The filtering efficiency of iron and salt of city rainwater by sand filtration process

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Abstract. The aim about the study was to improve the filtering efficiency of sand filter in the treatment of urban rainwater in residential area. In the experiment, a better sand filter was designed through changing the filtering materials and measuring the filtering efficiency for the urban rainwater treatment. Because of the weather conditions, not enough rainwater could be collected so that the stimulated rainwater which contained the same concentration of measured pollutants was used in the process of sand filtration. The experiment was divided into two parts, one part was the efficiency of salt removal and another was the efficiency of iron removal. In the salt removal testing, four sand filters were filled with different filtering materials which included 40 cm sand, 30 cm sand with 10 cm activated carbon, 30 cm sand with 10 cm zeolite, and 30 cm sand with 10 cm limestone, through pumping into a certain concentration of salt solutions and then getting the filtering efficiency of the sand filter. The second part of experiment was about iron testing. The iron testing included no salt iron testing which set three different concentration of iron (3 mg/L, 6 mg/L, 9 mg/L) and iron mixed with salt testing. (3 mg/L iron with 200 mg/L concentration or 400 mg/L concentration of salt, 9 mg/L of iron with 200 mg/L concentration or 400 mg/L concentration of salt). Then pumping into four sand filters filled with the same material like salt removal testing and get the efficiency of sand filter. The best filtering material and sand filter improvement would be determined through the two parts of the experiment and compared the filtering efficiency. Through the testing, the filtering material was strength the filter capacity. Otherwise, the zeolite had the best filtering efficiency in the salt testing and the following was limestone, activated carbon and sand. The iron testing was failed because the long stored of the filtering solutions.

1. Introduction

1.1. Background
Rainwater converted into water resources that can be utilized in other forms by human beings through various treatment and recycling methods. The collection and reuse of rainwater in urban communities refers to a process that collecting roof rainwater runoff and community road rainwater runoff and reuse it after certain treatment. The resource utilization of rainwater is one of the important criteria for measuring water saving in ecological residential quarters. Rainwater treatment and resource utilization can reduce the contradiction between urban water supply and demand, and it is also of great significance in saving water, flood control, and reducing non-point source pollution.
In the literature, the rain infiltration is a kind of indirect rainwater utilization technology, it is simple in technology, flexible design, convenient for construction, convenient operation and low investment, environmental benefits, etc. [1] Rain infiltration has added self-restraint of groundwater resources which improve the ecological environment and reduce the ground settlement. According to the different ways, it can be divided into scattered infiltration and concentrated injection technology, it also can be divided into artificial mandatory infiltration and natural penetration. Distributed infiltration can be applied to urban areas, living community, parks, roads, and the factory, it has simple facilities, could reduce the pressure on the rainwater collection, transmission system, complementing groundwater, it can also make full use of the purification function of surface vegetation and soil which reduces runoff into the water body pollution. But usually a penetration rate is slow in high underground water level, poor soil infiltration capacity or rain water pollution serious conditions such as application is restricted [2]. Centralized deep well injection capacity is big, it can be directly recharged to deep underground water, but it has higher requirements on ground water. Rain water quality, especially for the use of groundwater in city drinking water should be measured.

1.2. Aims and objectives
The aim about this dissertation is to optimize the filtering efficiency of the rain runoff pollutants in residential area using sand filter. In the experiment, we seek the best sand filtering condition through changing the filtering materials and measuring the filtering efficiency.

The experiment is divided into two parts, one part studies the efficiency of salt removal and another verifies the efficiency of iron removal. In the salt removal testing, four sand filter are filled with different filtering materials which includes all sand, sand and activated carbon, sand and zeolite, sand and limestone, through pumping into a certain concentration of salt solutions and then get the filtering efficiency of the sand filter. The second part of experiment is about iron testing, including no salt iron testing and iron mixed with salt testing. This is followed by pumping into four sand filters filled with the same material like salt removal testing, and determining the efficiency of sand filter. The best filtering material and sand filter improvement will be determined through the two parts of the experiment and compared the filtering efficiency.

2. Summary of literature review

2.1. Main pollutants in rainwater runoff
Rainfall and runoff have an obvious effect of flushing at the initial stage so that the urban surface accumulated pollutants are washed and transformed to the storm runoff with rainwater runoff discharged to the natural water bodies, which leads to the deterioration of natural water quality [3]. Because there are many different kinds of urban ground pollutants, the characteristics of pollutants in storm runoff pollution must be represented by the class of the pollution. The Environmental Protection Agency (EPA) recommended 11 kinds of storm runoff characteristic pollutants total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total phosphorus (TP), dissolved phosphorus (SP), total Kjeldahl nitrogen (TKN), nitrate nitrogen and nitrite nitrogen (NO₃⁻N, NO₂⁻N), copper (Cu), lead (Pb) and zinc (Zn) [4]. According to the pollutant characteristics, these can be divided into four broad categories, particulate matter, oxygen demand substance, eutrophication and heavy metal, respectively [5].

As the progress of raining, the concentration of pollutants in rainwater runoff is unstable, therefore it is difficult to describe the concentration of runoff pollutants. McLeod et al [6] used the method of event mean concentration (EMC) to calculate the average pollutant concentration of the stormwater runoff which is a more accurate approach for describing the amount of pollutants in storm runoff.

2.2. The main sources of storm runoff
In order to control the storm runoff pollutants effectively, it is important to know the source of rainwater runoff pollutants. Bannerman et al divided the Wisconsin residential area into the grass
(66.7 %), building house (12.8 %), community pavement (8.8 %), lane (5.5 %), street (5.1 %), and sidewalk (1.3 %) [7].

Table 1. The rain runoff pollution load contribution in residential area.

| Pollutants          | Grass (%) | Roof (%) | Road (%) | Lane (%) | Street (%) | Sidewalk(%) |
|---------------------|-----------|----------|----------|----------|------------|-------------|
| Total Solids (TS)   | 7         | 1        | 56       | 12       | 20         | 5           |
| Suspended Solids (SS)| 7         | 1        | 62       | 9        | 18         | 4           |
| TP                  | 14        | 1        | 39       | 20       | 19         | 8           |
| Cu                  | 3         | 1        | 33       | 13       | 45         | 5           |
| Zn                  | 2         | 2        | 42       | 11       | 38         | 5           |

Table 1 shows that the biggest contribution to the stormwater runoff comes from community roads and contact community streets, total copper and SS load contribution rate reached 58 %. However the permeable ground (grass) pollutant load contribution is less than 10%. Ruston research results show that the rain runoff pollution load contribution rate is significantly higher than the permeable surface impervious surface [8], therefore, the control of urban runoff pollution should focus on monitoring and managing. Storm runoff pollution source is very broad, including atmospheric dust, vehicles, transport and corrosion, erosion, corrosion of plant residues, animal manure and garbage erosion, etc.

3. Method

3.1. Sand particle size measurement

Fine sand is the material which has a good filtration efficiency of the large particles. In the experiment, sand is the main filling material for the filter so the size of sand particle has a critical influencing factor in the efficiency of filtration. Firstly, we decided to measure the particle size through four different apertures of sieves, 2 mm, 1 mm, 250 µm and 200 µm respectively. Four sieves were put on top of each other from large to the small so that the sand particles can be separated. Five hundred milliliter of sand is weighed and put on top of the sieve, and the sieves were shaken for several minutes which provides a better separating of sand particles until no sand is leaking out of the bottom sieves. Then the sand remaining on each sieve was weighed to confirm the percentage of each amount of particle size.

3.2. Pump testing

Pump is the device to move the rainwater to the sand filter in the experiment. The flow rate of pumps decides the flow rate of rainwater pumping in the sand filter. If the flow rate is too high, the water would overflow the sand filter. If the flow rate is low, the water would be below the filter medium which has an adverse effect in the efficiency of filtration. Four pumps marked A, B, C, D respectively are provided with the velocity controlled button from 0 to 9.9 and connected with a corresponding sand filter. After that we set the pump as 0.1 and began to pump tap water as the alternative of rainwater in measuring. Then we adjusted the pumps from 0.5 to 9.9 with each 0.5 interval using the same method and record each time.

3.3. Test the volume of sand and filter medium

Literature data suggest that the best filtration efficiency is obtained when the height of sand is 30-50 cm. Firstly, we poured the sand to the sand filter until the height of sand reaches 30 cm, and pumping the certain concentration of salt solution into the sand filter because the filtration efficiency can be calculated through the measurement of salt concentration in the percolate. Then we collected the discharging solution and measure the conductivity. The setting height of sand was 40 and 50 cm which is measured by the same method. The conductivity showed that 50 cm height has the best filtration
efficiency and 30 cm height sand was the worst which means that the higher height of sand has better filtration efficiency. However, the higher height of sand causes the longer filtering time. By comparing the efficiency and time, we choose the 40 cm height of sand as the filtering medium.

Three mediums are chosen as the filter material including active carbon, zeolite and limestone, considering the amount of active carbon provided and the method of control variables, the height of other filtering medium is 10 cm which replace the same height of sand in the columns B, C and D respectively. As the filtering medium needs to be washed after each group of experiments, the filtering materials are put into a bag so that they can be easily taken out.

3.4. Testing of salt filtration efficiency
Because the weather condition, we can’t collect enough rainwater for testing, so we decide to simulate the rainwater by mixing different compounds in distilled water. From the sand and other filtering medium height testing, the specific concentration changing of salt in the filtering process is certain. After collecting the discharging water from the column, the water is poured into a small beaker, the portable conductivity meter is inserted in solution and the conductivity is measured after 5 s’. The conductivity meter should totally immerse in the solution and the beaker needed to be shaken continuously, after each groups of measuring, the conductivity meter should be washed in the distilled water for twice which ensure the measurement accuracy; the ambient temperature should be controlled between 293-298 K. When the read on the conductivity meter is reach the highest point and unchanged, the simulate rainwater start to pump in the tap water, the diagram about the time and conductivity has a similar shape compared to the simulate rainwater pumping but the opposite change tendency.

3.5. Testing of ferric ion removal efficiency
In literature review, there are several main metal ions existing in rainwater such as copper, iron, lead and zinc to be considered. Because of the weather condition, rainwater was not enough using in the sand filtration so the experiment had to be simplified to simulate one metal ion concentration in rainwater and the different kind of effects about this metal iron. By comparing the four different metal ions, lead and its compounds have certain toxicity which cause the harm effects after entering the body to the nerve, blood, digestive, kidney, cardiovascular and endocrine system, so the simulated rainwater with dissolved lead ion is harmful and unsuitable in experiment. Otherwise, the analysis method of copper such as fluorescence molecular probe, atomic absorption method is simple, fast, accurate and low cost, however the measuring conditions are strict so that the range of application is restricted. Considering Atomic absorption spectroscopy (AAS) and spectrophotometry are cheap, common and easy to operate ways for iron concentration detection, it was decided to use spectrophotometry to measure the concentration of iron. After determining the simulated pollutant, the different situations also need be considered which affects the filtering efficiency. The concentration of iron ions is one of the influence factors which may cause the different filtering efficiency. So the experiment was divided to three different concentrations including low concentration (3 mg/L), normal (6 mg/L) and high concentration (9 mg/L), respectively. Otherwise, the weather conditions also have the influence on the filtering efficiency such in summer the NaCl in rainwater is low but in winter , NaCl is used in the thaw the ice on road. So the salt concentration is high which may cause an effect on the filtration, so the experiment was divided into eight groups, including low concentration of iron (3 mg/L) with no salt, medium concentration of iron (6 mg/L) with no salt, high concentration of iron (9 mg/L) with no salt, extreme concentration of iron (50 mg/L) with no salt, low concentration of iron (3 mg/L) with low concentration of salt (200 mg/L), low concentration of iron (3 mg/L) with high concentration of salt (400 mg/L), high concentration of iron (9 g/mL) with low concentration of salt (200 mg/L) and high concentration of iron (9 g/mL) with high concentration of salt (400 g/mL).
3.6. Main apparatus

3.6.1. Sand filter. The sand filter consisted of four same size columns. Each column is made of plastic, translucent in light blue. The sand filter is cylinder-shaped, 1 m in height, the inner and outer diameters being 8 cm and 10 cm, respectively. Each column is screwed down and placed parallel at 25 cm above the ground. There is a water inlet connected with the pump at the top of the column, and a nozzle at the bottom.

3.6.2. Pumps. The pumps used in the experiment is ECOLINE VC-380 which produced by the ISMATEC. It is the microprocessor controlled tubing pump with 3 roller providing lower pulsation and have slightly lower maximum flow rate. The depth/width/height of the pump is 256 x 169 x 138 mm, the weight is 5.3 kg and the flow rates of the pump is 1.6-5000 ml/min.

3.6.3. HI-98311 EC / TDS / Temperature Tester. EC, TDS and Temperature Tester, Low Range [HI-98311] Conductivity meter which is produced by HANNA instruments. The Dimensions are 163 x 40 x 26 mm (6.4 x 1.6 x 1.0”). The weight is 100 g (3.5 oz). EC range is from 0 to 3999 µS/cm, TDS range is from 0 to 2000 ppm and the temperature range is from 0.0 to 60.0 °C / 32 to 140.0 °F. The accuracy of EC and TDS is ±2 % F.S and the temperature accuracy is ±0.5 °C / ±1 °F.

3.7. Main materials
In the experiment, the main materials include sand (particle size < 2 mm), activated carbon, zeolite, limestone, NaCl and FeSO₄ • 7H₂O.

4. Results and discussion

4.1. The particle size of sand
The particle size meets the requirement of sand filter that 99.9 % of sand is below 1mm. Among them, the sand size ranged from 250 µm-1 mm occupied half the total sand and the size range from 200-250 µm and 0-200 µm have similar proportion.

4.2. The flow rate of pumps
The flow rate of pumps results show that the data displayed on pump has evident positive correlation with the flow rate. The equations of each pump are calculated as followed: Pump A is y=3.8170x-0.2307; Pump B is y=3.9251-0.1901; Pump C is y=3.9445 x-0.2373; Pump D is y=3.7528x-0.0873. The flow rate of pump A is from 0 to 37.56 ml/s, the flow rate of pump B is from 0 to 38.67 ml/s, the flow rate of pump C is from 0 to 38.81 ml/s, the flow rate of pump D is from 0 to 37.07 ml/s. So the actual power is C>B>A>D.

4.3. The filtering efficiency of salt in simulated rainwater
The Figure 1 shows the same concentration of salt solution filtered by different filtering media. It shows that the conductivity of filtering solution from the column filled with zeolite is the lowest at 0.56, and the column filled with activated carbon is the highest which the conductivity is 0.59. Because the conductivity is related to the concentration of the solution and the higher conductivity has a higher concentration. So the concentration of the filtering solution from the column filled with zeolite is the lowest which proves that the zeolite has the best filtering efficiency among the three filtering media and activated carbon’s filtering efficiency is the worst.
After analysing the filtering salt solution with the same filtering material and different height and the solution with the same height and different filtering material, the filtering efficiency of iron in simulated rainwater we can see the filtering efficiency of the column filled with two kinds of filtering material is better.

4.4. The efficiency of filtering iron from simulated rainwater

The graph is about the concentration of iron filtering changes using sand filter. From the graph, we can see the concentration of iron changes slight at the first 20 minutes, then a sharply increasing happened between 20 – 50 minutes. After 50 minutes, the concentration has a fluctuation changes but still have an increasing tread until 240 minutes. The Figure 2 shows that the iron concentration of filtering solution is from the column filled with 40 cm sand is the highest, the lowest concentration is from the column filled with 30 cm sand and 10 cm zeolite. Through the graph we can find the peak of each curve. The peak of curve represents the 40 cm sand is about 18 mg/L, the peak of 30 cm sand with 10 cm activated carbon, zeolite and limestone is 11 mg/L, 16.5 mg/L, 8 mg/L respectively. Because the initial iron concentration is 50 mg/L, so the efficiency of column A, B, C, D is about 64 %, 78 %, 67 % and 80 %. So the efficiency of the four sand filters is C > B > D > A. Compared to the efficiency of salt filtering, we can see the activated carbon has a better filtering efficiency in iron but the limestone have a better salt filtering efficiency.

Figure 1. Conductivity of salt after being filtered.

Figure 2. The concentration of filtering solution from the 50 mg/L iron simulated rainwater.
5. Conclusions and recommendations
Through the testing, the filtering material is better improved the filter efficiency. Otherwise, the zeolite has the best filtering efficiency in the salt testing and the following is limestone, activated carbon and sand. The iron testing is failed because the long stored of the filtering solutions.

Before experiment, we have already determined the testing components and the rainwater collection site through the article reading and group discussion. Because of the weather conditions, the rainwater was collected insufficiently which replaced by the simulated water. The simulated rainwater was the tap water, one or two chemical reagents were dissolved into water which similar with the concentration in rainwater. It may have a large difference between the rainwater causing the COD, SS which acts as the main polluted components in rainwater has not been analyzed in the experiment. Secondly, after using simulated rainwater, the experiment is simplified and mainly divided into two parts. The efficiency testing of the filtering salt solutions and the filtering efficiency of iron discharge through the sand filter. However, the second part of experiment is failure, and the results got in the experiment is not enough to have a convincing explanation about which medium has a better filtering efficiency. Thirdly, because the column is difficult to take down, so we didn’t change the sand or the filtering material since the first time filling into the column causing the decrease of filter capacity so that affect the experiment results.

In the future work, the simulated rainwater should be replaced by the certain area rainwater. BOD, TSS and NH3-N also need to measure to provide enough evidence in the filtering efficiency of the filtering medium. Otherwise, the samples should be stored in a closed environment and placed separately to avoid the influence of outside air and the interaction between samples.

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