A Preliminary Study on A Novel Water Treatment Pond Design Using Dredged Sediment, Shrub Willow and Recycling Hand Pumps for the Restoration of Water Pollution

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Abstract: The treatment of polluted water and sediment often costs too much and has little benefit. In this study, we proposed a novel design using dredged sediment, shrub willow (Salix spp.) and recirculating hand pumps for the restoration of polluted river water in Changchun city, China. Sediment was filled as a matrix for plant growth, shrub willow was transplanted for the absorption of nutrients, and ten hand-pumped water wells were built for recycling the polluted water. During the 5-month experimental period, the shrub willow growth and nutrient contents, sediment nutrient concentration and water quality were measured. The results showed that this pond system could effectively decrease the sediment pollutant levels, and its removal efficiencies of organic matter (OM), total nitrogen (TN) and total phosphorus (TP) could respectively reach as high as 11%, 10% and 26%. The dissolved oxygen (DO) content increased by more than 90% in August, and the chemical oxygen demand (COD) and total nitrogen (TN) content decreased by 44.93% and 19.82%, respectively. This means that the treatment pond could efficiently work toward the purification of polluted river water. The benefits and feasibility of this system application were also analyzed, and we found that it could be widely used for the treatment of polluted water and sediment in urban areas.

Keywords: pond system; hand pumps; dredged sediment; shrub willow; nutrient removal

1. Introduction

The eutrophication of waterbodies from nutrient-rich sediment and water is a common problem for freshwater bodies in urban areas. Many best management practices (BMPs) have been developed to treat these impaired waters, including the use of a pond system, artificial floating islands, contact oxidation and biomanipulation techniques [1–4]. In the United Kingdom, reed bed treatment systems are used in the Thames, which promotes the use of this system in Europe [5]. In Korea, restoration of the Cheonggyecheon stream was performed by demolishing concrete highways, reborning stream corridors, dredging sediment, increasing the aeration from water-fall landscaping and increasing the amounts of coastal vegetation [6]. Stormwater ponds are a common practice to improve water quality in urban landscapes. In the USA, sediment dredging and retrofitting retention ponds decrease the impairment of rivers [7]. Although these methods have improved water quality to some extent, they
have not fundamentally solved the economic problems of eutrophication, especially the sediment issue. Therefore, the development of engineered ecological systems to solve this problem is a great challenge.

The littoral zone of rivers and lakes is a critical ecological zone between land and water [8]. Water level fluctuation creates a shift in the redox potential involved in the treatment of contaminated waters with high nutrient levels [9]. The bankside has also been regarded as an ecologically active lateral zone of rivers and lakes, as the soil, roots and microbes contained therein form physical, chemical, and biological systems to remove nutrients from the water. Thus, building a treatment system that uses wetland features along the banks has a great potential for effectively treating water. At the same time, a water treatment system can play a valuable role in intercepting the runoff of pollutants from the land into the water and protecting the bank from erosive tides, waves, and storms [10].

Because the bankside area habitat is labile to be affected by water surface fluctuations, it is necessary to select plants that can adapt to such an environment. Herbaceous wetland plants are the main species used in creating the pond system [11,12], but they often need to be harvested in a timely manner to avoid plant tissue decomposition in autumn. Therefore, other water-tolerant, high-biomass woody plant species should be considered, especially in the colder, northern regions. Shrub willow (Salix spp.) is a typical wetland woody species that exhibits fast growth, high yield, and wide adaptability and is also popularly used as an ornamental plant for city landscaping, especially for adding greenery to the banks of rivers and lakes. Furthermore, shrub willow has commercial use as a sustainable feedstock crop for biofuel production [13]. Such growth characteristics and commercial value mean that the shrub willow can be widely used in environmental engineering for the phytoremediation of soil or water. However, its nutrient requirements and contaminant uptake from soil or water are not fully understood.

Effective water flow is a key process to maintain good water quality [14]. When a water body cannot flow freely, power-driven water circulation or electrically powered aeration are common measures used to activate the water [15,16], but these are not economical in terms of energy savings. Considering that the areas surrounding waters in urban regions are most often used by local people for leisure purposes, building human-powered water recycling facilities may be an ideal way to effectively impact the water quality through residents’ daily activities [17]. This measure can also capture people’s attention and encourage them to voluntarily take part in environmental protection activities, not only improving public awareness but also representing the ecological value of harmony between humans and nature.

Considering the characteristics of water pollution in the urban area surrounding the Yitong River in China, including eutrophication, stagnation, reduced vegetation in the riparian buffer and high sediment treatment costs, we proposed a novel water treatment pond filled with dredged sediment and planted with shrub willow (Salix spp.), with hand-pumped water wells that force water from the bottom of the pond into the bankside willow system. We constructed an artificial landscape lake near the Yitong River. The purpose of this study was to investigate the effects of this design and to evaluate the feasibility of this ecologically integrated system for the maintenance of aquatic health and to provide support for the restoration of the Yitong River using a novel technique.

2. Materials and Methods

2.1. Study Area

The study area is located in an artificial landscape lake near the Yitong River of Changchun City in Jilin Province, China (43°51′52″ N, E125°21′07″ E). In the last 30 years, the water quality of Yitong River in Changchun city has decreased substantially due to the urban construction and unconscionable anthropogenic activities, such as damage to riparian vegetation, over fertilization, pesticide application, industrial pollution and sewage discharge [18], decreasing the flow rate of river, increasing input nutrients from the run-off and algal bloom. Chemical oxygen demand (COD) and NH₃-N were the main factors and the statistics showed NH₃-N changed from 0.54 mg/L to 10.75 mg/L
and COD changed from 7.64 mg/L to 61.4 mg/L [19,20]. The river’s water self-purification capability was also weakened by the deposition of pollutants and the water stagnation which further cause the eutrophication problem. Sediment dredging in the Yitong River has also consumed a large amount of money, manpower and material resources.

2.2. Evaluation of Sediment Pollution

Sediment plays an important role in the organic matter cycle and the energy flow of water ecosystems and acts as a sink for the diverse pollutants that can be otherwise re-released into the water by other materials, causing secondary pollution [21,22]. The selection of sediment treatment methods depends on the pollution conditions present. To conduct an integrated evaluation of dredged sediment pollution, we chose ten river cross sections for sediment sampling and assessed their contaminant concentration on 25 April 2014 (Figure 1). Each section had 5 sampling points; we used a sediment sampler to take 0–80 cm of sediment that was collected with a plastic bag (free of air). The samples were transferred to the lab; after removing stones, rhizomes, animals and plant residues from the samples, they were filtered through a 100 mesh sieve. Heavy metal parameters and nutrient concentrations were measured and evaluated according to standard methods (GB/T 15618-2018) [23].

![Figure 1](image_url)  
*Figure 1. The location of the water treatment pond and the distribution of sampling sections.*

The sampling results from the different sections of the Yitong River (Table 1) were compared to the Chinese Environmental Quality Standard for soil, and it was determined that the samples were not contaminated with heavy metals, but the nutrient concentrations, especially the total phosphorus (TP), were the main sources of sediment pollution in the area. Therefore, the proposed, ecological design was determined to be an ideal solution for the river’s restoration.
mental analyzer (Smartchem). which the shrub willow (Salix spp.) seedlings were transplanted in rows spaced 20 cm apart. The pipe inlets of the hand-pumped water wells were situated above the sediment layer. The water was cycled from the bottom of the bank pond, the water of the pond also comes from the river. We set a filter membrane at the boundary between the water body and the sediment to address nutrient leakage. The pond surface was constructed approximately 30 cm higher than the water surface of the lake, after which the shrub willow (Salix spp.) seedlings were transplanted in rows spaced 20 cm apart. The pipe inlets of the hand-pumped water wells were situated above the sediment layer. The water was cycled from the pond to the lakeside pond system by means of local people freely using the hand-pumps. Figure 2 shows the working principle of the water treatment pond.

2.3. Ecological Engineering Design

In April 2014, an engineered treatment system, which included a bankside pond with hand-pumped water wells, was built in a 40 m × 1 m × 0.5 m (L × W × H) area near the Yitong River. The pond system contained 10 hand-pumped water wells and was filled with dredged sediment that was dug from the bottom of the bank pond, the water of the pond also comes from the river. We set a filter membrane at the boundary between the water body and the sediment to address nutrient leakage. The pond surface was constructed approximately 30 cm higher than the water surface of the lake, after which the shrub willow (Salix spp.) seedlings were transplanted in rows spaced 20 cm apart. The pipe inlets of the hand-pumped water wells were situated above the sediment layer. The water was cycled from the pond to the lakeside pond system by means of local people freely using the hand-pumps. Figure 2 shows the working principle of the water treatment pond.

![Figure 2. The system design and working principle of the water treatment pond.](image)

2.4. Data Collection and Analysis

From June to October 2014, the sediment of the pond system was sampled on-site on the 15th day of each month in order to measure indexes of organic matter (OM), TN and TP. Five points were sampled and mixed together evenly in three replicates. OM was determined using the wet dichromate oxidation method, TN and TP were measured using an elemental analyzer (Smartchem 200; AMS Alliance: Frépillon, France).

### Table 1. The pollution level of contaminants in the sediments of the Yitong River.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average</th>
<th>Standard</th>
<th>Reference</th>
<th>Pollution Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>As (mg/kg)</td>
<td>7.10 ± 2.35</td>
<td>&lt;5</td>
<td>GB/T 15618-2018</td>
<td>Unpolluted</td>
</tr>
<tr>
<td>Hg (mg/kg)</td>
<td>0.10 ± 0.003</td>
<td>&lt;15</td>
<td>GB/T 15618-2018</td>
<td>Unpolluted</td>
</tr>
<tr>
<td>Cr (mg/kg)</td>
<td>30.86 ± 8.34</td>
<td>&lt;0</td>
<td>GB/T 15618-2018</td>
<td>Unpolluted</td>
</tr>
<tr>
<td>Cu (mg/kg)</td>
<td>14.77 ± 3.54</td>
<td>&lt;5</td>
<td>GB/T 15618-2018</td>
<td>Unpolluted</td>
</tr>
<tr>
<td>Ni (mg/kg)</td>
<td>14.63 ± 3.75</td>
<td>&lt;0</td>
<td>GB/T 15618-2018</td>
<td>Unpolluted</td>
</tr>
<tr>
<td>Pb (mg/kg)</td>
<td>21.18 ± 2.2</td>
<td>&lt;5</td>
<td>GB/T 15618-2018</td>
<td>Unpolluted</td>
</tr>
<tr>
<td>Zn (mg/kg)</td>
<td>46.90 ± 13.04</td>
<td>&lt;0.00</td>
<td>GB/T 15618-2018</td>
<td>Unpolluted</td>
</tr>
<tr>
<td>Cd (mg/kg)</td>
<td>0.087 ± 0.01</td>
<td>&lt;0.2</td>
<td>GB/T 15618-2018</td>
<td>Unpolluted</td>
</tr>
<tr>
<td>TN (mg/kg)</td>
<td>1368.60 ± 232.56</td>
<td>1000 &lt;= 2000</td>
<td>EPA</td>
<td>Moderately polluted</td>
</tr>
<tr>
<td>TP (mg/kg)</td>
<td>3865.98 ± 408.41</td>
<td>650 &lt;</td>
<td>EPA</td>
<td>Seriously polluted</td>
</tr>
</tbody>
</table>
Simultaneously, the water flowing through the pond system and the original water in the lake was monitored to compare their water quality. The DO of water was measured by using an oxygen meter (SevenGo Duo pro-SG68; Mettler Toledo: Greifensee, Switzerland). The dissolved COD and TN were analyzed in accordance with standard methods [24].

The shrub willow plants were harvested in October to investigate their nutrient accumulation. Five plants with similar growth conditions were selected for investigation. The stems, leaves, and roots were dried at 105 °C for the measurement of their dry weight, grinding and filtration through a 100 mesh sieve. The filtered plant material samples were digested by sulfuric acid-hydrogen peroxide (H$_2$SO$_4$-H$_2$O$_2$). TN and TP were determined by using Smartchem 200. The accumulation of N and P was calculated by subtracting the initial amount measured for each element from the total N and P in the harvested shrub willow material. A Pearson correlation analysis was used to investigate the contribution of shrub willow to the water treatment efficiency.

3. Results

3.1. OM, TN and TP Removal of Sediment

According to our measurement of the sampling of the sediment in the pond system, the TN is the main pollutant which is different from the background of Yitong River, and the TP is about 0.46 g/kg that is moderately polluted. The nutrients removed from the pond sediment by the shrub willow during the 5-month sampling period are depicted in Figure 3, where all lines show the same decreasing trend. From June to October, the removal of P was 26%, and the final concentration was 0.34 g/kg from an initial P concentration of 0.46 g/kg. The TN concentration decreased from 1.23 g/kg to 1.10 g/kg, and the concentration of organic matter decreased from 22.35 g/kg to 19.81 g/kg. The retention rates of OM and TN (11% and 10%, respectively) were lower than those of TP. The concentrations of OM, TN, and TP had a slight increase in August, which may have been caused by the sediment and the growing plants trapping nutrients during the wet season. The continuous input of polluted water was also a reason why the nutrient removal rate was low in this pond system because the pollutants were absorbed by the pond sediment.

Figure 3. The organic matter (OM), total nitrogen (TN) and total phosphorus (TP) variations based on sediment used in the water treatment pond.

3.2. Water Quality Improvement from the Pond System

During the study period, when the pond system was working, we found that the system could work well for purifying polluted river water. Figure 4 shows that the DO concentration of the water treatment pond increased compared to that of the influent water, indicating that water circulation...
can effectively increase DO levels. The DO increase reached its maximum, 90.93%, in August. COD and TN were significantly reduced by the system. The COD removal rate was high in August, nearly 45%, but it also showed a decreasing trend as the system worked. The TN removal efficiency was high during plant growth. The highest TN removal rate was 20% in July and September, but the removal also decreased in October. During that time, the shrub willow almost stopped growing. This result suggests that the growth rate and the nutrient absorbance ability of the shrub willow were weakened. Hand-pumped water can decrease pollution through aeration, sediment can transform pollution via their frequent wet-dry alterations that cause water surface fluctuations, and sediments planted with shrub willow can absorb pollutants; therefore, the pond system was a good method for water treatment.

Figure 4. The water quality changes in the water treatment pond.
3.3. Plant Growth and Nutrient Removal

Well-developed plants that have a high biomass, are long-standing and have abundant roots in the pond system, which can increase the efficiency of the nutrient uptake and the rhizospheric microbial function for water purification in pond systems [25]. At the end of the experiment, the shrub willow stem biomass was 65.92 ± 3.8 g/plant, accounting for approximately 90% of the total plant biomass, while the roots and the leaves accounted for less than 2% and 9%, respectively. In autumn, it is important to harvest the decaying tissue from decomposing plants to avoid the re-release of nutrients and organic matter into the water. Because the shrub willow is a deciduous woody plant, its leaves and slim branches, though a small proportion of the total plant biomass, need to be pruned and removed to reduce the risk of plant residues returning to the water, while the main stem, with its large biomass, may be retained for sprouting and growth in the next spring. Therefore, woody wetland species show some advantages over herbaceous species with respect to their biomass accumulation and cultivation, especially in colder regions.

Plants in the pond system act as intermedia for sediment and water purification by directly utilizing nitrogen, phosphorous, and other nutrients [26]. Table 2 reveals the nutrient contents of the shrub willow. The nitrogen and phosphorus concentrations in shrub willow (Salix spp.) follow the order of leaf > root > stem. Although a high sediment rate could provide a greater supply of nutrients and improve the organic nutrient concentrations available, nutrient accumulation and distribution depend on the biomass partitions of different plant organs. In this experiment, the stem was the main organ for N and P accumulation, accounting for 73.3% of the total N accumulation and 76.7% of the P accumulation, while the total shrub willow N and P accumulation reached 703.38 ± 28.97 mg/plant and 666.81 ± 20.91 mg/plant, respectively (Figure 5). According to these results, N and P removal by the shrub willow can reach 17.59 g/m² and 16.6 g/m², respectively. Good levels of plant growth and effective N accumulation in the leaves prior to pruning would promote this system’s efficiency. This design also makes it possible for the in-situ treatment of dredged sediment.

Table 2. The plant growth and nutrient contents in the leaves, stems, and roots of shrub willow (Salix spp.).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Root</th>
<th>Steam</th>
<th>Leaf</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry weight</td>
<td>g/plant</td>
<td>1.32 ± 0.16</td>
<td>65.92 ± 3.8</td>
<td>5.85 ± 1.36</td>
<td>69.65 ± 4.27</td>
</tr>
<tr>
<td>Concentration N</td>
<td>mg/kg</td>
<td>12.77 ± 2.62</td>
<td>7.62 ± 1.07</td>
<td>29.5 ± 3.74</td>
<td>10.67 ± 1.49</td>
</tr>
<tr>
<td>Concentration P</td>
<td>mg/kg</td>
<td>14.23 ± 1.42</td>
<td>8.02 ± 0.69</td>
<td>23.45 ± 2.22</td>
<td>9.62 ± 0.89</td>
</tr>
<tr>
<td>Accumulation N</td>
<td>mg/plant</td>
<td>16.55 ± 1.29</td>
<td>513.63 ± 13.4</td>
<td>170.7 ± 14.25</td>
<td>703.38 ± 28.97</td>
</tr>
<tr>
<td>Accumulation P</td>
<td>mg/plant</td>
<td>18.77 ± 1.97</td>
<td>509.51 ± 10.79</td>
<td>136.01 ± 8.59</td>
<td>666.81 ± 20.91</td>
</tr>
<tr>
<td>Distribution N</td>
<td>%</td>
<td>2.4</td>
<td>73.3</td>
<td>24.3</td>
<td>100</td>
</tr>
<tr>
<td>Distribution P</td>
<td>%</td>
<td>2.8</td>
<td>76.7</td>
<td>20.5</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 5. The nutrient distribution in shrub willow (Salix spp.).
The Pearson correlation analysis (Table 3) shows that there was a significant positive correlation between plant growth and COD, TN removal of water. However, there was no significant correlation between plant dry weight and sediment treatment efficiency.

### Table 3. The correlations between shrub willow (*Salix spp.*) growth and treatment efficiency.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Weight</th>
<th>R²</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water DO increment</td>
<td>-0.946</td>
<td>0.054</td>
<td></td>
</tr>
<tr>
<td>Water COD removal</td>
<td>0.979</td>
<td>0.021 *</td>
<td></td>
</tr>
<tr>
<td>Water TN removal</td>
<td>0.972</td>
<td>0.028 *</td>
<td></td>
</tr>
<tr>
<td>Sediment OM removal</td>
<td>0.946</td>
<td>0.054</td>
<td></td>
</tr>
<tr>
<td>Sediment TN removal</td>
<td>-0.247</td>
<td>0.753</td>
<td></td>
</tr>
<tr>
<td>Sediment TP removal</td>
<td>0.081</td>
<td>0.919</td>
<td></td>
</tr>
</tbody>
</table>

Note: "*" Correlation is significant at the 0.05 level (2-tailed).

### 4. Discussion

From the results, we can see that the water qualities are clearly improved through this novel pond design with bankside shrub willow beds and hand pumps. The bankside is a critical ecological zone in the removal of nutrients from the water column [27]. It can reduce eutrophication levels through the cycle of nitrification and denitrification and the decomposition of organic matter [28,29]. Our pond system provides space for the on-site treatment of sediments using growing plants and enhanced treatment through the frequent wet-dry cycle.

Compared with traditional herbaceous plants, shrub willow could reduce the risk of plant tissue decomposition in autumn [30]. Its leaves and slim branches, which are only a small proportion of biomass, prevented the rerelease of nutrients and organic matter into the water. Pruning and removing the leaves in autumn can reduce the risk of plant residue pollution. Therefore, shrub willow is more manageable than herbaceous plants, especially in colder regions. Additionally, shrub willow can improve the aesthetic value of urban rivers.

Compared with traditional hard-bank revetment in urban areas, the use of sediment as a revetment matrix eliminates disadvantages, such as poor hydrophilicity, lower biodiversity, imbalanced ecological structure, and poor self-purification capabilities [31,32], and it also decreases the cost of sediment dredging. The application of sediment for revetment purposes highlights ecological function; increases habitat heterogeneity; regulates microbiological community structures, benthos, and fishes; and provides more space for plants. The methods of our study worked more efficiently for water and sediment treatments, but the impact of whether the sediment revetment changed the structure of zoobenthos, fishes, hydrobionts, and microbes needs to be surveyed further.

Based on our investigation and estimation, the hand pumps, which served as the recreation facilities of the water treatment pond, when worked for approximately 4 hours a day, can pumped about 8 tons of river water per day and increase the dissolved oxygen from 6.5 mg/L to 7.3 mg/L, and sequentially change the microbial activity to heighten the treatment efficiency of the water. This design can not only purify river water but also has social benefits. Real environment protection requires the friendly behavior of all people toward the natural ecosystem. Hand pumps are an important method to attract people to take part in environmental protection. When local people use the hand pumps for recreation and health purposes, they will gain an understanding that “water needs activity to be healthy, just as human beings require daily exercise for their health”.

In our water treatment pond, Shrub willow contributes to water treatment (Table 3), the removal of COD and TN were increased with the increment of plant growth. The result also suggests that the nutrient removal efficiency was low when the growth was weakened. The growth of shrub willow was not related to sediment treatment mainly because the pollutants of sediment are not in continued absorption. The riverbed system that formed by sediment and shrub willow can intercept nutrients,
which is also the reason why the OM, TN, and TP of sediment increase in August. The trait of shrub willow also can reduce the exogenous nutrient input to the water. Hand-pumped water can decrease pollution through aeration and get more people participating in environmental protection. Bankside riverbeds can transform pollution via their frequent wet-dry alterations that cause water surface fluctuations. The bankside shrub willow, dredged sediment, handpumps all play an important role in our pond system.

Compared with other sediment dredging treatment methods, this novel pond system will be built onsite along the bankside of lakes or rivers, and it does not cost more in labor but it does reduce the cost associated with sediment transportation, land occupancy, water for truck washing and the treatment of secondary water pollution caused by sediment. The hand pumps cost approximately $150 in total, and a 40 m² planting area of shrub willow with 1000 plants costs $500. The leaves of shrub willow are used as biomass energy materials, which creates additional economic benefits [33]. The net income from employing treatment ponds can be nearly $800–1000/hm². We are now considering wide applications of water treatment ponds for sediment and water treatment along the bankside of the Yitong River.

5. Conclusions

Our water treatment pond using dredged sediment, shrub willow and recirculating hand pumps were feasible in their economic and social benefits and were also highly effective in treating eutrophic water and polluted sediment. The removal rates of OM and N in sediment are, respectively, approximately 11% and 10%, and the rate for P can reach 26%. The system could improve the water quality significantly, the DO content even increased by more than 90% in August, and the COD and TN content decreased by 44.93% and 19.82%, respectively. The shrub willow played an important role in the construction of our pond system, and the total N and P accumulations reached 703.38 ± 28.97 mg/plant and 666.81 ± 20.91 mg/plant, respectively. Ecologically, this design provided not only landscaping and a protective barrier to keep out external pollutants but also a habitat for a variety of species. Additionally, the hand-pumped water well can make more people participate in environmental protection. Thus, our construction of a novel bankside pond system may offer sustainable urban sediment and water treatment.

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