Study on water purification ability and permeability of different filter materials in LID-type ditch

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Abstract. In rural areas of China, sewage is often discharged to ditch directly without any treatment. We propose a new type of ditch based on Low Impact Development (LID) strategy by replacing bed soil in rural ditch with mixed filter material of approximately 30cm in thickness. This new type of ditch is so-called LID-type ditch having the function of storage, penetration, purification and drainage. Four basic materials, red loam, sand, gravel and zeolite, are used to create 3 types of mixed filter materials by evenly mixing these basic materials with different mass ratios. Their saturated permeability coefficients and water purification ability are measured and compared. Results indicate that all 3 types of mixed filter materials are suitable to apply to LID-type ditch, and the all outflows meet the water quality standard for farmland irrigation. The best mixed filter material is type 1 with 50% of red loam, 30% of sand, 10% of gravel, and 10% of zeolite, it has removal rate for TP as high as 81.31% and average removal rate of 47.09% for TP, TN, NH3-N, COD, BOD₅.

1. Introduction

In the United States of America, traditional decentralized sewage treatment systems usually consist of two components: a buried septic tank and a soil dispersal system. Figure 1 is a schematic diagram of the decentralized treatment system of rural sewage in the United States [1]. After the treatment of septic tanks in rural areas in the United States, outflow almost becomes clear water and meets the secondary treatment standards stipulated by “the US Federal Water Pollution Prevention and Control Act”, and then outflow is discharged and infiltrated into the local soil. The secondary treatment standards are: 7-day averages of BOD₅ and TSS≤45mg/L, 30-day average of BOD₅ and TSS≤45mg/L, 30-day average of pH needs to be in the range of 6-9 [2].

In China, strengthening the construction of rural sewage treatment projects and improving the effectiveness of treatment have been stressed by the government work report. However, compared with the American current situation of rural sewage decentralized treatment, China currently has the following problems: 1) the sewage treatment systems in many rural areas simply copy the first-level-A standard of urban sewage discharge and the treatment process used in the urban sewage treatment plant. However, as we know, the environment characteristics of rural areas are very different from that of urban. Rural areas have a lot of permeable land full of nature soils and plants whereas urban has a lot of building and impervious area. These different environmental characteristics in rural areas require unique treatment system and cannot simply copy the practice of urban. The system should be focused on the ecological treatment process of using soil and plants for sewage treatment. Unfortunately, the application of ecological treatment processes in rural area nowadays is still very limited. Thus, research on ecological treatment processes for rural areas needs to be strengthened; 2) The rural decentralized treatment facilities are usually installed at a site far away from the place where sewage is
produced, and close to receiving water body like rivers and lakes. The sewage treated by facilities is directly discharged into the receiving water body. However, in the United States, the treatment facilities are constructed at the source site of sewage. As a result, the treated sewage by facility is infiltrated into the soil through a dispersal system buried under the surface instead of discharging into surface water directly. As to water body, the nitrogen, phosphorus and other substances in the sewage are the source of pollution to cause eutrophication whereas to soil they are nutrient sources for plant growth.

Figure 1. The decentralized treatment system of rural sewage in the United States

Therefore, we need to consider how to solve the above problems. Although many families in rural areas in China have built septic tanks, the water quality of household septic tanks built in rural China is usually not very stable and does not meet the water quality requirement for infiltrating into soil. It is difficult for us to copy the practice of the United States. Yan et al. have proposed a method to improve outflow quality by rebuilding septic tank and combining the use of soil percolation [3]. However, this method is not easy to be widely applied in practice in rural areas. The reason is that reconstruction of septic tanks of various households is not only time-consuming and laborious, but also difficult to implement in Chinese rural areas. Therefore, how to learn from the practices in the United States and use soils and plants to turn pollution sources into nutrient sources is worthy of further study.

On the other hand, in the late 1990s, a new type of urban rainwater management and utilization method was developed in the United States, that is Low Impact Development, namely LID. Various kinds of LID technologies such as bioretention, grass ditch, etc. are employed to reduce storm runoff volume and rainwater non-point source pollution through storage, infiltration, filtration, and evaporation [4]. LID is a decentralized, source governance strategy, and this kind of governance strategy is considered to be suitable for solving both rainwater problem and rural sewage problem.

There are many large and small soil ditches in rural areas of China, sewage produced by each family flows along these ditches and drain to receiving water body eventually. However traditional rural ditch usually has very low permeability, causing sewage to easily flow out from ditch and little infiltrate into soil through ditch bed to get purified. To overcome this issue of existing ditch, we propose a new type of ditch based on Low Impact Development (LID) strategy by building several weirs along ditch, replacing the bed soil of about 30 cm of thickness in the traditional ditch with filter materials, and covering a layer of coarse stone or pebbles on the top to avoid loss of filter materials. This new type of ditch is so-called new LID-type ditch having the functions of storage, infiltration, purification and drainage. The core component of new LID-type ditch is the filter material which needs to consider its purification performance, permeability and economy. Thus, this study carried out experimental comparisons on the purification ability and permeability of various filter materials produced in our
laboratory, and briefly compared the cost of the filter materials. The study results provide a new way to treat rural sewage at the source site which is effective, ecological and economical.

2. Materials and method

2.1. Materials

It is better to choose filter materials which are not only cheap and easy to obtain but also having good purification ability. By consulting the related literature, four kinds of basic filter materials, Xiamen natural red loam, sand, gravel and zeolite are selected as the test materials.

2.1.1 Xiamen local natural red loam soil: It is the typical soil type in Fujian Province which has good adsorption to phosphorus and may reach a adsorption amount of 1.61mg/g [5]. Red loam soil is iron and aluminum-rich, the amorphous iron and aluminum content in red soil effectively promote absorbing phosphorus by chelation[6]. However, its permeability coefficient is only about 0.098mm/min [7], which is much less than the recommended infiltration rate (>1.143mm/min) based on experience by Prince George’s County [8], thus its permeability needs to be improved artificially by adding some sands, gravel and etc.

2.1.2 Sand: It has a good adsorption effect on COD. The adsorption of COD by sand is mainly physical adsorption. Its large specific surface area can promote the contact adhesion of COD[9]. Xiamen local sand with particle size of 0.2-0.5mm is selected as test material.

2.1.3 Gravel: It has a good adsorption effect on TN, its adsorption is the main reason for the removal of TN from water [10].The gravel with particle size of 4-8mm which is the products of Miaoyuan Water Treatment Material Co., Ltd in Gongyi City of China is selected as test material.

2.1.4 Zeolite: It is a hydrous silicate mineral with a cluster-like structure. Cavities and pores with a certain pore size in the zeolite framework create its adsorption and ion exchange properties [11]. Zeolite has a good effect on the removal of ammonia nitrogen due to its chemical adsorption and ion exchange on ammonia nitrogen [12]. The gravel with particle size of 4-8mm, purchased from Miaoyuan Water Treatment Material Co., Ltd in Gongyi City of China, is selected as test material.

The above 4 kinds of basic materials are used to generate 3 types of mixed filter materials by mixing these basic materials together with different mass ratios as shown in table 1. From type 1 to 3, the total mass ratios of red loam and sand decrease from 80% to 40% and that of gravel and zeolite increase from 20% to 60%.

| Table 1. Mass ratios of various basic materials for 3 types of mixed filter materials. |
|-----------------|---------|--------|--------|--------|
| type | Red loam(%) | Sand(%) (0.2-0.5mm) | Gravel(%) (4-8mm) | Zeolite(%) (4-8mm) |
| 1   | 50       | 30     | 10    | 10     |
| 2   | 30       | 30     | 20    | 20     |
| 3   | 20       | 20     | 30    | 30     |

2.2. Experimental device

In order to compare the purification effects of 3 types of mixed filter materials, an experimental device as shown in Figure 2, is employed to fill 3 types of filter materials separately. Diameter of cylinder included in the device is 20cm and the height is 60cm. The device is mainly composed of 4 parts which are material filling cylinder, seepage board, overflow hole, water outlet. Seepage board is enlarged to be shown in Figure 3.

2.3. Indicators and determination methods

2.3.1. Water quality Indicators and determination methods: According to the monitoring indicators of rural sewage commonly used in Fujian Province of China, five water quality indicators are selected as monitoring indicators for our experiment which are total phosphorus (TP), ammonia nitrogen (NH₃-N), total nitrogen (TN), chemical oxygen demand (COD) and five-day biological oxygen demand (BOD₅).
The determination methods and instruments for these five indicators are shown in table 2 and table 3 respectively.

**Table 2. Water quality indicators and its corresponding determination methods**

| Water quality indicators | Determination methods                                      |
|--------------------------|------------------------------------------------------------|
| TP                       | High-pressure digestion of potassium persulfate,           |
|                          | Stannous chloride spectrophotometry                         |
| TN                       | Alkaline potassium persulfate digestion, ultraviolet       |
|                          | spectrophotometry                                           |
| NH$_3$-N                 | Nessler reagent spectrophotometry                           |
| COD                      | Rapid digestion spectrophotometry                           |
| BOD$_5$                  | Dilution and inoculation                                    |

**Table 3. Water quality indicators and corresponding determination instruments**

| Water quality indicators | Determination instruments                                                |
|--------------------------|------------------------------------------------------------------------|
| TP, TN                   | Palintest Digital Digester, Palintest-7100 Photometer                 |
| NH$_3$-N                 | Palintest-7100 Photometer                                              |
| COD                      | LianHua 5B-I(V8) Intelligent Multi-Parameter Digestion Reactor,       |
|                          | Lianhua 5B-3B(V8) Multi-Parameter Water Analyzer                     |
| BOD$_5$                  | Boxun Model SPX-250B-Z Biochemical Incubator,                        |
|                          | Hach BODTrak Water Quality Analyzer                                   |

2.3.2. **Permeability Indicator and determination methods**: Saturated permeability coefficient of $K_s$ is used as an indicator to evaluate the permeability of the mixed filter materials. $K_s$ is measured based on fixed head measurement method by using Model IK-4012 Saturated Soil Infiltration Instrument made in Japan.
2.4. Experimental method

1) Produce three types of mixed filter materials by evenly mixing 4 kinds of basic materials which are red loam, sand, gravel and zeolite based on the corresponding mass ratios shown in table 1. The mass of all these three types of mixed filter materials are controlled to be equal to 12.3kg.

2) Fill each type of mixed filter material to the experimental device shown in Figure 2 one by one. The heights of mixed filter materials filled in cylinder are 30cm, 30.5cm, 31cm for type 1, type 2 and type 3 respectively.

3) Collect rural domestic sewage from main drainage ditch of sewage in Yincun village of Houxi town nearby our university, and slowly pour the same volumes of sewage of 10L into three experimental pipes respectively.

4) Collect the outflow water samples from the outlet shown in Figure 2.

5) Determinate the five water quality indicators of inflow and outflow, TP, TN, NH₃-N, COD and BOD₅ based on the method stated in 2.3.1.

6) Measure the saturated permeability coefficient of $K_s$ based on the method stated in 2.3.2.

7) Analyse the experimental results.

3. Results and analysis

Purification experimental results for the mixed filter material of type 1, type 2 and type 3 are shown in table 4, table 5 and table 6 respectively. Comparison of the removal rate of each water quality indicator for 3 types of mixed filter materials are shown in Figure 4. The average removal rates for five water quality indicators of TP, TN, NH₃-N, COD and BOD₅ and saturated permeability coefficients of $K_s$ for three types of mixed filter materials are shown in table 7.

### Table 4. Purification experimental result for the mixed filter material of type 1 (unit: mg/l)

| Water quality indicators | Water samples       | TP    | TN   | NH₃-N | COD   | BOD₅  |
|--------------------------|---------------------|-------|------|-------|-------|-------|
|                          | Inflow of type 1    | 1.98  | 33   | 7.4   | 179.1 | 97.6  |
|                          | Outflow of type 1   | 0.37  | 23   | 5     | 87.3  | 58.4  |
|                          | Removal rates (%)   | 81.31 | 30.30| 32.43 | 51.26 | 40.16 |

### Table 5. Purification experimental result for the mixed filter material of type 2 (unit: mg/l)

| Water quality indicators | Water samples       | TP    | TN   | NH₃-N | COD   | BOD₅  |
|--------------------------|---------------------|-------|------|-------|-------|-------|
|                          | Inflow of type 2    | 2.95  | 36   | 7.8   | 21    | 10.9  |
|                          | Outflow of type 2   | 1.31  | 26   | 4.9   | 12    | 6.2   |
|                          | Removal rates (%)   | 55.59 | 27.78| 37.18 | 42.86 | 43.12 |

### Table 6. Purification experimental result for the mixed filter material of type 3 (unit: mg/l)

| Water quality indicators | Water samples       | TP    | TN   | NH₃-N | COD   | BOD₅  |
|--------------------------|---------------------|-------|------|-------|-------|-------|
|                          | Inflow of type 3    | 1.64  | 86   | 12.5  | 34.61 | 20.8  |
|                          | Outflow of type 3   | 0.61  | 45   | 6.8   | 27.09 | 13.4  |
|                          | Removal rates (%)   | 62.80 | 47.67| 45.60 | 21.73 | 35.58 |
Figure 4. Comparisons of removal rates for 3 types of mixed filter materials

Table 7. Average removal rates and $K_s$ for three types of mixed filter materials

| Type of mixed filter material | Average removal rate | Saturated permeability coefficient $K_s$ Unit: m/s |
|------------------------------|----------------------|-------------------------------------------------|
| Type 1                       | 47.09%               | 9.131*10^{-5}                                   |
| Type 2                       | 41.31%               | 2.889*10^{-4}                                   |
| Type 3                       | 40.99%               | 2.062*10^{-3}                                   |

From table 4-7 and Figure 4, it can be seen that:

1) Type 1 has obvious advantages in removing TP and COD compared to type 2 and type 3. The reason is attributed to that the mass ratios of soil and sand for type 1 are the highest among three types of mixed filter materials while soil and sand have good purifications for TP and COD respectively [5,6,9].

2) Type 3 has obvious advantages in removing TN compared to type 1 and type 2. The reason is due to that the mass ratios of gravel and zeolite are the highest in three types of mixed filter materials while gravel and zeolite have good purifications for TN [10-11].

3) Type 2 has no obvious removing advantage for a certain water quality indicator. Since the sum of mass ratios of red loam and sand are at an average level among three types of mixed filter materials, and so do the sum of mass ratios of gravel and zeolite, thus, no outstanding performance can be seen for type 2.

4) The comprehensive purification capacity of type 1 is strongest with average removal rate up to 47.09%, while type 2 and type 3 have the same removal rate of approximately 41%.

Besides, from table 1, it can be known that the costs of three types of mixed filter materials follows this order in values, type 1 < type 2 < type 3, since soil and sand are cheaper than gravel and zeolite, and from type 1 to 3 the total mass ratios of red loam and sand decrease from 80% to 40% and that of gravel and zeolite increase from 20% to 60%.

Table 8 shows the discharge limits of the related five water quality indicators regulated in “Discharge standard of pollutants for municipal wastewater treatment plant (GB 18918-2002)” and “Farmland irrigation water quality standard (GB5084-2005)” in China, where the value of NH$_3$-N outside the parentheses is the limit when the water temperature is higher than 12°C, and the value in parentheses is the limit when the water temperature is lower than 12°C. Our experiments are conducted in winter and the temperature of water is lower than 12°C, thus the limits in parentheses should be applied in analysis.

Comparing the water quality conditions of outflow shown in table 4-6 to the standards shown in table 8, the following conclusions can be obtained.
1) Water quality of outflow for all of three types of mixed filter materials meets the requirement of both paddy and dry fields regulated by “Farmland Irrigation Water Quality Standard (GB5084-2005)”.

2) Except the indicator of BOD5, water quality of outflow for all of three types of mixed filter materials meets the requirement of level 2 discharge standard regulated by “Discharge standard of pollutants for municipal wastewater treatment plant.

| Standards | Discharge standard of pollutants for municipal wastewater treatment plant (GB 18918-2002) Unit: mg/L | Farmland irrigation water quality standard (GB5084-2005) Unit: mg/L |
|-----------|---------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| Indicators | Level 1A Level 1B Level 2 Level 3 | Paddy field Dry field |
| TP        | 0.5 1 3 5 | - - |
| TN        | 15 20 - - | - - |
| NH3-N     | 5(8) 8(15) 25(30) - | - - |
| COD       | 50 60 100 120 | 150 200 |
| BOD5      | 10 20 30 60 | 60 100 |

Table 8. Discharge limits of 5 related water quality indicators in two kinds of standards

4. Conclusions

A new LID-type ditch has been proposed in this study to treat rural sewage by replacing the bed soil in rural ditch with the mixed filter material for a thickness of about 30cm and setting several weirs along the ditch. Three types of mixed filter material have been generated by evenly mixing four basic common materials, red loam, sand, gravel and zeolite based on three different sets of material mass ratios. Their purification ability for TP, TN, NH3-N, COD, BOD5 and their saturated permeability coefficients have been analysed. The following conclusions can be drawn based on the study:

1) For purification ability, type 1 is better than type 2 and type 3 in general. The average removal rate for TP, TN, NH3-N, COD, BOD5 of type 1 achieves to 47.09%, while that of type 2 and type 3 have almost the same removal rate of approximately 41%. However, in particular, each type of mixed filter material has its own performance. Type 1 has obvious advantages in removing TP and COD, its removal rates of TP and COD achieve to 81.31%. Type 3 has an obvious advantage in removing TN with removal rate of 47.67%. While type 2 has no obvious removing advantage for a certain water quality indicators.

2) For permeability, type 1<type 2<type 3. Although the saturated permeability coefficient of type 1 is smallest with a value of $K_s=9.131\times10^{-5}$m/s, its permeability still can meet the required design
sewage treatment for most of Chinese village with a population of less than 2000. That means all three kinds of mixed filter materials are usually applicable in Chinese rural areas.

3) For economical performance, the total material costs of type 1 < type 2 < type 3, i.e., type 1 is cheapest and type 3 is the most expensive.

4) In summary, type 1 of mixed filter material with 50% of red loam, 30% of sand, 10% of gravel, and 10% of zeolite is the best one for the application of LID-type ditches in rural areas based on the comprehensive comparison of purification, permeability and costs.

5. References

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