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Original Research Paper

# Application of Bio-retention Hydrologic Performance Tool for Urban Runoff Pollutants Removal

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## ABSTRACT

To achieve more reasonable and effective treatment of urban stormwater, researchers proposed the Low Impact Development (LID) method, which is regarded as a sustainable solution. Studies have shown that the bio-retention system was effective in tackling urban runoff problems and was one of the most commonly used LID. In hydrologic modeling, DRAINMOD has a new application in bio-retention simulation. A model named Hydrologic Performance Tool (HyPer Tool) is proposed based on the output of DRAINMOD simulations on various bio-retention designs. This paper utilized HyPer Tool to simulate the bio-retention system in the urban road runoff in Xi'an, China with different rainfall conditions and characteristics. Meanwhile, this paper discussed and analysed the dynamic changes of pollutants and impurities during bio-retention system runoff purification in the four typical designs of HyPer Tool bio-retention ponds so as to provide an objective evaluation on bio-retention – an urban rainfall-flood management approach.

## INTRODUCTION

In recent years, many cities need to manage urban water cycle and its allocation with the rapid development of urbanization when they have been undergoing problem of stormwater. As a response to this problem, many researchers attempted to develop various methods as a solution. Low impact development (LID) is generally regarded as a relevant sustainable solution for urban stormwater management than conventional urban drainage systems (Qin et al. 2013). Bio-retention system is one of the most commonly used LID implementations (Brown et al. 2013). They can be designed and constructed with a variety of specifications including media depth, underdrain configuration, media composition, drainage area to bio-retention area ratio, and surface storage volume (Brown & Hunt 2011). However, hydrologic performance has varied greatly in past studies owing to the effect of the specifications mentioned above. LID can generate an annual water balance to describe the hydrologic performance (Brown & Hunt 2010). But, it is difficult to apply specific values to a bio-retention water balance because of the variety of site and design variables (Brown et al. 2013). For this purpose, DRAINMOD, a long-term and continuous simulation drainage model that was first developed in the 1970s at North Carolina State University is further improved and expanded to a new application system, Hydrologic Performance Tool (HyPer Tool), which is applied to simulate bio-retention hydrology.

With regard to the urban stormwater management, it not only includes flood control and drainage problem (Samuel et al. 2012), but also rainfall runoff non-point source pollution control (Zhang et al. 2014). Some researches have also put forward that the urban rainfall runoff is the main non-point pollution sources (Lee et al. 2012, Rhee et al. 2012, Kim et al. 2014). When it rains, the ground, especially the impervious areas in urban cities, is not able to soak up all the water. The excess water flows into underground stormwater drains which often lead directly into nearby bodies of water such as streams, rivers and oceans. As the rainwater flows over paved surface it picks up pesticides, fertilizers, bacteria, soil, grease, oil and litter. Therefore, the bio-retention attempt is necessary for removal of urban road surface pollutants.

The city of Xi'an is located at 107°40'-109°49' east longitude and 33°39'-34°35' north latitude in the north of China. Once being the capital of China for over a thousand years, it is also a major tourism city for its long history. The city now covers an area of 3582 square kilometres with a population of 8 million. With its rapid industrialization, urbanization and high-tech development in recent decades, this city has been the centre of the economy, culture, manufacturing and education in northwest China (Chen et al. 2012). As the city is enjoying rapid economic growth, growing number of high-rise buildings and increased impervious surfaces are changing the urban hydrology further. In recent years, the city has attached greater and greater importance to greening so as to fend against the side effect of urbanization. The local rainfall is often characterized by short duration and high intensity although the total amount of rainfall categorizes the city only into the semi-arid and semi-humid region (Quan et al. 2012).

Based on the model HyPer Tool, this paper aims to simulate different rainfall conditions, observe the characteristics of urban road runoff in Xi'an, with the application of bio-retention system, discuss the design of HyPer Tool bio-retention ponds of various sizes, and analyse the dynamic changes of pollutants and impurities during bio-retention system runoff purification, so as to provide an objective evaluation on bio-retention and an urban rainfall-flood management approach.

## MODEL DESCRIPTION

The North Carolina Long-Term Bio-retention HyPer Tool is a model used to simulate the hydrologic cycle and purification effect of water quality in bio-retention cells with specific hydraulic design features. Analysis is performed on an arbitrary bio-retention system containing the recommended soil media by North Carolina Department of Environment and Natural Resources in 2009. The designs are optimized for project constraints by adjusting the depth of soil media, internal water storage (IWS), average surface ponding depth, and surface storage volume (relative to the water quality volume). HyPer Tool is a Macro-Embedded Excel Spreadsheet model developed by North Carolina State Stormwater Engineering Group. All the process data of HyPer Tool are developed from 432 DRAINMOD simulations as defined in Final Report to WRRI of the University of North Carolina, namely "Long-term Modeling of Bio-retention Hydrology based on DRAINMOD".

Compared with DRAINMOD, HyPer Tool has many flexible features which are too complex to be entirely controlled by beginners. It is capable of quantifying hydrologic performance through different soil types, various design specifications, and undersized/oversized systems to avoid using a "one-size-fits-all" approach. It can compute total volume reduction of stormwater network and so on. As a simplification of DRAINMOD (using the output from DRAINMOD simulations of various bio-retention designs for the state of North Carolina), HyPer Tool can be used to describe the water movement in bio-retention cells more easily for beginners of DRAINMOD.

**Water balance principle of the model:** Bio-retention is increasingly used as a runoff management practice in urban areas and its media acts as a flow restrictor for water storage. But overflow, infiltration and exfiltration still lead to failure of restricting certain amount of water (David et al. 2012). Bio-retention cells, also known as bio-infiltration facilities or rain gardens, are a form of urban stormwater and Low Impact Development (LID) that reduces runoff quantity and improves water quality in a natural and aesthetically pleasing manner, and is becoming one of the most popular LIDs (Davis et al. 2009). Unlike wetlands, however, bio-retention cells rely on terrestrial forested ecosystems and are designed to drain within hours.

The movement of stormwater in bio-retention cells, when installed with underdrain, is very similar to a flow restrictor. As such, bio-retention cells can be conceptually modelled in DRAINMOD because many of the model inputs correspond to bio-retention cell design specifications (Brown et al. 2010). The water balance in bio-retention cells could be roughly described by the following equation.

$$Vol_{Runoff} = Vol_{Overflow} + Vol_{Drainage} + Vol_{ET} + Vol_{EXF} \quad ...(1)$$

Where, *VolRunoff* = runoff volume, *VolOverflow* = overflow volume, *VolDrainage* = drainage volume, *VolET* = evapotranspiration volume, and *VolEXF* = exfiltration volume. The simple schematic plot of HyPer Tool is shown in Fig. 1 (Brown et al. 2013).

**Introduction of four default modes in the model:** In HyPer Tool, there are four typical designs (A, B, C and D) that act as the main performers of a specific hydraulic simulation in bio-retention cells. Users get the simulation results directly by choosing four kinds of typical soils. Each typical design soil of the model has their respective vertical conductivity of restricting layer. A summary of these parameters is shown in Table 1. The theoretical values in Table 1 refer to the reliable results of the study by Rawls and his co-authors (Rawls et al. 1998), which are defined by soil textural class.

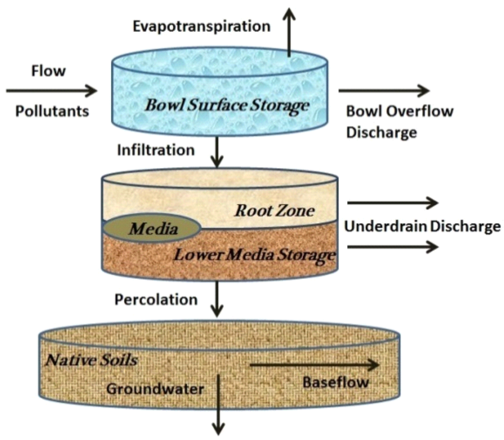


Fig.1: The general hydrology performance and water balance mechanism in HyPer Tool.

Table 1: The vertical conductivity of restricting layer related to the HyPer Tool's typical design (A, B, C and D).

| Typical design | Measured value (site and soil type) | Theoretical value (soil type) | Model output |
|---|---|---|---|
| A | 6~9cm/hr (Rocky Mount Sand Cell) | 6.40cm/hr (Sand)<br>3.05cm/hr (Loamy Sand) | 3.0cm/hr |
| B | 0.21~0.33cm/hr (Rocky Mount SCL Cell)<br>0.37cm/hr (Graham-South) | 0.51cm/hr (Sandy Loam<br>0.28 cm/hr (Loam) | 0.35 cm/hr |
| C | 0.03~0.05cm/hr (Greensboro-1)<br>0.02 cm/h (Graham-North)<br>0.05~0.08cm/hr (Knightdale-Small)<br>0.03~0.04cm/hr (Knightdale-Large) | 0.10cm/hr( Sandy Clay Loam)<br>0.03cm/hr (Sandy Clay)<br>0.02cm/hr (Clay Loam) | 0.05cm/hr |
| D | - | 0.03cm/hr (Clay) | 0.005cm/hr |

Furthermore, the end of model output values (maximum subgrade $K_{sat}$) are based on the decision of the DRAINMOD procedure.

In light of other researchers' design, these parameters can be found in DRAINMOD such as the ponding zone in bio-retention design corresponding to the max surface storage ($S_m$) in DRAINMOD and so on. The surface storage depth in HyPer Tool, based on NC regulation, is 23 cm (9 inch) or 30 cm (12 inch). Such kind of acquiescent parameters appear on the drainage configuration of the HyPer Tool like drain spacing (4.5 m (15 ft)) and drain diameter (15cm (6 in)). The drainage efficiency is limited to 20 cm/day (restricted drainage network), 40 cm/day (restricted drainage network), and 60 cm/day (unrestricted drainage network). Because IWS reduces hydraulic gradient on outlet, the restricted network drainage coefficient is smaller. Moreover, the related developers of the model refer to the data collected at Knightdale bio-retention cells by Luell's thesis (Luell et al. 2011) whose study confirms that the maximum drainage rate is 15 and 21 cm/day.

## MATERIALS AND METHODS

**Study site and experimental data description:** Stormwater samples were collected from South Second Ring in Xi'an city and the results showed that runoff from urban road surface has much greater pollution intensity of suspended solid (SS) and chemical oxygen demand (COD), and has less biodegradability. Continuous sampling of surface runoff was carried out at the gutter inlet on one side of the motorway at South Second Ring Xi'an city during two rainfall events. A continuous period was taken from each rainfall, but the measuring was conducted after the beginning of each rainfall. Samples were collected between 2:40-4:40, 04/23/2011 and between 20:35-21:45, 05/02/2011. Runoff samples were collected every 5-15 minutes, while flow and rainfall intensity were measured once (the mean for every 5-15 min). At the same time, SS and COD of the samples taken from each time were also measured with the results shown in Figs. 2 and 3. Fig. 2 presents the result of the event on 4/23/2011, whose rainfall intensity ranged from 38 to 202 mm/min with an average intensity of 87.3 mm/min. The SS concentration varies from 242 to 1306 mg/L with an average of 602.6 mg/L, while the COD varies from 143 to 624 mg/L with an average of 328.1 mg/L. Fig. 3 shows the result of the event on 5/2/2011, whose rainfall intensity ranged from 24 to 92 mm/min with an average of 40.7 mm/min. The SS concentration varies from 456 to 2322 mg/L with an average of 934 mg/L, while the COD varies from 226 to 835 mg/L with an average of 392 mg/L. According to the statistical results of SS and COD during the two days, the SS concentration of the event is greater than Level III (> 400 mg/L) in Integrated Wastewater Discharge Standard (GB8978-1996), while COD concentration is greater than Level II (150-500 mg/L) in Integrated Wastewater Discharge Standard (GB8978-1996). For this reason, urban road surface runoff suffers from high pollution intensity. Such high-intensity urban road surface runoff drainage will have serious impacts on the water quality of rivers.

It can be seen from Figs. 2 and 3 that although rainfall intensity during the two days is different, the SS and COD concentrations have similar variation regulation, namely the peak value of SS and COD concentrations happens in both events with the change trend of increasing first and then decreasing.

**Modeling approach:** With HyPer Tool simulation model for water quality, the paper designed a bio-retention system with four different fillers in view of rainfall runoff to simulate the dynamic changes of SS and COD concentration. First, SS and COD concentrations at different times on April 23, 2011 and May 2, 2011 are converted in accordance with HyPer Tool preset unit; then the filler configuration of A, B,

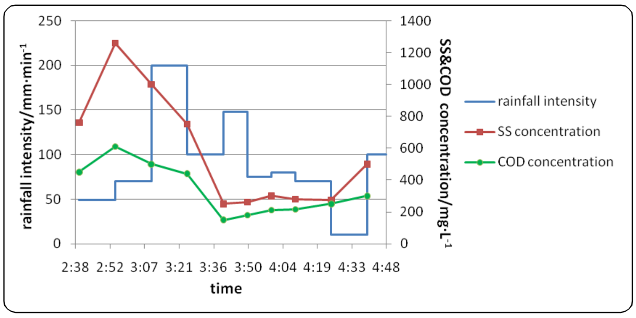


Fig. 2: The SS and COD concentration of rainfall intensity and road surface runoff pollutants on April 23, 2011 surveyed from South Second Ring in Xi'an, China.

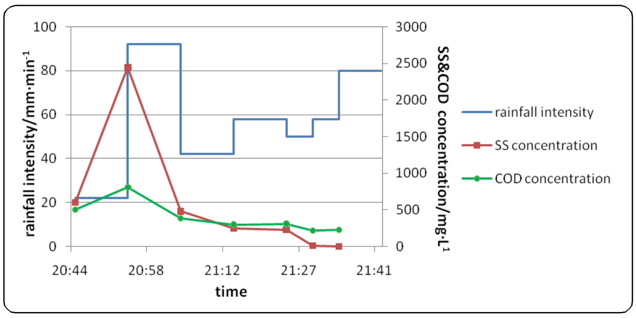


Fig. 3: The SS and COD concentration of rainfall intensity and road surface runoff pollutants on May 2, 2011 surveyed from South Second Ring in Xi'an, China.

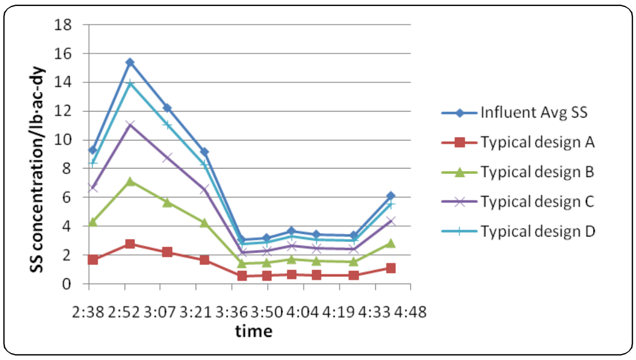


Fig. 4: The SS concentration change of influent and effluent rainfall from four typical designs of bio-retention (A, B, C and D) on April 23, 2011 surveyed from South Second Ring in Xi'an.

C and D retention system is set with the lowest surface water storage efficiency of 50%, since samples were taken on one side of the motorway where there is great disturbance. For the four retention systems, surface storage depth equals 23 cm (9 inch); drainage area: bio-retention area = 10.2:1. Finally, the converted SS and COD concentrations at different times on April 23, 2011 and May 2, 2011 are put in the model that is operated with the four typical designs.

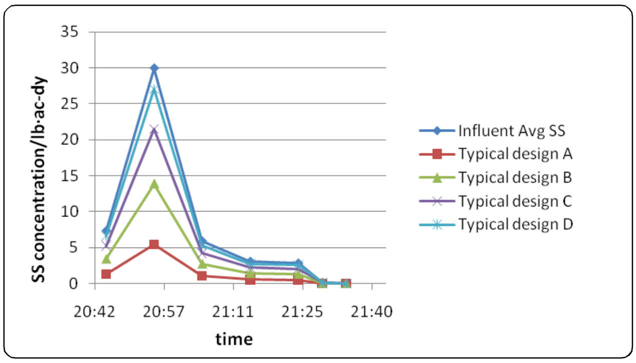


Fig. 5: The SS concentration change of influent and effluent rainfall from four typical designs of bio-retention (A, B, C and D) on May 2, 2011 surveyed from South Second Ring in Xi'an.

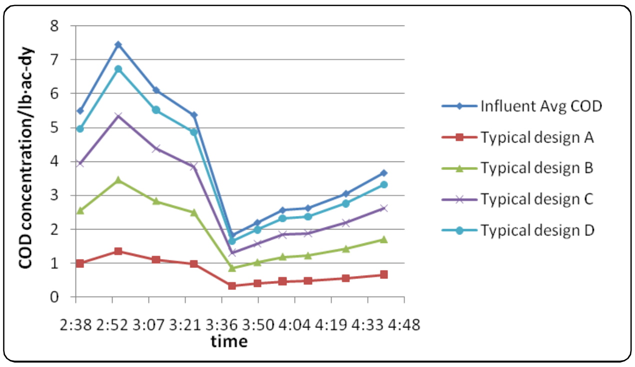


Fig. 6: The COD concentration change of influent and effluent rainfall from four typical designs of bio-retention (A, B, C and D) on April 23, 2011 surveyed from South Second Ring in Xi'an.

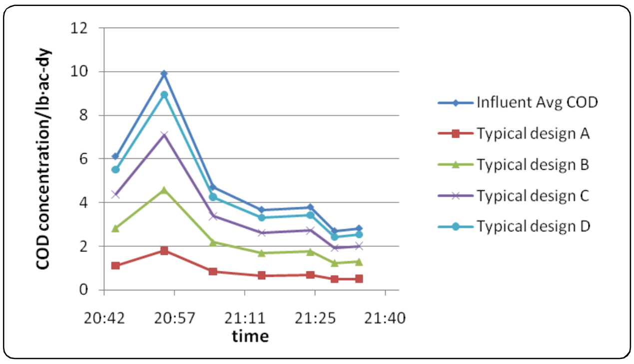


Fig. 7: The COD concentration change of influent and effluent rainfall from four typical designs of bio-retention (A, B, C and D) on May 2, 2011 surveyed from South Second Ring in Xi'an.

## RESULTS AND DISCUSSION

HyPer Tool is utilized to simulate the concentration change of SS and COD in the two rainfall runoff events mentioned previously and the results are presented below.

In Figs. 4 and 5, influent average SS represents the

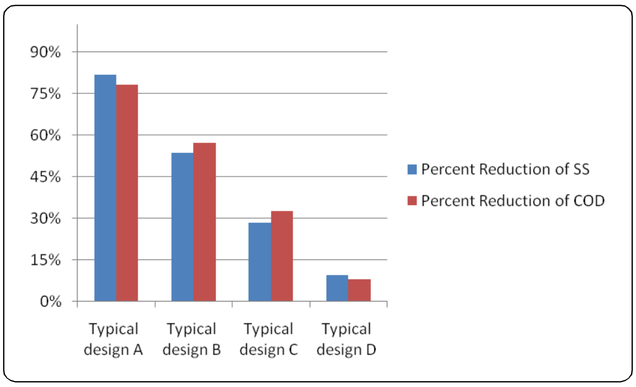


Fig. 8: Percentage reductions in typical Designs A, B, C, and D of stormwater pollutants.

outcome values of SS concentration at various time points in two rainfall events on April 23, 2011 and May 02, 2011 converted according to the unit default of HyPer Tool, namely the SS concentration flowed into the water of bio-retention cell.

Typical designs A, B, C and D indicate the transformation process of SS concentration contained in overflow water and pond drainage after the runoff formed during the two rainfalls flowing through A, B, C and D-four kinds of bio-retention cells. Simulated results in Figs. 4 and 5 manifest that after setting bio-retention cells, SS concentration declines at various time points to varying degrees. Among them, simulated results of two rainfall events both reflect that stain removal effect of bio-retention cell D is the worst, the SS removal rate being 9.5%; the effect of bio-retention cell A is the best, the SS removal rate being 81.9%. Likewise, it could be seen from Figs. 6 and 7 that four kinds of bio-retention cells also have similar effect of removing COD. In other words, the removal effect of bio-retention cell D is still the worst, the COD removal rate being about 8.1%; the effect of bio-retention A is still the best, the COD removal rate being about 78.3%. The statistic results of removal rate after arrangement are shown in Fig. 8.

Based on the above results, with bio-retention system in Design A which has the best decontamination effect, the removal rate of SS and COD reach 81.9% and 78.3% respectively. According to statistics, SS and COD concentrations of 2:40-4:40 on April 23, 2011 runoff can be restrained between 43.8-236.4mg/L and 31.0-135.4mg/L with the average concentration reduced to 109.1mg/L and 71.2 mg/L respectively. SS and COD concentration of 20:35-21:45 on May 2, 2011 runoff can be restrained between 82.5-420.3mg/L and 49.0-181.2mg/L with the average concentration reduced to 169.1mg/L and 85.1mg/L respectively. In light of SS and COD concentration simulation effect in bio-retention system A which produces the best decontamination effect, SS average concentration of rainfall runoff on April 23, 2011 reaches Level II (70-150mg/L) of Integrated Wastewater Discharge Standard (GB8978-1996), while COD average concentration reaches Level I (≤100mg/L) of Integrated Wastewater Discharge Standard (GB8978-1996). SS average concentration of rainfall runoff on May 2, 2011 reaches Level III (150-400mg/L) of Integrated Wastewater Discharge Standard (GB8978-1996), while COD average concentration reaches Level I of Integrated Wastewater Discharge Standard (GB8978-1996). Therefore, bio-retention system can, to some extent, remove impurities and pollutants in water, more over, COD removal effect is better than SS removal effect. But even the most ideal bio-retention configuration fails to reduce SS concentration to Level I (≤ 70mg/L) of Integrated Wastewater Discharge Standard (GB8978-1996). In addition, when COD concentration reaches its peak during a rainfall, the concentration result processed by bio-retention system A still lingers at Level II (100-150mg/L) of Integrated Wastewater Discharge Standard (GB8978-1996).

## CONCLUSION

From the above study, the following conclusions of simulating runoff pollutant SS concentration with HyPer Tool in urban road in Xi'an City can be drawn.

1. Urban road surface runoff harbours high-intensity pollutants and such high-intensity runoff discharge will produce severe impacts on the water quality of road surface and rivers.
2. Bio-retention technology can, to some extent, reduce SS and COD concentration in urban road surface runoff.
3. With bio-retention system A having the best decontamination effect, the removal rate of SS and COD reaches 81.9% and 78.3% respectively.
4. Based on the statistics of the two indicators, the bio-retention design in the model presents better effect on COD removal than SS removal.
5. Applying HyPer Tool bio-retention design to SS and COD in surface runoff at South Second Ring, Xi'an can achieve certain purification effect, though the decontamination ability is still open to improvement compared with the input cost, more samples should be collected to optimize the model of HyPer Tool so that it can be applied in the practice of environment pollution governance effectively with low cost.

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