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Research article

Modeling the effects of parameter optimization on three bioretention tanks using the HYDRUS-1D model

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ABSTRACT

The operation effects of bioretention on different tanks were investigated through tests and simulations. Three layered bioretention tanks, namely, #1, #2, and #3, were selected for intermittent operation tests. The artificial filler layers of the tanks consisted of mixed fillers of fly ash and sand, blast furnace slag, and planting soil. Models were established by using HYDRUS-1D software based on test results. The sensitivity of model parameters was analyzed through Morris screening method. Results showed that return period, thickness of media layer, and solute concentration in the liquid phase were the parameters that significantly influenced the operation effects. The Nash–Sutcliffe efficiency coefficients of the models were greater than 0.85. The simulation results showed that the reduction effects at different inflow loads were better under low loads than under high loads. The comprehensive reduction rate of pollutant load was 5.22% less under high concentrations than under low concentrations. The comprehensive reduction rates of water and pollutant loads were 35.97% and 20.68% greater, correspondingly, in the 1 year return period than in the 10 year return period. The artificial fillers comprising a mixture of fly ash and sand also showed the optimal reduction effects, with comprehensive reduction rates of 69.33% and 83.08% for water and pollutant load, respectively. The reduction effects of water and pollutants for the #1 tank presented an upward trend, whereas those for the #2 tank showed a downward trend given an increase in planting soil thickness. An increase in media thickness enhanced the reduction effects. The media with 60 cm thickness demonstrated the optimal effect.

1. Introduction

Stormwater disasters result in considerable economic losses to cities and exacerbate nonpoint source pollution (Jiang et al., 2017). Traditional drainage network systems exhibit a low control rate for rainwater (Xu et al., 2017). At present, low-impact development (LID), proposed by the United States, is widely recognized as a technical system for sustainable management and control of urban water (Jia et al., 2013). The LID can provide more sustainable solutions than the traditional drainage network systems. This technical system improves sustainability by utilizing bioretention facilities, green roof, vegetation swale, artificial permeable ground, and other technical measures (Traver and Ebrahimian, 2017). Moreover, this system can effectively control the total runoff, runoff peak, and runoff pollution through infiltration, storage, purification, adjustment, and transfer of rainwater (Chen et al., 2016). Other countries have proposed some flood management measures on the basis of the LID concept or the actual situation in the country. In 1990s, Britain proposed a concept called sustainable urban drainage systems (SUDS) (Ellis et al., 2003). Australia has proposed a water sensitive urban design(WSUD) (Gardner et al., 2006). New Zealand's Auckland district government issued a ‘Low impact design’ guide in 2000(Easton and Ansen, 2014). Although Germany did not put forward an internationally influential stormwater management concept, experts in some EU countries, dominated by Germany, carried out a SWITCH project in 2011 (Che et al., 2014). By the end of 2013, the Chinese government proposed a LID system-based sponge city construction. The main purpose of the sponge city construction was to control waterlogging and nonpoint source pollution (Jia et al., 2015; Ren et al., 2017). The “six-word” principle,

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that is, infiltrate, detain, store, cleanse, use, and drain, are considered the guidelines for urban stormwater management (Jia et al., 2017). Bioretention systems, as a typical sponge city construction technology, are considered one of the best management tools for water recycling/reuse systems (Lau et al., 2016). This technology provides a favorable prospect in China (Li et al., 2017).

In the past few years, numerous simulation studies on large-scale control effects of LID have emerged, while the researches on parameter optimization of specific LID facility are few. The operation effects of bioretention are influenced by numerous factors (Debusk and Wynn, 2011). A large amount of data are required to analyze the effect of these factors on the operation. If tests are used to obtain the data required for such an analysis, then a heavy workload can be expected. Actual tests involve many uncertainty factors that affect the test results. By contrast, models based on actual test data are reliable and convenient when used to simulate the transport of water and solutes. In particular, the HYDRUS model offers a wide range of applications. Migration of water and solutes can be simulated comprehensively with this model, which requires minimal input data and which results are reliable. The HYDRUS model has been used in the agricultural and environmental fields (Ramos et al., 2011; Yi and Fan, 2016).

Based on related research results, an experimental scheme was made and the pilot tests were performed on bioretention tanks. The HYDRUS-1D software was utilized to analyze the influence of media type, thickness of artificial fillers, planting soil thickness, rainfall, and pollutant concentration on purification effects of bioretention tanks. Then, the effects on the operation of bioretention tanks under various situations were simulated. The simulation was mainly aimed at optimizing the parameters of bioretention tanks. The main purpose was to optimize the parameters of bioretention tanks to enhance their reduction effects on water and pollutants, and provide design services to the stormwater remediation community in Xi'an regions and the potential applications to other regions.

2. Materials and methods

2.1. Natural survey of the study area

A bioretention device was built in the outdoor field of Xi'an University of Technology. Xi'an City is located in Guanzhong Basin in the middle of the Yellow River Basin. The annual average temperature in the plain area of the city is 13 °C. The average rainfall in all municipal districts and counties of the city is 537.5–1028.4 mm, whereas the annual average rainfall in urban areas is 583.7 mm. The average number of rainfall days in all municipal districts and counties of the city is 88–105, whereas the annual average number of rainfall days in urban areas is 96.6; furthermore, the longest number of days with continuous rainfall is 13–19 (Li et al., 2016a).

2.2. Devices and schemes of the tests

A unit composed of medium-sized bioretention devices was designed and constructed in the outdoor field of Xi'an University of Technology. The unit comprised 10 bioretention tanks. Five bioretention tanks on the right were semipermeable, whereas the bioretention tanks on the left were impermeable. The experimental bioretention tanks were rectangular in shape (length = 2 m, width = 0.5 m, and depth = 1.05 m). All of the 10 tanks shared one water tank with a volume of 2700 L. The bottom of the gravel drainage comprised layered perforated pipes, and the drain was cupped by permeable geotextile. Triangular weirs (30°) were installed on the inlets, outlets, and overflow outlets of the bioretention tanks. XTHJ recorders (They are the instruments for measuring water level. The flow of each time point can be calculated according to the measured water level) were installed before the weirs to monitor the flow of water in the inlets, outlets, and overflow outlets. A flood plan and a cutaway view of the tanks are illustrated in Fig. 1.

Tanks #1, #2, and #3 were used to analyze the regulation effects of bioretention tanks on water and solutes. The influencing factors included the type of artificial fillers, influent water volume, influent concentration, interval time, and depth of the submerged area (Zhang, 2014; Liu and Elizabeth, 2017). Three types of artificial fillers, namely, mixed fillers of fly ash and sand, blast furnace slag, and planting soil, were utilized. The assumed rainfall intensities of the test were calculated with the rainstorm intensity formula of Xi'an City under two return periods of two and five years. Then, the amount of rainfall was obtained at a rainfall duration of 120 min. The results of influent water volume are summarized in Table 1.

The pollutant indexes for analysis mainly included chemical oxygen demand (COD), nitrate nitrogen (NO_3—N), ammonia nitrogen (NH_3—N), total nitrogen (TN), and total phosphorus (TP). The concentrations of water distribution were based on the results of urban rainfall runoff pollution of an earlier period monitored by our research group. Two cases of influent concentration, that is, high concentration (initial rainwater) and low concentration (middle and late rainwater), were designed. In the case of high concentration, COD, NO_3—N, NH_3—N, TN, and TP were 600, 14, 6, 20, and 2.5 mg/L, respectively. In the case of low concentration, COD, NO_3—N, NH_3—N, TN, and TP were 300, 8, 3, 11, and 1 mg/L, correspondingly. In the present study, the influent concentration of a single session was kept constant. The simulation of a complete rainfall process was also crucial. The rainfall pattern in Chicago can satisfy this requirement and the general requirements for accuracy (Li et al., 2016b). Thus, we selected this pattern with a rainfall peak coefficient of 0.3.

The tanks were washed with water before the tests. Hydrographs of effluent water volume and effluent concentration under difficult working conditions were obtained through these tests. The characteristics and mechanism of pollutant removal of the bioretention tanks were summarized. The specific test arrangements are displayed in Table 2.

Tests 2 and 3 were used to compare the differences of effluent effects under different depths of the submerged area. Tests 4 to 6 were used to compare the differences of effluent effects under different interval times. Tests 7 and 8 were used to compare the differences of effluent effects under different influent water volumes. Tests 8 and 9 were used to compare the differences of effluent effects under different influent concentrations.

2.3. Sampling arrangement and detection method

The sampling stage lasted for 2 h. Outlet water samples were collected every 15 min in the sampling stage when the sampling ports began to flow. Two bottles of inlet water samples were collected in the initiation stage.

The analysis indexes mainly included COD, NO_3—N, NH_3—N, TN, and TP. In accordance with the Environmental Quality Standard for Surface Water (GB3838-2002) and the Surface Water Monitoring Technology Standard of the Environmental Protection Industry (Ministry of Environmental Protection of the People's Republic of China, 2002a), COD was determined through a fast digestion spectrophotometric method, while NO_3—N was determined using a spectrophotometric method with phenoldisulfonic acid. NH_3—N was determined via Nessler's reagent spectrophotometry, while TN was determined via potassium supersulfate oxidation—ultraviolet spectrometry. TP was determined with the molybdenum—antimony anti-spectrophotometric method