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IMPACTS OF DIFFERENT SOIL TEXTURE AND ORGANIC CONTENT ON HYDROLOGICAL PERFORMANCE OF BIORETENTION

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ABSTRACT

The land development and increase in urbanization in a watershed affect adversely both surface water and groundwater resources. Low Impact Development (LID) Best Management Practices (BMPs) such as bioretentions, vegetated rooftops, rain barrels, vegetative swales, permeable pavements and storm water wetlands have been implemented in order to diminish adverse effects of urbanization. LID-BMP is a land planning method which is used to manage storm water runoff by reducing peak flows as well as simultaneously improving water quality. In this study, a particular LID-BMP, i.e. bioretention is investigated. For this purpose, an experimental setup called as Rainfall-Watershed-Bioretention (RWB) System is developed which involves an artificial rainfall system, drainage area and bioretention columns. Four bioretention columns with different soil textures and organic content are constructed in order to investigate their effects on water quantity. Runoff volume, hydrograph, peak flow rate and delay in peak time at the exit of bioretention columns are observed under various rainfalls in order to understand the role of both soil types used in bioretention columns and rainfall intensities. Results show that different local soil types in bioretention implementation affect surface runoff and peak flow considerably. Finally, the connection among rainfall, surface runoff and flow reduction after bioretention is established via kinematic waves and modified Green-Ampt method.

BACKGROUND

LID BMPs is an approach of land re-development in order to manage storm water runoff and quality. Preserving and recreating natural landscape features, minimizing effective imperviousness to create functional and appealing site drainage, which treats storm water as a resource rather than as a waste product, are intended by implementing LID. There are several LID type of storm water BMPs such as bioretention facilities, green roof, rain barrels, vegetative swales and permeable pavements. LID has several benefits beneath improving management of runoff and flooding such as protecting animal habitats and ecology of the watershed.

(a) (b) (c) (d)

Figure 1. Types of LID in the literature (a) green roofs (TonyTheTiger, 2008), (b) vegetative swale (Pennsylvania Stormwater Best Management Practices Manual, 2006), (c) permeable pavement (JJ Harrison, 2011), (d) rain barrel (Abby Hall, U.S. EPA).

Bioretention is one of the most frequently used LID-BMPs implementation. Bioretention is used to decrease runoff volume and peak flow rate, increase evapotranspiration, infiltration and ground water recharge, and reduce the pollutant loading in surface and ground water. The following types of Bioretention are in the literature.

Figure 2. Bioretention pictures in the literature (Davis, 2002, 2003, 2007).

Kinematic Waves

For overland flows, the continuity and momentum equation and their combined form for kinematic waves are given as follows (Chow et. al. 1988):

$$\frac{\partial y}{\partial t}+\frac{\partial q}{\partial x}=i-f$$

$$\left.\begin{aligned}&\frac{\partial y}{\partial t}+\frac{\partial q}{\partial x}=i-f\\ &q=\alpha y^{m}\end{aligned}\right\}\Rightarrow \frac{\partial y}{\partial t}+\alpha\frac{\partial (y^{m})}{\partial x}=i-f$$

Modified Green-Ampt Method

The modified version of the Green-Ampt method during unsteady rainfall is given by Chu (1978).

$$F_p=\frac{K_z MS}{(i_j-K)}$$

$$F_{j+1}=F_p+K_z(\Delta t-\delta t)+MS\,\ln\left[\frac{F_{j+1}+MS}{F_p+MS}\right]\Rightarrow f_j=\frac{F_{j+1}-F_j}{\Delta t}$$

$$\delta t=\frac{(F_p-F_j)}{i}$$

EXPERIMENTAL SETUP

Rainfall-Watershed-Bioretention (RWB) System

RWB System is constructed on Avcılar Campus of Istanbul University in Istanbul, Turkey. The system contains 40 m^2 of drainage area for watershed simulation, 40 rainfall nozzles for artificial rainfall simulation and 4 bioretention columns. The system is set up outdoor so that bioretention may also be tested under natural rainfall.
The slope of the area is fixed to 0.7% for the experiments conducted in this study but is adjustable. The artificial rainfall system is constructed 1 m above the drainage area to simulate rainfall with different intensities. A water tank with 5 ton capacity and a pump are used for the artificial rainfall system setup.

Figure 3. Photos of Rainfall-Watershed-Bioretention (RWB) System.

Bioretention Columns

Bioretention columns have cylindrical shape with inner diameter of 54 cm and height of 118 cm and are made from polyethylene material. In general, gravel is used to accelerate infiltration and to prevent clogging in drainage pipes.

Table 1. Composition of bioretention column media.

Column No	Sand (% by weight)	Local Soil (% by weight)	Turf (% by weight)	Gravel (kg)	Mulch (kg)
1	70	30	0	40	3.5
2	70	20	10	40	3.5
3	85	15	0	40	3.5
4	55	45	0	40	3.5

Table 2. Mechanical analyses of bioretention columns.

Media	d_{10} (mm)	d_{60} (mm)	d_{60}/d_{10}	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Classification	Organic content (%)
Sand	0.27	0.72	2.67	3.04	96.79	0.17	0.00	sand	0.86
Local Soil	0.003	0.32	106.67	5.00	48.50	37.50	9.00	loamy sand	6.41
Gravel	NA	NA	NA	100	0	0	0	gravel	0.19
Turf	NA	NA	NA	NA	NA	NA	NA	NA	47.37
Mulch	NA	NA	NA	NA	NA	NA	NA	NA	67.23

NA= Not Applicable

Indian mustard (brassica juncea), black mustard (brassica nigra), grass (lolium spp.), hottentot fig (carpobrotus edilus), and heartleaf ice plant (aptenia cordifolia) are planted in bioretention columns.

A standard bioretention column consists of gravel, soil mixture of sand and local soil, mulch and plants

Figure 5. Photos of mulch, torf, local soil, sand and gravel (left to right) samples used in bioretention columns.

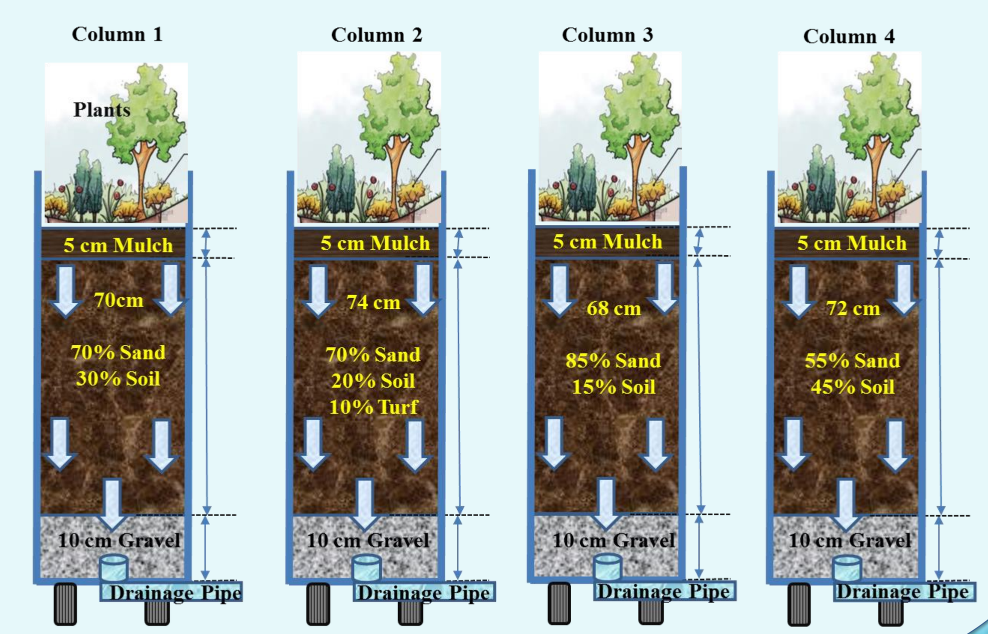

Figure 4. Schematic of bioretention columns.

Mechanical Analyses

Particle size analyses of sand and local soil used inbioretention columns are conducted by using sieves and hydrometer

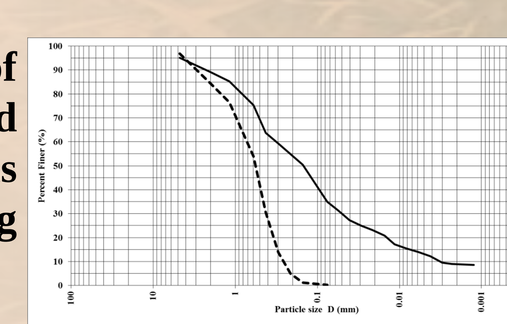

Figure 6. Particle size distribution curves for sand and local soil in Istanbul, Turkey.

Permeablity Test

permeability test is conducted for each column by using Darcy'slaw.

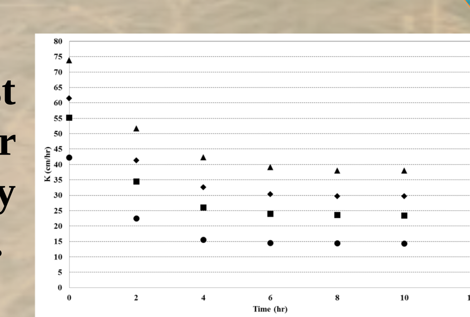

Figure 7. Hydraulic conductivity (K) versus time graph.

RESULTS

RWB Tests: Water Quantity

In this part of the study, different flows are generated on part of the RWB System under 5 artificial rainfall events with constant rainfall intensity. 8 m^2 drainage area, which corresponds to 2.9% of bioretention area, is used during these experiments. We are interested in the measured arrival time, the magnitude of peak flow rate, ponding depth, and the shape of the hydrograph of the outflow from bioretentions in order to understand the effect of different soil textures in each bioretention column. The inflow and outflow are measured at the entrance and exit of each column for 180 minutes. Figures show the inflow and four outflow hydrographs, which belong to four bioretention columns, measured during the rainfall events I-V.

Formulation of Rainfall-Runoff-Bioretention Flow Relation

In this part of the study, a relation among the rainfall, surface runoff over the watershed and outflow from the bioretention is established by integrating the modified Green-Ampt method into kinematic wave theory. The kinematic wave method neglects the local acceleration, convective acceleration and pressure terms in the momentum equation for dynamic waves.

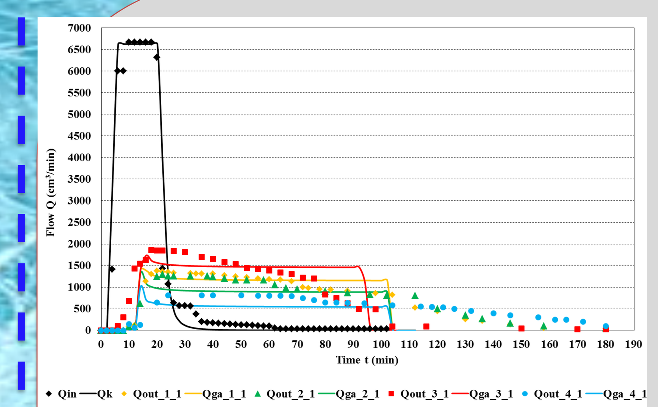

Figure 8. Measured and calculated inflow and outflow hydrographs of four bioretention columns during Rainfall Event I.

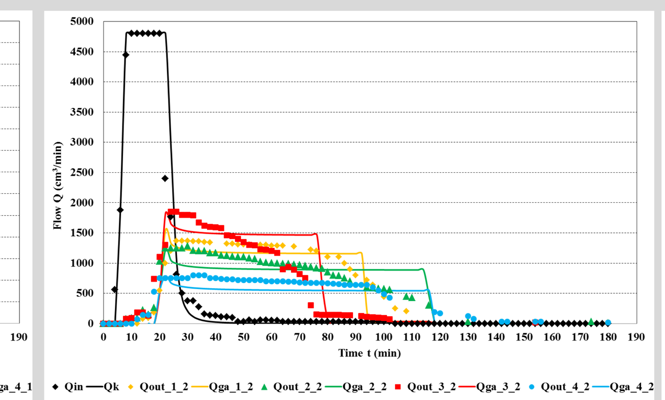

Figure 9. Measured and calculated inflow and outflow hydrographs of four bioretention columns during Rainfall Event II.

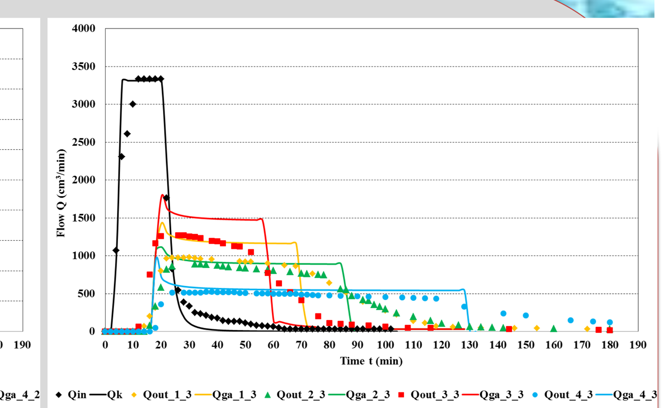

Figure 10. Measured and calculated inflow and outflow hydrographs of four bioretention columns during Rainfall Event III.

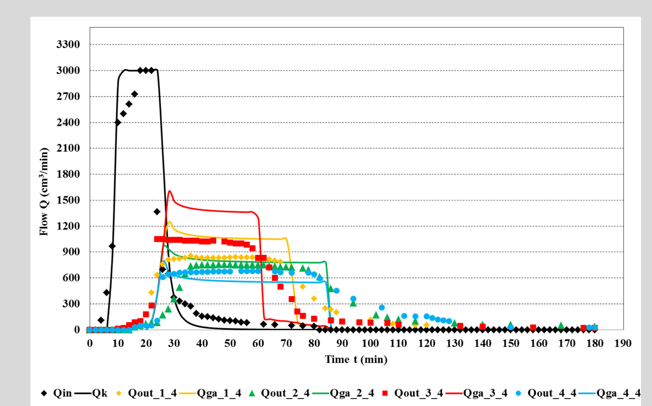

Figure 11. Measured and calculated inflow and outflow hydrographs of four bioretention columns during Rainfall Event IV.

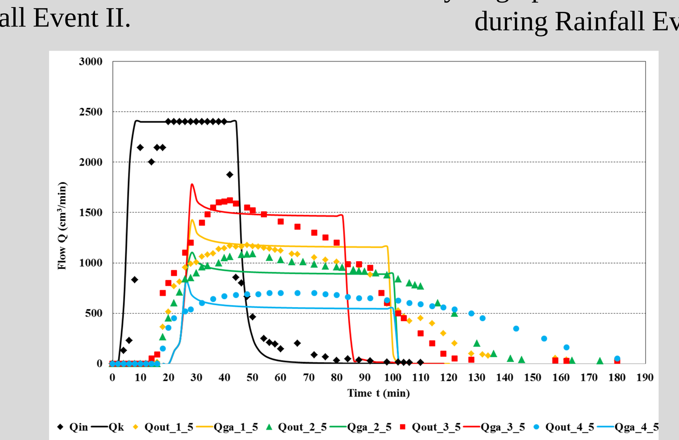

Figure 12. Measured and calculated inflow and outflow hydrographs of four bioretention columns during Rainfall Event V.

CONCLUSIONS

Following conclusions are reached based on the analyses carried out in this study:

i.) Inflow and outflow hydrographs obtained during the experiments with RWB System show that the local conditions have considerable effects on hydrological performance of bioretention due to different infiltration capacities of various combinations of local soil, sand, and turf. Turf decreases the peak outflow of bioretention. Contrary to this situation, it is observed that high sand ratio in bioretention results in a decrease in lag time and an increase in the peak outflow.

ii.) The highest ponding is observed in the fourth bioretention column which prevents the functionality of the bioretention. Therefore, a local soil ratio above 45% is not recommended.

iii.) Rainfall intensity and duration affect peak flow reduction and arrival time and shape of the hydrograph. Low arrival time, high ponding and high peak outflow are observed under high intensity rainfall. During long rainfall events, ponding and peak outflow increase and the shape of the hydrograph spreads out.

iv.) A mathematical representation of the relation among the rainfall, surface runoff over the watershed and outflow from the bioretention is developed by incorporating kinematic wave equation into the modified Green-Ampt Method. The rainfall intensity in modified Green-Ampt method is represented by the inflow per unit surface area of bioretention which may be obtained from kinematic wave solution using the measured rainfall data. Variable rainfall cases may be taken into account by using the modified Green-Ampt method. Thus, employing the modified Green-Ampt method helps significantly in understanding and explaining the hydrological mechanism of a bioretention cell where the Darcy law or the classical Green-Ampt method is inadequate which works under constant rainfall intensities. Consequently, the rainfall is directly related with the outflow through the bioretention.