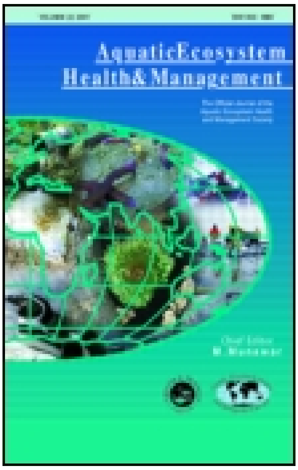

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Water quality remediation in a heavily polluted tidal river in Guangzhou, South China

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Water quality remediation in a heavily polluted tidal river in Guangzhou, South China

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A field-scale experiment was performed to remediate a heavily polluted river located in the urban area of Guangzhou, China using biological and chemical techniques combined with engineering processes. Before comprehensive remediation was undertaken, several small-scale experiments to test river-water remediation techniques were successfully performed. After comprehensive remediation, the average reduction rates of chemical oxygen demand and biochemical oxygen demand and removal rates of other pollutants were all above 70 percent. Furthermore, the unpleasant odor emanating from the polluted river was also greatly reduced. The field-scale experiment thus indicated the feasibility and validity of the method applied to remediate this heavily polluted river; this method can therefore be applied to remediate other heavily polluted rivers in the Guangzhou urban area and elsewhere.

Keywords: comprehensive remediation, bioremediation, aeration, water body

Introduction

With the continuing development of industry, commerce and other fields, Guangzhou is becoming the political, economic, educational, cultural, scientific and technological center of the entire Pearl River Delta. However, with the rapid population growth and development of urbanization and industrialization, increasing amounts of domestic sewage and wastewater are being discharged into the municipal rivers. Although the local government has taken some steps to resolve this problem, the results have not been significant. Therefore, the quality of river water in Guangzhou urban area has been steadily deteriorating. There are 231 rivers running through the Guangzhou area and most of them have been used as drainage ditches in recent decades. The total length of these rivers is about 913 kilometers, and nearly 80 percent of them are directly connected to the Pearl River. Therefore, the pollution of these rivers directly threatens the water quality of the Pearl River in the Guangzhou section (Tao et al., 1999). Unfortunately, the water in some local rivers currently resembles black ink and emits an unpleasant odor (these watercourses are locally referred to as black-odor rivers), and such heavily polluted rivers can be seen almost everywhere in Guangzhou city, especially in arid seasons. Therefore, the study of remediation methods for these rivers is necessary and extremely urgent. In recent years, local governments have implemented a number of efforts to remediate the rivers, such as washing the riverbeds with tidewater, truncating the pollutant drainage and carrying it to the wastewater treatment plant by pipeline, and covering the riverbed with concrete slabs. Washing the riverbed with tidewater consists of opening the

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floodgate at the entrance of the Pearl River when a flood tide occurs and closing it during ebb tide. After the ebb tide, the floodgate is fully opened to allow the water to flow into the Pearl River at a high speed, carrying with it a great quantity of pollutants. This method obviously carries with it a higher risk to the water quality of the Pearl River. Some departments have also used tap water to wash riverbeds, but this is too expensive to utilize in all the rivers. Although truncation of the pollutant drainage entrance and diversion to the treatment plant does achieve some short-term benefits, it also faces many serious problems. First, there are many rivers connected to each other and each of them has a large influx of polluted headwater, and long-distance transportation of the polluted water for treatment is very difficult. Moreover, the task of separating the polluted water from rainwater is also quite complicated. Second, some of these rivers have had a history of pollution problems for over 100 years; there are black and malodorous sediments on the bottoms of some riverbeds exceeding depths of one meter (Sheng et al., 2011). To ultimately remediate the water environment, the question of how to avoid recontamination should first be addressed. Third, after diverting the polluted headwaters, parts of these rivers run dry, exposing the black and odorous riverbeds on sunny days or in arid seasons, with the diffusion of malodorous volatiles over the surrounding area (Muzeeinoglu, 2003; Sheng et al., 2008). Furthermore, this phenomenon would obviously affect the scenic environment of the Guangzhou urban area. Covering a riverbed with concrete slabs also has its disadvantages, making it difficult to dredge with water current when a blockage occurs and affecting the flood discharge on rainy days.

There have been only a few reports in recent years concerning the remediation of heavily polluted rivers (Sun et al., 2009), and most of these studies were focused on the analysis of polychlorinated biphenyls (PCBs), organochlorine pesticides, persistent organic pollutants (POPs), polycyclic aromatic hydrocarbon (PAHs) and other toxic compounds dissolved in the river water or adsorbed in sediments (Fu et al., 2003; Zhang et al., 2004). Techniques using combined biotechnological and engineering steps to remediate heavily polluted rivers have been attracting increasing attention in the environmental-protection field. This study addressed the applicability of using comprehensive bioremediation and engineering steps to remediate a heavily polluted river in Guangzhou urban. The objective was to explore and establish some actual methods or techniques for heavily polluted river water remediation in site. The results of this study demonstrated that the technique employed was feasible and inexpensive, and a long-lasting remediation was achieved.

Materials and Methods

Description of treated river

The experimental river is located in the Fangcun District of Guangzhou. The detailed location is indicated in Figure 1. The total length and average width of this river are $\sim$1,000 m and $\sim$17 m, respectively.

This river was a typical scenic river in recent decades but has now become a black and odorous river, and it greatly diminishes the scenic effect of the beautiful buildings alongside it. The headwaters of this river consist mainly of domestic sewage and a small quantity of industrial wastewater. Of course, irrigation water and rainwater also feed into this river periodically. The total influent volume of domestic sewage and industrial wastewater fed from the upriver drainage is about 1,000 m^3 per day. The depth of the river is about 0.1–1.2 m, and the thickness of the sedimentary sludge is about 0.2–0.7 m (a length about 400 m of the bottom of this riverbed was covered with stones in 1997). The height of the riverbank is about 3.6 m; it was built with concrete and large stones in the last few decades.

Microbial culture and small-scale tests

Microbial culture

Two kinds of microbial reagents were utilized in this work. The dominant microbes in these reagents were photosynthetic bacteria (PSB) and *Bacillus subtilis*. PSB are microorganisms that use sunshine as energy source and use naturally occurring organic compounds and sulfur compounds for nutrition (Chen et al., 2000). In addition to these characteristics, they also can perform photosynthesis alone to remove the pollutants dissolved in a polluted water body. In this study, samples containing PSB were collected from the sedimentary sludge of the Fangcun River (the treated river). After a series of enrichment, culture, separation and purification steps, this PSB culture was identified as

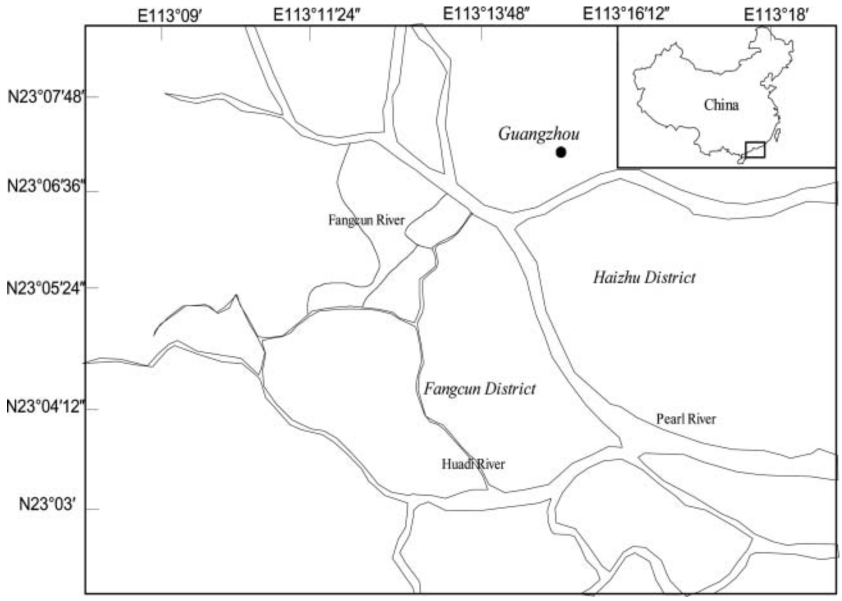

Figure 1. The location of the treated river (Fangcun River).

belonging to the *Rhodopseudomonas* group. Culture medium mainly composed of CH_3COONa, NH_4Cl, NaCl, $MgSO_4$, KH_2PO_4, K_2HPO_4, $CaCl_2$ and yeast extract, ferment conditions were of temperature 30°C, pH 7.5- 8.5, inoculation 20% and 40-watt-bulb illumination. After six days, the bacterial abundance of PSB reached to 3–5 billion cells per milliliter. This original reagent can be used directly through proper dilution. Another microbial reagent applied in this experiment contained a great deal of *Bacillus subtilis*, and was also selected from the Fangcun River, carried on the complex clay. Its main function was to remediate the heavily polluted sedimentary sludge and degrade dissolved pollutants (Aiying et al., 2005). Several other chemicals used in this test were purchased from local markets in Guangzhou.

The methods and process of the small-scale tests were as follows. Water samples were taken from the river in clean barrels and transported to the laboratory within six hours, then transferred to beakers. The beakers were placed in a constant-temperature incubator, and different concentrations of a PSB suspension were added to each beaker. Finally, different temperatures and lighting times were set and microbial growth was observed. These results indicated that the appropriate addition of PSB was 10 mg l^{-1}. Using the same method, 10 mg l^{-1} also was determined to be the appropriate addition of *Bacillus subtilis* powder.

Artificial aeration

Dissolved oxygen (DO) is an important water-quality parameter. At a DO concentration below 2 mg l^{-1}, the creatures living in a water body will be endangered, even including several microorganisms. Furthermore, sufficient DO in water body can allow for the direct oxidation and rapid degradation of pollutants. Thus, increasing the DO concentration in water body is one of the most important steps in remediating polluted water. However, the DO concentration in the tested river water was almost zero. Therefore, artificial aeration was applied in the small-scale experiments, as follows. Three clean glass boxes were prepared in an open field near the lab, all of the same dimensions: 0.5 × 0.5 × 0.3 m (length, width and height, respectively). A circular hole, 0.15 m in diameter, was cut in the top of surface. The water samples and sediment samples were taken from the river with clean plastic buckets and plastic membrane, respectively. Two of boxes were filled with sediment to a depth of 2 cm on the bottom and covered with 40 L of river water in each. An air pump and a water pump in one of boxes were used as an aerator and blender, respectively. The second tank had only a small water pump in it to circulate the water constantly. A third tank was filled with 40 L of fresh tap water without any pumps as a control. At the beginning of the test, optimal quantities of PSB suspension and *Bacillus subtilis* powder were added to all three tanks.

Field-scale experiment

To maintain sufficient hydraulic retention time and ensure the growth and reproduction of the microbial system, two dams were constructed upstream and downstream of the test section of the riverbed. Because the most important function of these municipal rivers is draining floodwater to the Pearl River in the rainy season, the height of these dams was only 0.8 m. Such dams should not influence flood drainage, but should contain the polluted water sufficiently so as to maintain an appropriate retention time (~20 h) to affect some degree of pollutant removal. Furthermore, this method allows the riverbed bottom to remain constantly covered with water, resulting in improved environmental aesthetics. Four floating waterwheels and four sets of aeration pumps were used as aerators located at different sections of the water surface. All the floating-waterwheel aerators were located on the wider section of the river (at a width of ~25 m) and all the pump aerators were located on the narrow section (width ~13 m). The power consumption of these aerators was 1.5 KW and 0.75 KW, respectively; they were purchased from Zhejiang Fordy Machinery Co., Ltd. (China). The biological reagents were distributed equally over the river surface from a small boat. The reagents were directly diluted with river water before inoculation. The dosing levels of biological reagent were calculated with the water volume capacity between two dams, and the concentration was maintained at about 10 mg l^{-1} in water bodies by supplying biological reagent periodically. Dosing frequency was biweekly at the beginning; as the experiment progressed, the dosing frequency was decreased according to the conditions of the recovering river-water quality.

Detection methods

All pollutants in this study were detected with the methods specified in the State Standards of China, as follows: suspended solid (SS), GB/T11901-1989; chemical oxygen demand (COD_{Cr}), GB/T11914-1989; biochemical oxygen demand (BOD_5), HJ/T86-2002; sulfide, GB/T16489-1996; ammonia-N (NH_3-N), GB/T7479-1987; total-nitrogen (TN), GB/T 11894-89; total phosphorus (TP), GB/T 11893-89. DO and temperature were measured using a YSI 550A Handheld Dissolved Oxygen and Temperature System purchased from TechTrend International Limited, USA.

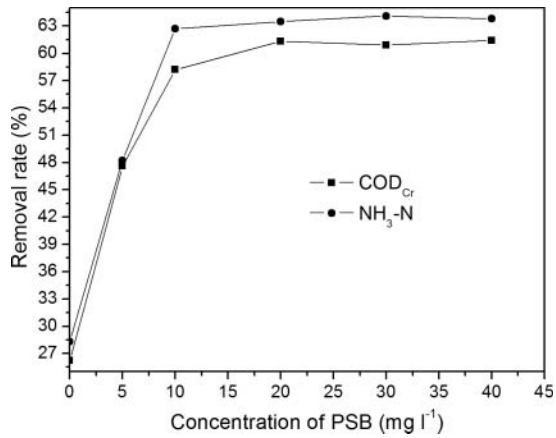

Figure 2. Relationship between removal rates and concentrations.

Results and Discussion

Suitable concentrations of reagents and operating conditions

The removal rates of COD_{Cr} and NH_3-N using different concentrations of diluted PSB suspension were determined in the small-scale experiments. The purity level of all chemical reagents used in the analysis was analytical reagent or better. The relationship between PSB concentration and removal rate is illustrated in Figure 2. Data were obtained under the following conditions: artificial illumination at 40 watts, a temperature of 30° and 96 h of biological reaction time. The original concentration of COD_{Cr} was 169.8 mg l^{-1} and that of NH_3-N was 36.4 mg l^{-1}.

The results of the small-scale experiment indicated that the removal rate increased with the increase of PSB concentration. However, the removal rate showed no further increase when the concentration was above 10 mg l^{-1}. Therefore, 10 mg l^{-1} was regarded as the most appropriate concentration for the remediation of the polluted water body. The COD_{Cr} and NH_3-N removal (corresponding removal rate are all over 60%) indicated that PSB degraded large quantity of pollutants dissolved in water bodies, and the nearly unchangeable removal rate maybe indicated that adding excessive PSB could not make further removal of pollutants, without regarding to self-pollution of PSB solution. At the end of the test, a 2-mm thick layer on top of the sediment sludge in the beaker with PSB added had become obviously lighter in color. This phenomenon indicated that selectively cultured microorganisms

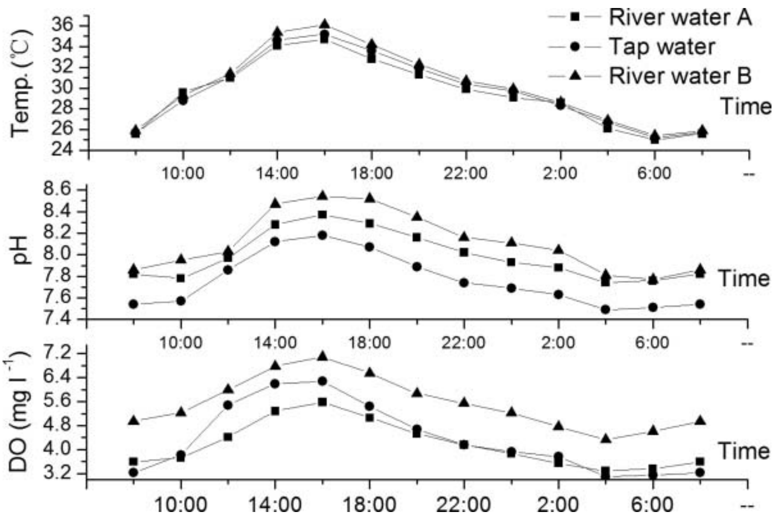

Figure 3. Variations in DO, pH and temperature over 24 h.

can not only degrade the pollutants in water body, but can also strengthen the cleansing abilities of the microorganisms naturally occurring in sediments. Using the same experimental technique, similar results were obtained for the *Bacillus subtilis* powder added to the polluted water under the same operating conditions as with the PSB. Unexpectedly, the removal rate of the parallel control test (without the addition of PSB or *Bacillus subtilis*) also reached nearly 30 percent. The reasons for this phenomenon were likely related to the fact that when the polluted water was not flowing, some pollutants in the water body would be deposited on the sediment, effectively decreasing the level of suspended pollutants. Furthermore, native microorganisms in the polluted water body could also have degraded the pollutants to some extent.

The effects of temperature and illumination on the removal rate were also studied. The results indicated that a higher temperature was beneficial for increasing the removal rate. The illumination test indicated that sufficient illumination could increase the removal rate by over 20 percent. Overall, the best time for dosing the bioreagents was in the morning on a sunny day.

Effects of artificial aeration

To determine the appropriate aeration time and intensity, three different water bodies were tested; detailed descriptions of the results are shown in Figure 3. *River water A* was incubated without additional action applied in its tank, but *River water B* was aerated and stirred by a small pump throughout the testing period. The date of experiment was August 10, 2004, a sunny day.

An obvious relationship can be seen in Figure 3 for three factors: DO, pH and temperature. The reasons were perhaps that plentiful oxygen was released into the water as the microbial and algal activity was intensified with increasing temperature and stronger illumination. Simultaneously, the abundant dissolved carbon dioxide was consumed by algae and some bacteria during photosynthesis (Neal, 1998). The synchronization in the variations of DO, pH and temperature were also perhaps correlated with the intensity of aeration and illumination, respiration or photosynthetic activity of the microbes, or other environmental factors (Tadesse et al., 2004; Tare et al., 2003; Pedersen, 2000). Another result was evident from these data: the increase of DO was mainly dependent on natural atmospheric aeration, and artificial aeration was only suitable for emergent conditions or some special periods. Furthermore, constant mechanical aerating raises the operating cost, and provides only a small advantage in DO, even with the tap water.

Variability of COD_{Cr}, TN, TP in different test water bodies

While observing the variability of DO, the COD_{Cr}, TN and TP were measured every three days to determine the how the comprehensive removal efficiency of the pollutants was influenced by biological reagents with artificial aeration. All pollutant

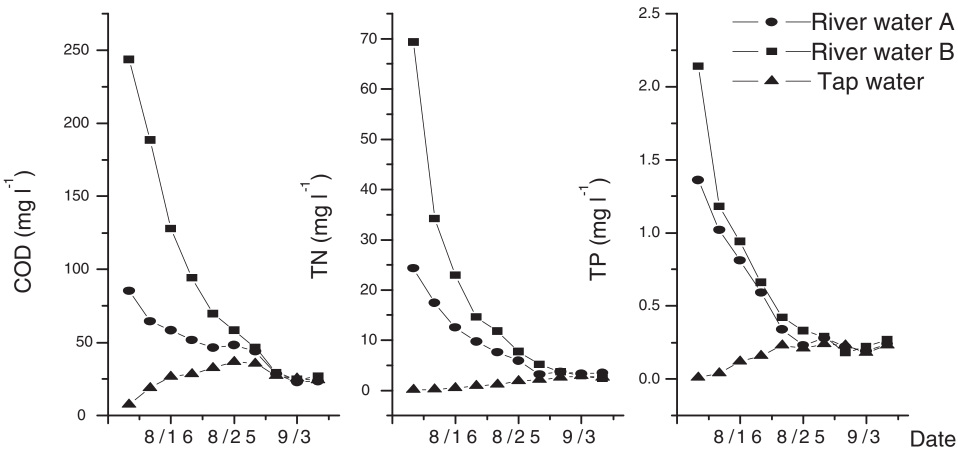

Figure 4. Variations of CODcr, TN and TP in different water treatments.

parameters were analyzed in the laboratory according to the State Standards (China); detailed results are shown in Figure 4.

The initial concentrations of each pollutant were detected on the first day of the experiment. The great difference in initial concentrations between *River water A* and *B* was mainly caused by the strong stirring in tank *B*, which distributed the sedimentary sludge throughout the water, leading to a higher measured pollutant level. The sampling and analysis time was chosen at 10:00 a.m. It can be seen from the test data that higher a DO in a water body provided for stronger oxidation, especially at the beginning of experiment, during which the reduction of all pollutants reached nearly 80 percent. However, after running the experiment for two weeks, the trend of pollutant decrease leveled off, and the differences in these water samples were no longer evident (i.e. the pollutant levels in these three water treatments were similar). The reason for these results was perhaps because the systems of all these water treatments were close to equilibrium. In contrast, all the pollutant levels in tap water showed a continuous increase from the beginning to the end of the experiment. Furthermore, the color of water turned from clear to pea green, and a great deal of algae and some zooplankton were produced in this tank. It was obvious that external pollution from ambient air played an important role in the extent of pollutant increase.

Field-scale test

Based on the results of the small-scale tests, a field-scale test was undertaken in October, 2004. The conditions of the river water and sewage drained from a spray drain at the beginning of the experiment are listed in Table 1.

It was obvious that the tested river was heavily polluted (Table 1). The clarity of this polluted river water was only ~8 cm (as determined by the use of a Secchi disk), and an obvious unpleasant odor could be smelled while standing near the bank. Many gas bubbles were continually released from the sediment under the black water. There were almost no algae or zooplankton living in the water body. After two months of comprehensive remediation, the ecosystem in the water body gradually began to recover. The detailed variations in the measured data during the period of comprehensive remediation are listed in Table 2. The data are reported as the average values of samples taken from three different locations.

Table 1. Average pollutant concentrations in river water and sewage (mg l^{-1}).

	SS	COD_{Cr}	BOD_5	Sulfide	NH_3-N	DO
River water	97	189	97.5	1.05	45.6	0.12
Influent sewage	117	426	164	1.14	60.9	ND

SS: suspended solids; ND: not detected.

Table 2. River-water quality during the experiment (units: mg l^{-1}).

	SS	COD_{Cr}	BOD_5	Sulfide	NH_3-N	DO
Oct. 10th	127	189	97.5	1.05	45.6	0.12
Oct. 18th	70	126	76.5	0.28	34.6	0.88
Oct. 26th	60	88	50.5	0.19	22.8	2.27
Nov. 3rd	110	135	90	0.22	27.9	1.06
Nov. 11th	85	91	64	0.08	16.5	2.93
Nov. 19th	70	72.4	47.6	0.05	11.9	3.62
Nov. 27th	66	54.1	36.5	ND	5.22	4.29
Dec. 5th	68	46	28.5	ND	4.03	4.07

ND: not detected.

Sampling time was fixed at 10:00 a.m.; all samples were analyzed within eight hours. These steps were performed once a week.

Except for SS, the total removal rates for each pollutant all exceeded 70 percent. DO increased dramatically during the remediation process. The SS concentrations were nearly constant; the stirring of the water body by the aerators was the most likely reason. Two months after the beginning of the experiment, the DO concentrations exceeded 3.5 mg l^{-1}, at which point all running aerators were stopped. On 3 November 2004, the concentrations of various pollutants all increased abruptly due to the inrush of a huge flood tide into the river. When such incidents occurred, a calculated quantity of supplementary reagents should be dosed immediately, and the aerators should be operated simultaneously.

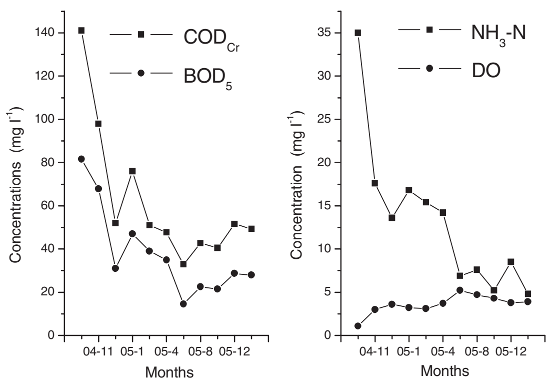

Figure 5. Monthly variation of pollutant concentrations.

Present conditions of the tested river

After two months of continuous comprehensive remediation, the quality of the water body showed an obvious improvement. The sporadic work of dosing reagents and cleansing the river water surface are only needed at present to maintain a fairly good water environment, because a preferable biota has been built up in the water body. Pollutant levels have remained stable; the monthly river-water quality data are shown in Figure 5.

In Figure 5, the data corresponding to the period from October, 2004 to February, 2006 were obtained monthly, but the subsequent data were obtained only every two months. There were a great numbers of algae and zooplankton living in the river, even a number of fish. The release of odor from the river water was obviously reduced. The river now has a stronger capability to cleanse itself, and some pollutants have reached or are approaching levels meeting Degree V of the State Standards for surface water (GB3838-2002, China), listed in Table 3 for comparison. In contrast to other common methods, bioremediation method is the preferred method for its lower cost, convenience, feasibility and sustainability, the cost was only about $14,000 per kilometer (nearly ¥100,000) in study site.

Although the water quality in the treated river section did not fully meet the qualifications of the

Table 3. Comparison of treated river-water quality and Degree V of the State Standards for surface water (units: mg l^{-1}).

	COD_{Cr}	BOD_5	Sulfide	NH_3-N	DO	TN	TP
River water	43	17.2	0.08	4.22	4.69	6.1	0.8
Degree V standard	40	10	1.0	2.0	2.0	2.0	0.2

State Standards for surface water, dramatically improved aesthetic qualities were provided to the surrounding area and the anticipated objectives of the test were achieved. Therefore, in order to bring the water quality to the acceptable levels, another accessorial technique may be needed, such as bioremediation with aquatic plant floating island construction, and its detailed efficiency needs further study.

Conclusions

A feasible and effective method using a combination of biological techniques and engineering steps was applied to remediate a heavily polluted urban river. A mass of selectively cultured microorganisms can not only consume the pollutants in a water body, but can also strengthen the self-cleansing abilities of natural microorganisms living in the water body or sediment sludge. When the concentrations of DO exceed 4 mg l^{-1}, the aeration should be stopped, and artificial aeration used afterward only for emergencies. This inexpensive means of comprehensive remediation can be applied to other heavily polluted rivers in the Guangzhou urban area.

The disadvantages of this technique lay mainly in two aspects. First, even after performing a number of processes, the water quality still did not meet the levels mandated in the State Standards. This problem should be studied in more depth in the future. Second, building dams on a riverbed does pose a certain level of flooding risk during the rainy season, although their height was only 0.8 m. Special floodgates may perhaps be more appropriate for maintaining a sufficient hydraulic retention time to remediate the heavily polluted river water.

Acknowledgements

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