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Sheng, Y., Qu, Y., Ding, C., Sun, Q. and Mortimer, Robert ORCID logoORCID: <https://orcid.org/0000-0003-1292-8861> (2013) A combined application of different engineering and biological techniques to remediate a heavily polluted river. *Ecological Engineering*, 57. pp. 1-7.

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1 **A combined application of different engineering and biological techniques to**
2 **remediate a heavily polluted river**

3
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10
11 **Abstract**

12 River pollution is becoming a serious problem worldwide. A field-scale experiment
13 was undertaken to remediate a heavily polluted river using a combined engineering
14 approach of aeration, microorganisms, biological aerated filtration, artificial biofilms
15 and ecological floating beds. Prior to remediation, the river water was black, anoxic and
16 highly sulfidic. With remediation, the chemical oxygen demand decreased from ~250 to
17 ~50 mg L⁻¹, NH₄⁺-N decreased from ~27 to ~4 mg L⁻¹, sulfide decreased from ~3 to
18 ~0.3 mg L⁻¹, and total suspended solids decreased from ~270 to ~40 mg L⁻¹. At the
19 same time, dissolved oxygen increased from ~0.1 to ~3.5 mg L⁻¹, and water clarity
20 increased from ~6 to ~40 cm. Furthermore, the unpleasant odor emanating from the

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1 polluted river was also stopped, and local farmers have begun using the water for
2 irrigation. This field-scale experiment thus indicates the potential usefulness of this
3 combined engineering approach to remediate heavily polluted rivers.

4
5 **Keywords:** Polluted river; Aeration; Biological aerated filter; Bioremediation; China

6
7 **1. Introduction**

8 Rapid industrialization, urbanization, and population growth has led to the pollution of
9 rivers and degradation of ecosystems, especially in municipal rivers in developing
10 countries (Scholes et al., 2008; Longe and Omole, 2008). River water is easily polluted
11 by domestic wastewater effluent, rainwater, agricultural run-off, and industrial
12 wastewater, which result in severe degradation of water quality, the water becoming
13 black and odorous, and loss of fish (Scholes et al., 2008; Palmer, 2009; Caraballo et al.,
14 2011). In northern China, the majority of rivers have been used for agricultural
15 irrigation due to the shortage of water, especially in arid seasons. However, most of
16 these rivers have become heavily polluted. Sewage is one of the main components of
17 municipal river water in northern China, and Zhang (2008) demonstrated that long-term
18 sewage irrigation influences soil microorganisms and soil quality. Accordingly,
19 remediation of river water quality has become a significant concern, both regionally and
20 worldwide (Alvarez-Vázquez et al., 2009; Sheng et al., 2012). In situ bioremediation is
21 a potentially effective process for purification of polluted surface water (Everard and

1 Moggridge, 2012; Zhao et al., 2012). Indeed, many in situ remediation processes such
2 as ecological floating bed techniques and constructed wetlands have been developed for
3 bioremediation of polluted surface waters (Sun et al., 2009; Vymazal, 2009; Wu et al.,
4 2011). However, these techniques have many disadvantages, such as being
5 time-consuming, costly and requiring significant space (Zhu et al., 2011; Meyer, 2012;
6 Saeed and Sun, 2012). Techniques using combined biotechnological and engineering
7 methods to remediate heavily polluted rivers have been attracting increasing attention in
8 the environmental protection field (Arini et al., 2012; Sheng et al., 2012). This
9 combination and proximity of different engineering and biological techniques are of
10 importance for the overall removal effectiveness and are amongst the key advantages of
11 polluted water remediation in rivers, as compared to other technologies. There have
12 been only a few reports concerning the remediation of heavily polluted rivers (e.g. Sun
13 et al., 2009; El-Sheikh et al., 2010; Wu et al., 2011), and most of these studies were
14 focused on off-line treatment or laboratory work (e.g. Li et al., 2009; Palmer, 2009; Cao
15 et al., 2012). This study focused on the application and efficiency of a comprehensive
16 engineered bioremediation process for a heavily polluted river using a combination of
17 aeration, microorganisms, optimized biological aerated filters (BAF), biofilms and
18 ecological floating beds. The targets of this engineering are 1) decreasing the COD
19 under 60 mg g^{-1} ; 2) decreasing the $\text{NH}_4^+\text{-N}$ under 6 mg g^{-1} ; 3) ensuring the water quality
20 is suitable for fish. Because there was no fish in tested river, so fish addition was
21 necessary. The two objectives of our study were: (1) to assess the feasibility of applying

1 different in situ treatment units to remediate a heavily polluted river; and (2) to evaluate
2 the water quality improvements and removal efficiency of chemical oxygen demand
3 (COD_{Cr}), ammoniacal nitrogen ($\text{NH}_4^+\text{-N}$) and other pollutants under continuous flow
4 conditions.

5

6 **2. Materials and methods**

7 **2.1. Description of treated river**

8 The Dihe River is located in the Changyi, Shandong province, northern China
9 ($36^\circ 25' 36''\text{N}$, $119^\circ 13' 42''\text{E}$). The climate is cold and dry in spring and winter, and warm
10 and wet in summer and autumn, and is characterized by annual precipitation of $\sim 630\text{mm}$
11 and an average temperature of 11.9°C . The experimental reach is 23km long, and
12 averaged 30m in width and 0.6m depth. This river is a drainage river, originating from
13 the Changyi City urban area, carrying about 80% of the municipal sewage of the
14 city, which amounts to 90,000 tons per day. At the start of the study, the river water
15 resembled black ink and gave off an unpleasant odor due to H_2S (this watercourse is
16 locally referred to as the “black-odor river”) (Wu et al., 2012). The thickness of
17 sedimentary sludge on the river bed exceeded 1 m , and this contained many toxic
18 compounds, including Dechlorane Plus and organochlorine pesticides (Zhao et al., 2011;
19 Zhong et al., 2011). Because of the serious pollution problem, local farmers had given
20 up using this river water for irrigation many years ago. Although the local government
21 has dredged and flushed the channel many times to try to resolve this problem, this has

1 had little impact. Therefore, the water quality of this river has been steadily
2 deteriorating, ultimately threatening the coastal water quality of Laizhou Bay, Bohai Sea,
3 an important fishery.

4 **2.2. Design of field-scale experiment**

5 One bar screen and three dams were constructed from upstream to downstream (5
6 Km interval) to maintain sufficient hydraulic retention time (~24 h) to ensure the growth
7 and reproduction of the microbial system in the filters and on the biofilm substrate in
8 the river. Each dam has a floodgate (2 m width) to drain floodwater in the rainy season.
9 The height of these dams is 0.8 m, with two 20 cm high steps (~40 cm interval) on the
10 downstream slope (obliquity is ~30°) to aid oxygenation. Nine floating waterwheels
11 (power consumption 1.5 KW; Zibo Tianmiao Marine-biological Technology Co., Ltd,
12 Zibo, China) were placed within the experimental reach for use as aerators. The
13 schematic diagram of the field-scale engineering set-up is shown in Fig. 1. The detailed
14 elements of the engineering process were: 1) setting a steel bar screen in area S1 to
15 prevent floating rubbish (Fig. 1); 2) constructing dams in areas S2, S3 and S4 to
16 maintain enough hydrological retention time; 3) installing aerators in area S1, S2 and S3
17 at the beginning of the field experiment; 4) installing ecological floating beds with some
18 local hydrophytic plants (such as cannas, candocks) in area S3; 5) dosing with
19 microbiological reagents in areas S1, S2, S3 and S4 (Fig. 1).

20

21

Fig. 1

1

2 High DO can enhance the removal of nutrients in water bodies (Albuquerque et al.,
3 2012). In order to increase the DO in river water, aerators were installed in reach
4 sections S1, S2 and S3 (Fig. 1) for emergency oxygenation at the beginning of the
5 project or after heavy rain (wastewater and sewage will be discharged directly during
6 heavy rain). Furthermore, the downstream slope of each dam was designed with two
7 steps to further aerate the falling water.

8 Biofilm techniques are helpful in remediating polluted surface water (Fechner et al.,
9 2012). The carrier for biofilms directly influences treatment efficiency and energy
10 consumption (Cao et al, 2012). Inert carriers have a relatively long film-forming culture
11 time and lower biomass for bioremediation of polluted surface water. Therefore, it is
12 essential to seek a better carrier for more rapid biomediation of polluted surface water.
13 In this study, Beier Film (patent protected, with 200-300 m² m⁻³ specific surface area for
14 microorganisms, Zhongyu Ecological Science and Technology Co. Ltd. Zhongshan,
15 China) was used as artificial biofilms. This was suspended in the river water (S2 and S3,
16 Fig. 1) by ropes with floats in order to increase biomass and prevent added organisms
17 (microbial reagents) from flowing away with the river current.

18 In order to enhance the purification by ecological floating bed (Hadad and Maine,
19 2007; Shan et al., 2011; Jia et al., 2011), local hydrophytic plants were used to set up
20 ecological floating bed along the riverbank at different locations. In order to recover the
21 river ecosystem also improve its aesthetic appeal, mechanical aeration, biological

1 aerated filters, artificial biofilms and ecological floating bed all were combined.

2 **2.3. Microbial reagents application**

3 Addition of Photosynthetic bacteria (PSB) reagents and *Bacillus subtilis* powder can
4 enhance the activity of organisms and aid improvements in water quality (Sheng et al,
5 2012; Khan et al., 2012). PSB and *Bacillus subtilis* are found in many natural aquatic
6 environments, where they remove pollutants (i.e. sulfide, $\text{NH}_4^+\text{-N}$) and enhance
7 biological activity and water quality (Chen et al., 2000; Sheng et al., 2012; Nimrat et al.,
8 2012). PSB are microorganisms that use sunlight as their energy source and use
9 naturally occurring organic compounds and sulfur compounds as electron donors for
10 photosynthesis (Chen et al., 2000). In this work, PSB were collected from the
11 sedimentary sludge of the Dihe River (the treated river) after a series of enrichment,
12 culture, separation and purification steps. Another microbial reagent (*Bacillus subtilis*)
13 applied in this experiment was also selected from the Dihe River, carried on the
14 complex clay. PSB and *Bacillus subtilis* were used to enhance the purification of the
15 polluted river water and remove C, N, and remediate the heavily polluted sedimentary
16 sludge (Sheng et al 2012; Lu et al., 2012). PSB microbial reagent (total viable count
17 $\sim 4 \times 10^9$ cfu g^{-1}) and *Bacillus subtilis* reagent (total viable count $\sim 5 \times 10^8$ cfu g^{-1}) were
18 from Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences. A
19 dosage rate of 10 mg L^{-1} was selected as the most appropriate concentration for PSB
20 and *Bacillus subtilis* to remedy the polluted water body (Sheng et al., 2012). In the field,
21 the levels of biological reagent were calculated with the water volume capacity between
22 two dams and runoff. The microbial reagents were directly diluted with river water and
23 distributed evenly over the river surface. Dosing frequency was weekly at the beginning
24 of the experiment, but was then decreased each month as the engineering progressed,
25 based on the measured quality of the recovering river-water.

26 **2.4. Filter materials, biofilms, ecological floating bed and fish fry preparation**

27 Media used in biological aerated filters (BAF) must have suitable specific surface

1 area to allow good biofilm development (Albuquerque et al., 2012). A mixture of
2 converter slag and coal cinder can be used as adsorbent for the removal of phosphorous,
3 COD and $\text{NH}_4^+\text{-N}$ (Yang et al., 2009). Coal cinders produced by a local electricity
4 factory were selected as filter materials for this field experiment. The diameter of these
5 irregular cinders was ≥ 10 cm. They were packed in a nylon net bags (mesh diameter ~6
6 cm), each containing ~30 Kg of cinders. During the field experiment, these cinder bags
7 were overturned periodically to rinse to unclog them and allow better flow-through to
8 be reestablished. Beier Film was suspended in the river water to increase biomass and
9 prevent added organisms from flowing away with the river current.

10 Macrophyte restoration using floating, emergent and submersed plants is considered
11 crucial to regulating lake biological structure, limiting algal growth by competing for
12 nutrients and sunlight, and also increasing herbivorous fish biomass by providing food
13 and refuge (Thie'baut et al., 2006; Brisson and Chazarenc 2009; Li et al., 2010). Planted
14 floating-beds can be used for treating eutrophic water in a simple and cost-effective
15 manner (Nahlik et al., 2006; Hadad and Maine, 2007; Li et al., 2010). Plants using for
16 ecological floating beds in this work were local hydrophytic plants, such as *aquatica*,
17 *candocks*, and water spinach (*Ipomoea aquatica Forsk.*). Some of them are vegetables
18 in China and are also widely used for water pollution control (Li et al., 2007; Song et al.,
19 2009). Water spinach has a world-wide distribution in tropical and subtropical warm
20 regions and is a fast-growing herbaceous vine commonly found along muddy stream
21 banks or floating in freshwater marshes and ponds. The framework of floating bed was

1 made using 10cm diameter bamboo and was 2.5 m long and 1.5m wide. Fish fry in this
2 work were purchased from local fishery, they were *ctenopharyngodon idellus* and
3 cyprinoid fish with length ~8 cm. During the engineering process, when the COD and
4 $\text{NH}_4^+\text{-N}$ decrease to 80 and 8 mg g^{-1} , and the DO exceeding 2 mg L^{-1} , then the fry were
5 added.

6 **2.5. Sampling and analysis**

7 All sampling equipment and storage containers were cleaned with distilled water
8 before use, and all water samples were collected without disturbing the sediment-water
9 interface. Water samples were collected in 500-ml polypropylene bottles from
10 mid-stream at about 0.2 m below the water surface. The bottles were completely filled
11 with water (no bubbles or headspace), sealed with gastight screw caps, and kept in an
12 icebox under an inert (N_2) atmosphere. Water samples were collected at site S4 at
13 regular intervals and were analysed in triplicate within 24 h. Chemical oxygen demand
14 (COD_{Cr}), total suspended solid (TSS), sulfide (total S^{2-}), $\text{NH}_4^+\text{-N}$ and Total dissolved P
15 (TP) were measured with the methods specified in the standard methods for the
16 examination of water and wastewater (APHA, 1998). DO, pH and temperature (T) were
17 measured using a YSI 550A Handheld Dissolved Oxygen and Temperature System
18 purchased from TechTrend International Limited, USA. A secchi disc was used to
19 measure water clarity. Surface sediments were collected using a stainless steel spatula
20 and were immediately placed in 250-ml polypropylene containers. The containers were
21 fully filled with sediment and sealed with gas-tight screw-caps. Before analysis, all

1 sediment samples were homogenized by mixing with a glass rod under a stream of N₂.
2 Total organic carbon (TOC) was determined by Shimadzu TOC-VCP (Japan), and total
3 sulfur (TS) and total nitrogen (TN) were determined using an Elemental Analyzer
4 (Elementar, Vario EL cube, Germany). The purity level of all chemical reagents used in
5 the analysis was analytical reagent or better, and analytical precision was to within < 5%.
6 The glassware and plastic ware were soaked in 1M HCl and rinsed with de-ionized
7 water prior to use.

8 The initial fieldwork was conducted on May 15th, 2010. About one month later, a
9 steel bar screen, three dams and boiler coal cinders bags were prepared. On July 10th,
10 section S1, S2, S3 and S4 were filled with river water, then aquatic fibre films and
11 ecological floating bed were conducted in corresponding sections (Fig. 1). Water
12 samples were collected at S4 and analyzed every 15 days to determine the removal
13 efficiency.

14

15 **3. Results and discussion**

16 **3.1. Characteristics of water quality and sediment of tested river**

17 The concentrations of different pollution parameters in the water samples and
18 sediments are presented in Table 1 (sampling and analysis date was June 5th, 2010). For
19 water samples, the average concentrations of COD_{Cr}, TSS, TP and NH₄⁺-N were much
20 higher than the lowest Chinese Standard level (V), US Standard and EU Standard level
21 of surface water quality (Table 2). For COD_{Cr}, this river is similar to the Ciliwung River

1 in Indonesia but higher than Koayase River in Japan (Kido et al., 2009). In terms of
2 overall pollution level, this river is similar to the Borkena River in Belgium and rivers
3 in some developing countries (Beyene et al., 2009). The average concentrations of
4 TOC, TN and TS in surface sediments were 7.8 wt %, 1.4 wt % and 0.8 wt %, respectively.
5 The clarity of this polluted river water was only ~5 cm, and there was an
6 obvious unpleasant odor of H₂S (Wu et al., 2012). We observed almost no algae or
7 zooplankton living in the water body. Sediment sulfide and total Fe concentrations
8 reached to 6.3 mg g⁻¹ and 15.2 mg g⁻¹ respectively, showing that conditions were highly
9 anoxic. Therefore, the remediation strategy was based around oxidation of the iron and
10 sulphide, together with providing an enhanced microbial and plant community to help
11 tackle the elevated TOC and nutrients that were driving the anaerobic microbial activity.

13 **Table 1**

15 **3.2. Remediation efficiency for COD_{Cr}, NH₄⁺-N and TSS in downstream**

16 The initial concentrations of each pollutant were measured on the first day of the
17 fieldwork. All pollutant parameters were analyzed in the laboratory except for pH, T and
18 DO. Detailed results are shown in Fig. 2. COD_{Cr} decreased from 232 to 37 mg L⁻¹, then
19 increased to ~50 mg L⁻¹, which is close to the level V Chinese Standard (40 mg L⁻¹).
20 NH₄⁺-N decreased from 22.6 to 3.3 mg L⁻¹, then increased to ~ 5 mg L⁻¹, which was
21 still higher than level V Standard (2 mg L⁻¹). It can be seen from Fig. 2 that after 21st

1 August, the reduction of COD_{Cr}, NH₄⁺-N and TSS reached ~85 percent. This
2 phenomenon can be explained by following processes: 1) the hydraulic retention time
3 was prolonged by constructed dams, which enhanced the sedimentation of pollutants
4 and suspended solids in the river water; 2) the artificial aeration increased the DO level
5 in water body, which provided stronger oxidation to degrade the pollutants
6 (Albuquerque et al., 2012); 3) after one month, the microbial community in the water
7 body, BAF and artificial biofilms will have built up, enhancing the removal of
8 pollutants (Cao et al., 2012; Sheng et al., 2012); 4) the plant roots of the ecological
9 floating bed began to consume the C, N, P as nutrition (Hadad and Maine, 2007; Jia et
10 al., 2011). In this work, filter materials (coal cinders) used in BAF and artificial biofilms
11 (Beier Film) have specific surface area for biofilm production, providing living space
12 for PSB, *Bacillus subtilis* and native-born microorganisms. These microorganisms can
13 consume sulfur compounds, NH₄⁺-N and organic compounds to decrease odor pollution.
14 Besides direct consumption, plant roots spreading like fiber mats in water perform as
15 filters and catch floating objects. In the plant root sphere, zooplankton and small
16 creatures feeding on the substances filtered by plants' roots multiply, and food chains
17 are formed (Song et al., 2009). Furthermore, the rhizosphere is of high importance for
18 contaminants removal due to the release of oxygen from the plant roots into the
19 surrounding environment, various microbiological transformations, such as
20 mineralization of organic carbon, nitrification, denitrification and oxidation of S²⁻
21 compounds occur simultaneously on a small spatial scale (Wu et al., 2012). Finally,

1 pollutants transformed into the organisms are taken out of the water, which decreased
2 the COD_{Cr} and NH₄⁺-N indirectly.

3 **Fig. 2**

4
5 TSS decreased from 173 to 21 mg L⁻¹, and then increased to ~26 mg L⁻¹ (removal
6 rate 88%). TSS was mainly caused by the strong water current, which distributed the
7 sedimentary sludge throughout the river water, leading to a higher measured pollutant
8 level. In this experimental reach, the dams have slowed the current and hence reduced
9 the resuspension of bed load. Furthermore, with the engineering process conducted,
10 suspended solids with small particle size were filtered by the series of BAFs
11 (Albuquerque et al., 2012). Although the aerators disturbed the sedimentary sludge, the
12 solids re-deposited out of the influence scope of aerators. TP decreased from 1.4 to 0.1
13 mg L⁻¹, and then increased to ~ 0.3 mg L⁻¹. The results indicated BAF process and
14 ecological floating bed can remove phosphate (Yang et al., 2009; Shan et al., 2011),
15 decreasing TP concentration significantly.

16 **3.3. Variation of DO, S²⁻, TP and water clarity**

17 DO increased dramatically during the remediation process. Two months after the
18 beginning of the engineering, the DO concentrations exceeded 3.5 mg L⁻¹ (>2 mg L⁻¹),
19 at which point all running aerators were stopped intermittently to decrease the running
20 costs. On October 2nd, the concentrations of various pollutants all increased abruptly
21 due to the inrush of a huge flood rainstorm into the river. When such incidents occurred,

1 a calculated quantity of supplementary reagents were dosed immediately, and the
2 aerators were operated simultaneously.

3
4 **Fig. 3**

5
6 DO increased from 0.1 to 5.6 mg L⁻¹, then decreased to ~ 3 mg L⁻¹. Water clarity
7 increased from 6 to 44 cm, and then fluctuated around 32cm. Total S²⁻ decreased from
8 2.9 to 0.1 mg L⁻¹, then increased to ~ 0.2 mg L⁻¹. Aeration led to oxygenation and
9 oxidation, during which S²⁻ reached nearly zero. In heavily polluted river, the odorous
10 compounds, especially the odorous volatile sulfur containing compounds will be
11 produced and release from anaerobic water bodies (Sheng et al., 2008; Sheng et al.,
12 2011). In this work, the average final value of DO was ~ 3 mg L⁻¹, the production of
13 reduced sulfide was restrained, so the odorous pollution was decreased. After two
14 months of comprehensive remediation, chironomid larvae, algae and duckweeds
15 occurred in river water, the ecosystem in the water body gradually began to recover.

16 For the whole engineering process, there were very significant initial improvements
17 in COD_{Cr}, NH₄⁺-N, TSS, TP, S²⁻, DO and water clarity up to 21st August, but then a
18 slight relaxation towards slightly worse values. This reflects effective engineered
19 systems at the start of the project, followed by local rainy season in July and August,
20 there are many during this period, increasing run off over polluted land, then water
21 quality was influenced by the big flood frequently.

3.4. Relationships of DO-water clarity, DO-S²⁻ and S²⁻-water clarity

Fig. 4

The relationships of DO-water clarity, DO-S²⁻ and S²⁻-water clarity in river water were illustrated in Fig. 4. R² of DO-water clarity was 0.78, a statistically significant positive correlation, clearly indicating that DO controls water clarity. However, R² of DO-S²⁻ and S²⁻-water clarity were 0.73 and 0.85, respectively, both statistically significant negative correlations. This suggests that increased water clarity is effectively limited by the S²⁻ concentration, and S²⁻ is effectively limited by the DO. In this engineering experiment, artificial aeration and falling water aeration increased the DO and maintained a high level in the water body, which enhanced the growth and reproduction of natural and added microbes, strengthening the self purification capability of the water. Generally, the production of FeS (S²⁻ and Fe²⁺, under anaerobic conditions) is the main reason for the river water becoming black. In this work, prior to treatment, the river was full of suspended particles, including FeS. The particles and FeS prevented algae etc, further restricting DO. Aeration raised the DO and caused oxidation of the FeS and the engineering also changed the flow regime, allowing sedimentation to dominate over suspension. Oxidation of FeS and sedimentation improved clarity and the higher DO plus the seeding with microorganisms and plants allowed primary producers to re-colonise, restarting the usual diurnal cycle of

1 photosynthesis and respiration. So, DO caused a reduction in sulphide, which caused an
2 increase in clarity. High DO restrained the production of any further H₂S within the
3 water column and at the same time Fe²⁺ in river water was oxygenated to Fe(OH)₃ (river
4 water pH>7), which fell to the sediment surface (Perera et al., 2010).

5 **3.5. Present conditions of the tested river**

6 After two months of continuous comprehensive remediation, the quality of the water
7 has shown an obvious improvement, with average removal rates of COD_{Cr}, TSS,
8 NH₄⁺-N, TP and S²⁻ all above 70 percent (Table 2). The sporadic work of dosing
9 reagents and cleaning the river water surface is all that is needed at present to maintain
10 this new level of water quality, because a healthy ecosystem has built up in the river.
11 Pollutant levels have remained stable at these much lower concentrations, and
12 consequently local farmers began to use the river water for irrigation again (Fig. 5).

13

14

Fig. 5

15

16

Table 2

17

18 There are a great numbers of algae, zooplankton and a number of fish living in the river.
19 There is no longer any smell of odor. The river now has a stronger capability to cleanse
20 itself, some pollutants have reached or are approaching levels meeting Degree V of the
21 State Standards for surface water, and the key project targets (COD_{Cr} and NH₄⁺-N below

1 60 and 6 mg g⁻¹, respectively) were achieved. Although the water quality in the treated
2 river does not fully meet the standards, dramatically improved aesthetic qualities have
3 also been provided to the surrounding area, and the water is suitable for fishing and
4 irrigation. Because of many reasons, local government use same drainage system for
5 wastewater, rainwater and sewage collection. These water will be discharged to Dihe
6 River directly (without any treatment) in rainy season, increasing pollution load and
7 degradation of water quality. Therefore, accessorial techniques such as diffluence of
8 rainwater and sewage with different drainage systems should be adopted to bring the
9 water quality to the acceptable levels. Furthermore, strengthening the environmental
10 management of wastewater drainage will help water quality to reach the Standards. In
11 contrast to other common methods, combined application is the preferred method for its
12 lower cost, convenience, feasibility and sustainability, the cost was only about \$25,000
13 per kilometer in Dihe River. Due to their low maintenance and operational cost
14 requirements together with high removal capacity for different pollutants, this combined
15 application is feasible.

16

17 **4. Conclusions**

18 The comprehensive remediation of a heavily polluted river using a combined
19 application of aeration, microorganisms, biological aerated filters, biofilms and
20 ecological floating beds has been shown to be feasible and effective. After remediation,
21 the average removal rates of COD_{Cr}, TSS, NH₄⁺-N, TP and S²⁻ were all above 70

1 percent. DO increased from 0.01 to 3.26 mg L⁻¹. Furthermore, the unpleasant odor of
2 H₂S emanating from the polluted river has gone. Fish have been reintroduced and are
3 surviving, and many farms began to use the river water for irrigation. The field-scale
4 experiment indicated the feasibility and validity of the method applied to remediate this
5 heavily polluted river. This method could be applied to remediate other similarly
6 polluted rivers.

7

8 **Acknowledgements**

9 This work was financially supported by the National Natural Science Foundation
10 of China (Grant No.: 40906045). We acknowledge the contribution of Mr. Tielou Wang
11 and Mr. Peng Chen from the Changyi Municipal Environmental Protection Bureau for
12 their kind help in the engineering construction and management.

13

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1 **Figure captions:**

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3 Fig. 1 Schematic diagram of field-scale field-scale set-up

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5 Fig. 2 The variations of COD_{Cr}, TSS and NH₄⁺-N in river water

6

7 Fig. 3 The variations of TP, S²⁻, DO and water clarity in river water

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9 Fig. 4 Relationships between DO, S²⁻ and water clarity in river water

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11 Fig. 5 Comparison of river water remediation. Left: before remediation (black and
12 odorous); middle: engineering processing; right: after remediation (used for irrigation).

13

1 Table 1 The average parameters of polluted river water and sediment (Unit: mg L⁻¹)

Water sample	COD _{Cr}	TSS	NH ₄ ⁺ -	TP	S ²⁻	DO	pH	Water clarity (cm)
			N					
Upstream	257	273	27.4	1.6	3.4	0.1	8.2	4
Downstream	209	184	22.6	1.1	2.9	0.8	7.8	6
Standard (V)	40	/	2	0.4	1.0	2	6-9	/
US Standard	/	40	0.5	0.1	2	3	6.5- 8.5	/
Sediment	TOC	TN	TS	Total Fe	Sulfide			
	(%)	(%)	(%)	(mg g ⁻¹)	(mg g ⁻¹)			
Upstream	8.9	1.6	0.9	15.2	6.3			
Downstream	6.7	1.1	0.7	14.8	4.5			

2

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1 Table 2 The average parameters of river water after remediation (Unit: mg L⁻¹)

Water	COD _{Cr}	TSS	NH ₄ ⁺ -N	TP	S ²⁻	DO	pH	Water clarity (cm)
Mean	53	27	4.5	0.2	0.3	3.9	7.6	37
value*								
Standard	40	/	2	0.4	1.0	2	6-9	/
(V)								

2 * These values are means calculated from the data during 23rd Agu. to 15th Dec., 2010.

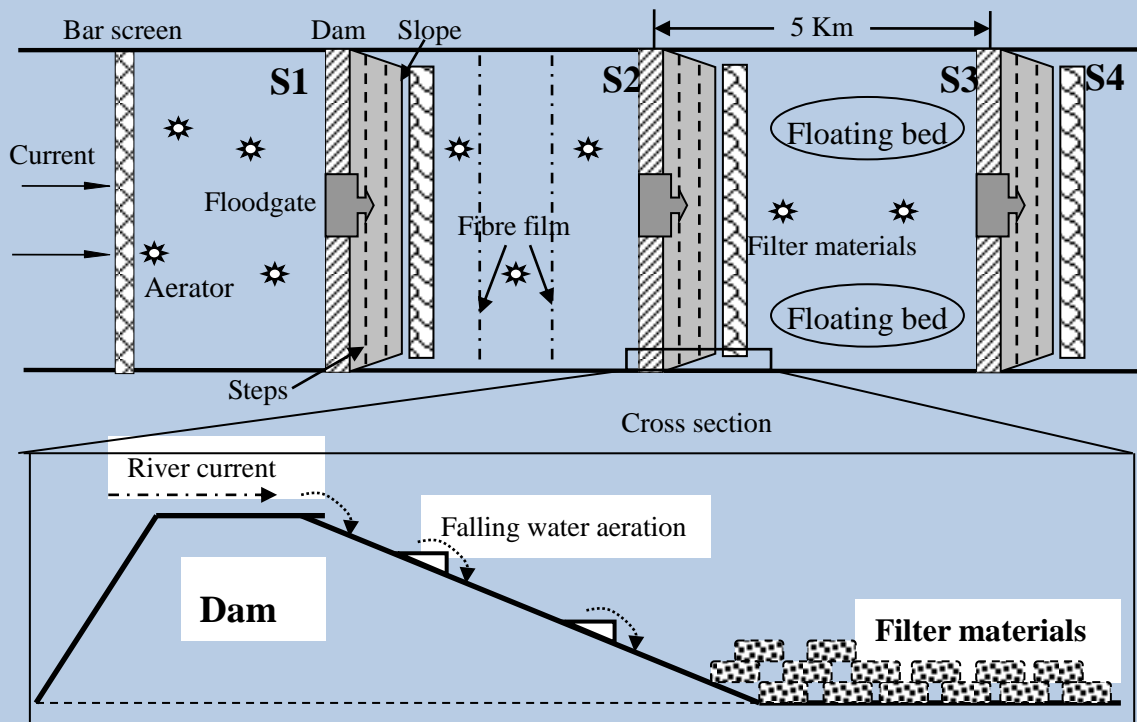
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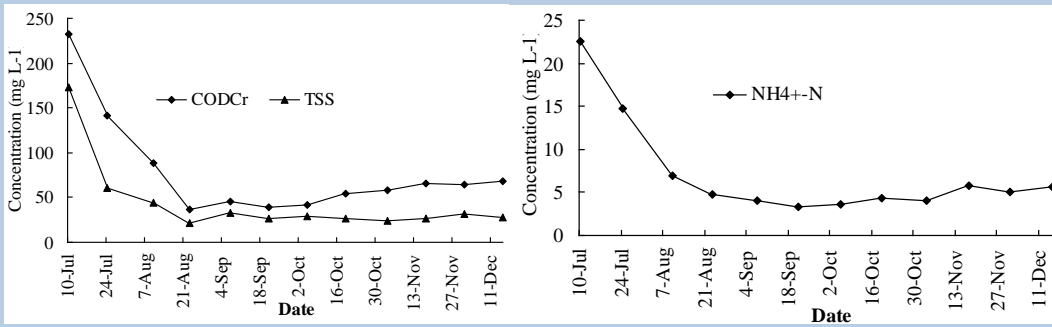
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Fig. 1

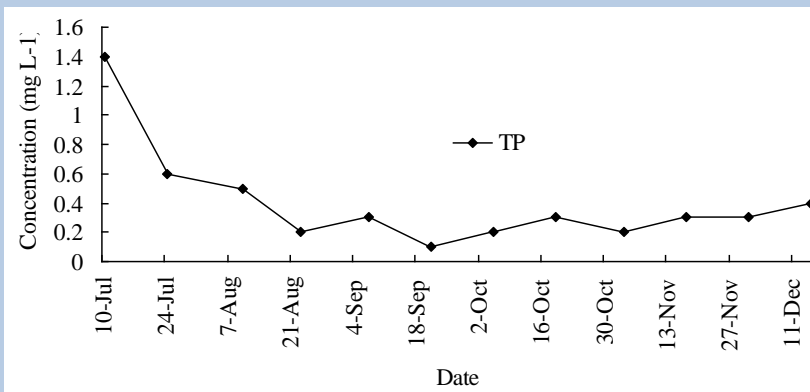
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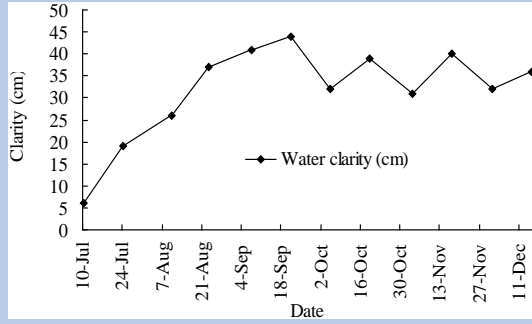
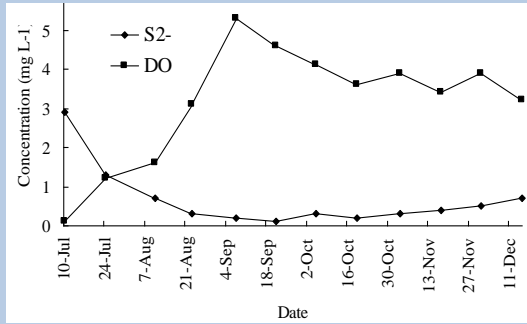
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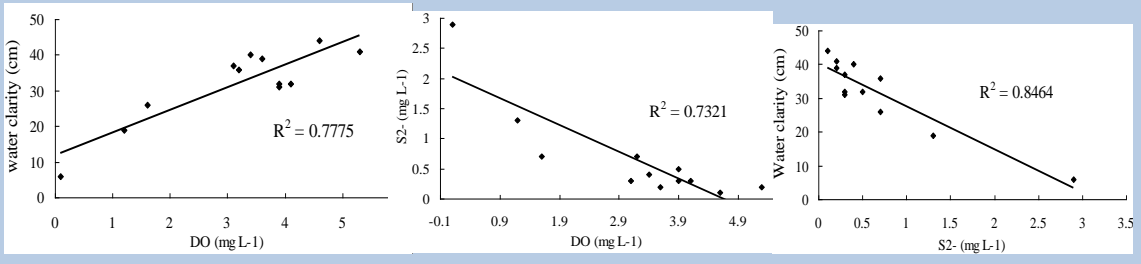
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Fig. 3

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Fig. 4

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Fig. 5

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