatment (e.g., filtration) and sterilization.

Photo 2. Plants and oyster shells in the constructed wetland of the Fengtang River. Photographer: Tian-Zhu Ning.

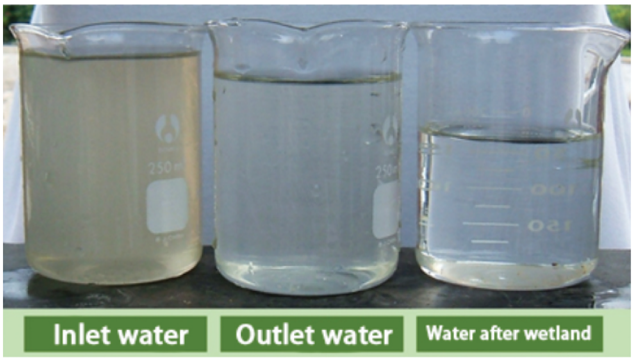

Photo 3. Examples of water that flows into the treatment plant (left), that flows from the treatment plant to the artificial wetland (center), and that flows from the artificial wetland to the natural wetland (right) in October 2012. Photographer: Tian-Zhu Ning.

Ecological restoration of the riverbank

Before the restoration, the bed and bank of the river in the estuary of Shenzhen Bay had been lined with cement (Photo 4, left). The concrete surface was not favorable for minute surface-attached plants and animals. During the river restoration, the concrete surface was replaced with a new type of "hexahedron and bamboo strip slope" protection system. In addition, native plant species were planted to convert the riverbank into a restored natural embankment (Photo 4 right, Photo 5). Through the construction of artificial plant communities in these hexahedrons, ecosystem productivity has been improved and animal and plant diversity has been increased. These treatments further improved the quality of the water flowing into the estuary.

Ecological restoration model: reshaping of the tidal flat–mangrove–*gei wai* system

Tidal flats, mangroves, and "*gei wai*" have long formed a system in Shenzhen Bay (*gei wai* are excavated ponds used for shrimp and fish farming in coastal areas). The

Photo 4. Fengtang River before (left) and after restoration (right). Photographer: Hua-Lin Xu.

Photo 5. The hexahedrons provide a habitat for animals and plants. Photographer: Hua-Lin Xu.

spatial distribution of these components provides effective habitat for waterfowl. The tidal flat is the main place where waterfowl forage. Mangrove communities can meet the food and resting needs of waterfowl. At high tide, fishponds are visited by waterbirds, especially waders. During the ecological restoration of the estuary, different plant communities were established according to the habitat characteristics of the area from the outer bank to the inner bank to restore the riparian vegetation and to establish an integrated "mangrove, semi mangrove, shore-based plant" ecosystem. This integrated ecosystem restored the main functions of the mangrove wetland estuary ecosystem (Yang 2012). At the same time, a certain proportion of fishponds, mangroves, and tidal flats were maintained in the original spatial pattern to provide a habitat and an ecological space for many types of organisms (Photos 6 and 7).

The mangrove plant *Sonneratia apetala* is an exotic species that was introduced into Shenzhen Bay in 1993. The plant grows and reproduces rapidly and is therefore highly invasive (Ren et al. 2009). In addition to posing a threat to the survival of native mangroves, *S. apetala* expands rapidly and occupies most of the tidal flat, crowds with native mangrove plants, and changes the estuary's ecosystem (Photo 8). A goal of the restoration project was to remove *S. apetala* to ensure the stability of the tidal flat area. During this process, the following native mangroves were planted: *Acanthus ilicifolius, Aegiceras corniculatum, Avicennia marina* (Forsk.) Vierh, and *Kandelia obovata*. The river water that left the restored mangroves was 52–74% cleaner than the water that entered the mangroves (Yang et al. 2014). The weed and shrub communities on the land adjacent to *Gei Wai* were also transformed into near-natural plant communities dominated by native trees, which contributed to the restoration of native plant diversity (Photo 9).

Markedly increased ecological benefits

With the described environmental management and ecological restoration steps, the water quality of the Shenzhen Bay Estuary was considerably improved, and the richness and abundance of alien invasive plants were significantly reduced (Ren et al. 2014). The diversity of native plants was also greatly increased, which improved the habitat quality for other organisms. The project ultimately helped to restore the biodiversity in the estuary, and a relatively complete food web was formed (Yang 2012). Our observations indicate that the restored fishponds attracted the black-faced Spoonbill, which is a protected bird that inhabits the restored habitat; its abundance in the estuary increased from 134 in 2005 to 336 in 2021 (Photo 10). The density of phytoplankton significantly increased and provided more food for other organisms without leading to eutrophication or red tide (Table 2, Photo 11). The

Photo 6. The tidal flat–mangrove–*Gei Wai* system of the Fengtang River before restoration (2004). Photographer: Hua-Lin Xu.

Photo 7. The tidal flat–mangrove–*Gei Wai* system of the Fengtang River after restoration (2020). Photographer: Hua-Lin Xu.

Photo 8. The exotic mangrove species *Sonneratia apetala* before (left) and after (right) management. Photographer: Shenzhen Mangrove Wetland Conservation Foundation, China.

Photo 9. Restored native mangroves and terrestrial vegetation. Photographer: Hua-Lin Xu.

Photo 10. Black-faced Spoonbills in the Fengtang estuary. Photographer: Hua-Lin Xu.

Table 2. The biodiversity data before and after ecological restoration.

Biological group	2007	2019
Number of phytoplankton species	52	30
Density of phytoplankton (cell/L)	0.33×10^7	1.07×10^7
Number of macrobenthos species	29	71
Number of waterfowl species	61	72
Individuals of waterfowl	31,782	40,671

Photo 11. Some of the many species of waterbirds that inhabit the restored Fengtang estuary. Photographer: Hua-Lin Xu.

Photo 12. *Prionailurus bengalensis* and *Corvus pectoralis* in the mangroves of the Fengtang estuary. Photographer: Hua-Lin Xu.

macrobenthos species richness increased by more than 50% (Table 2). The number of the waterfowl species and individuals of the waterfowl significantly increased (Sun et al. 2019). A leopard cat was also recorded for the first time in the Fengtang estuary, which is a carnivore that feeds on the birds in the area (Photo 12). The species and abundance of amphibians and reptiles also increased significantly and have subsequently tended to be stable (Photo 13) (Cai 2015).

Photo 13. Macrobenthos and amphibians living in the restored Fengtang estuary. Photographer: Hua-Lin Xu.

Photo 14. A view from the restoration zone toward Shenzhen Bay. Photographer: Hua-Lin Xu.

Conclusions

In the coastal zone of Southern China, the rapid development of large cities led to changes in land use and increased water pollution in many estuaries. The restoration project described in this report reduced the water pollution in the Shenzhen Bay estuary by improving water quality in a step-wise manner as the water flowing from the land to the estuary. With consideration of the integrity and ecosystem health in the flow area, the following components were combined into a complete water-treatment system: diversion of runoff and sewage to a treatment plant, followed by sequential flow through constructed wetland, natural wetland, river, mangrove, and finally into the bay. The project required both engineering measures and biological measures to achieve ecological restoration and to establish a stable and diverse estuary ecosystem. In addition to improving the quality of water flowing into the bay, the project has improved the habitat for coastal plants and animals and has created a more complete food web. The project has substantially increased the biodiversity and ecosystem services in the Shenzhen Bay estuary and suggests that it is possible for humans and other organisms to sustainably coexist in an urban coastal wetland (Photo 14). After the implementation of the Fengtang River estuary ecological restoration project, good ecological benefits have been achieved and investment costs have been saved. It has become a successful example of the ecological restoration of rivers entering the sea in China. Its concepts and technologies have been applied to the Hengqin area (2011) in cooperation with the central government and the Macao Special Administrative Region, the Qianhai area (2012) in cooperation with the central government and the Hong Kong Special Administrative Region, and the Shenzhen Pingshan River mainstream comprehensive treatment project (2018). These concepts and technologies have certain application prospects in estuarine pollution control and ecological restoration in tropical and subtropical coastal areas around the world.

Disclosure statement

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