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INVESTIGATING THE EFFECTS OF LOW IMPACT DEVELOPMENT (LID) ON SURFACE RUNOFF AND TSS IN A CALIBRATED HYDRODYNAMIC MODEL

Sezar Gülbaz and Cevza Melek Kazezyilmaz-Alhan*

Department of Civil Engineering, Istanbul University, 34320 Avcılar-Istanbul,Turkey

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Abstract: The land development and increase in urbanization in a watershed affect water quantity and water quality. On one hand, urbanization provokes the adjustment of geomorphic structure of the streams, ultimately raises peak flow rate which causes flood; on the other hand, it diminishes water quality which results in an increase in Total Suspended Solid (TSS). Consequently, sediment accumulation in downstream of urban areas is observed which is not preferred for longer life of dams. In order to overcome the sediment accumulation problem in dams, the amount of TSS in streams and in watersheds should be taken under control. Low Impact Development (LID) is a Best Management Practice (BMP) which may be used for this purpose. It is a land planning and engineering design method which is applied in managing storm water runoff in order to reduce flooding as well as simultaneously improve water quality. LID includes techniques to predict suspended solid loads in surface runoff generated over impervious urban surfaces. In this study, the impact of LID-BMPs on surface runoff and TSS is investigated by employing a calibrated hydrodynamic model for Sazlidere Watershed which is located in Istanbul, Turkey. For this purpose, a calibrated hydrodynamic model was developed by using Environmental Protection Agency Storm Water Management Model (EPA SWMM). For model calibration and validation, we set up a rain gauge and a flow meter into the field and obtain rainfall and flow rate data. And then, we select several LID types such as retention basins, vegetative swales and permeable pavement and we obtain their influence on peak flow rate and pollutant buildup and washoff for TSS. Consequently, we observe the possible effects of LID on surface runoff and TSS in Sazlidere Watershed.

Keywords: Low Impact Development, TSS, hydrodynamic model, SWMM, Sazlıdere.

* Correspondence to: Sezar Gülbaz. E-mail: sezarg@istanbul.edu.tr

INTRODUCTION

Peak flow rates and huge amount of TSS yield problems such as flooding and poor water quality. These problems are observed more frequently due to the extensive urbanization within watersheds. We need to find solutions in order to cope with these problems. At this point, implementing Low Impact Development (LID) type of storm water Best Management Practices (BMPs) is recognized as a useful solution. LID is an approach of land re-development in order to manage storm water as close to its own nature source as possible. 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, rain gardens, vegetated rooftops, rain barrels, and permeable pavements (US EPA, 2000). LID has several benefits such as protecting animal habitats, improving management of runoff and flooding, and reducing impervious surfaces. Furthermore, LID increases surface water quality like reducing TSS. In the literature, there are many studies and examples related to LID BMP implementation (Fassman, 2012; Alfredo *et al.*, 2010; Elliott *et al.*, 2010; Lucas, 2010; Gilroy and McCuen, 2009; Bedan and Clausen, 2009). Zhang *et al.* (2009) present a study on the use of BMPs for controlling nonpoint pollution in the Xikeng Reservoir watershed located in Shenzhen, China. LID BMPs are used in this study and they obtained good results in reducing TSS. Haifeng *et al.* (2012) make an analysis of implementing LID type of BMPs for urban runoff control and obtained the benefits of optimized LID BMP implementation in reducing runoff volume and peak flow rates.

In order to analyze water quality and quantity, Environmental Protection Agency Storm Water Management Model (EPA SWMM) is selected. In the literature, there are many studies related to water quantity and quality modeling by using EPA SWMM (Gülbaz and Kazezyılmaz-Alhan, 2008). Chang *et al.* (2008) formed a model by using EPA SWMM for two industrial parks in Taiwan in order to correlate the relationship between pollutant mass and the runoff volume. Aad *et al.* (2010) developed new modeling techniques for two BMPs, which are rain gardens and rain barrels, implemented in EPA SWMM. Surface runoff and several water quality parameters measured on a watershed in Santander (Spain) were modeled by Temprano *et al*. (2006).

In this study, Sazlidere Watershed located on the European Continental side of Istanbul in Turkey is selected as the study site. Protecting and improving Sazlidere Watershed have great importance as it supplies a major portion of drinking water of Istanbul. There are some studies related to water quality and quantity of Sazlidere Watershed (Taner *et al*., 2011; Birpinar *et al*., 2006; Akça, 2005). Sazlidere area is composed of high and low density residential and commercial areas, forest and dam area. And also, LID BMPs application can be used in Sazlidere Watershed. The aim of this study is to investigate the effects of implementation of LID type of BMPs on amount of surface water and TSS control by using a calibrated hydrodynamic model for Sazlidere Watershed. For this purpose, EPA SWMM is employed to model Sazlidere Watershed by using data related to watershed characteristics. The hydrodynamic model is calibrated by using rainfall and flow rate measured on the field site. Then, by using the hydrodynamic model, we simulate the surface runoff and TSS generated over the watershed under measured storm events. Finally, we select some LID types of BMPs such as retention basins, vegetative swales and permeable pavement and we obtain their influence on runoff volume and peak flow rates and pollutant buildup and washoff for TSS. Consequently, we observe the possible effects of LID BMPs on surface runoff and TSS in Sazlidere Watershed.

MATERIALS AND METHODS

Governing Equations

EPA SWMM is a dynamic simulation model for the surface runoff which develops on a watershed during a rainfall event (Rossman, 2010; Huber and Dickinson, 1988). EPA SWMM calculates the quantity and the quality of surface runoff on each subcatchment; the flow rate, depth, and concentration in each conduit and junction. The change of rainfall intensity through time (hyetograph) is given as input to the program; change of flow rate (hydrograph) and change of concentration (pollutograph) through time are obtained as output from the program.

Surface Runoff Functions

In order to calculate flow rate, EPA SWMM solves the continuity and momentum equations for flood routing. The most general form of the flood routing equations is the dynamic wave equations which describe unsteady non-uniform flow. Kinematic and diffusion wave equations are obtained from dynamic wave equation by neglecting some forces acting in momentum equation. The diffusion wave equation obtained from the dynamic wave equation for flow routing is used in our study and is given as follows (Ponce 1989):

$$\left.\begin{array}{l} \dfrac{\partial A}{\partial t}+\dfrac{\partial Q}{\partial x}=0 \\ S_f = S_0 - \dfrac{\partial y}{\partial x} \end{array}\right\} \Rightarrow \frac{\partial Q}{\partial t}+c\frac{\partial Q}{\partial x}=K\frac{\partial^2 Q}{\partial x^2} \quad \} \quad \Rightarrow \quad c=mV \quad K=\frac{Q}{2BS_0} \tag{1}$$

where Q is the flow rate (L3/T), A is the cross-sectional area (L2), y is the water depth (L), Sf is the friction slope (L/L), S0 is the bed slope (L/L), t is the time (T), x is the distance (L), c is the diffusion wave celerity (L/T), V is the velocity (L/T), K is the hydraulic diffusivity (L2/T), B is the width (L) and m is given according to the flow rate-friction slope relationship. Green-Ampt Method is used to calculate infiltration in our study and the equation for Green-Ampt Method is given as follows (Huber and Dickinson, 1988):

$$\begin{aligned} &\text{for } \underline{F < F_s} : f = i \\ &\quad \text{if } i > K_s \Rightarrow F_s = \frac{S_u M}{i/K_s - 1} \\ &\quad \text{if } i < K_s \Rightarrow F_s \text{ is not calculated} \end{aligned} \tag{2}$$

$$\text{for } \underline{F \geq F_s} : f = f_p \text{ and } f_p = K_s\left(1 + \frac{S_u M}{F}\right) \tag{3}$$

where F is the cumulative infiltration (L), F_s is the cumulative infiltration of saturated soil (L), i is the rainfall intensity (L/T), Ks is the hydraulic conductivity for saturated soil (L/T), S_u is the suction head (L), M is the initial moisture deficit (L/L), f is the infiltration rate (L/T), and f_p is the infiltration capacity (L/T).

Pollutant Buildup and Washoff Functions

Pollutant accumulation in EPA SWMM is calculated as proportional to time raised to some power, until a maximum limit is achieved by using Power Function. For Exponential Function, pollutant buildup follows an exponential growth curve. And finally, for Saturation Function, pollutant buildup begins at a linear rate. Furthermore, the amount of pollutant accumulation is a function of number of preceding dry days. In this study, power function is used for pollutant buildup and is given as follows (Rossman, 2010):

$$B = Min\left(C_{1p}, C_{2p}\, t^{C_{3p}}\right) \tag{4}$$

where B is the pollutant buildup (M/L^2), C_{1p} is the possible maximum buildup (M/L^2), C_{2p} is the buildup rate constant (M/TL^2), C_{3p} is the time exponent for the buildup parameter (dimensionless) and t is the time (T).

Pollutant washoff in EPA SWMM is calculated as proportional to the product of runoff raised to some power and to the amount of buildup remaining by using Exponential Function. For Rating Curve Function, pollutant washoff is calculated as proportional to the runoff rate raised to some power. And finally, Event Mean Concentration is a special case of Rating Curve Washoff where the Rating Curve exponent is 1. Rating Curve washoff function is used in our study and is given as follows (Rossman, 2010):

Fig. 1 Location and boundary of Sazlidere Watershed (Retrieved from Istanbul Metropolitan Municipality (IBB)).

$$W_{rc} = C_{3rc}\, Q^{C_{4rc}} \tag{5}$$

where Wrc is the amount of washoff pollutant (M/T), $C3rc$ is the washoff coefficient (M/L^3), $C4rc$ is the washoff exponent (dimensionless) and Q is the runoff rate (L^3/T).

Study Area

Sazlidere Watershed located on European Continental side of Istanbul, Turkey has 165 km^2 of drainage area and the surface runoff generated over Sazlidere Watershed flows to Sazlidere Dam Lake (**Figure 1**). In this study, part of the Sazlidere Watershed, of whose area is approximately 40 km^2, is selected and modeled. The water capacity of the lake is 91 600 000 m^3/year according to the measurements of Istanbul Municipality Waterworks (ISKI). The altitude of the watershed from the sea level in reservation areas is between 6-20 m and it reaches 170 m in the north and south topographic boundaries (Birpinar *et al.*, 2006; Akça, 2005).

Model Development

In order to determine the input parameters for hydrodynamic and water quality model in EPA SWMM, topographical map of the modeled area, cross-sectional area of the main stream called Türkköse Stream and soil properties of the study area are used. In addition to these parameters, flow rate and rainfall data are measured on the field site by setting up a rain gauge in the middle of the watershed and a flow meter near downstream of Türkköse Stream. The rainfall data is continuously collected by automatic data logger during November 2009-May 2010 and flow rate is measured during 5 rainfall events. The measured data is used for calibration and verification of the hydrodynamic model.

The parameters, i.e., Manning's roughness coefficient (N) for pervious and impervious area, depth of depression storage (d) on pervious and impervious area, Manning's roughness coefficient (n) for conduits, hydraulic conductivity (K), and parameters that define the soil type are obtained via calibration. In order to establish the water quality model in EPA SWMM, Power Build-up and Rating Curve Washoff functions are defined for buildup and washoff, respectively. Then, TSS is selected as the water quality parameter in order to investigate sediment transport in the Türkköse Stream which is the main channel in the modeled area.

As the final step, we apply LID BMPs to the calibrated model. We define three types of LID which are retention basin (bio-retention cell), vegetative swale and permeable pavement (porous pavement). In order to implement these three types of LID to the model, we define parameters such as vegetation volume, void ratio, porosity, field capacity etc. These parameters depend on the surface, pavement, soil, and storage layers. The values for these parameters are selected by using EPA SWMM manual and are given in **Table 1**. Then, about 5% of the modeled area is selected to perform the LID BMPs. The surface layer properties are used to describe the surface properties of bio-retention cells, porous pavement, infiltration trenches, and vegetative swales; the pavement layer properties are used to define values for porous pavement LID; the soil layer properties are used to describe the properties of the engineered soil mixture used in bio-retention types of LIDs; the storage layer properties are used to define the properties of the crushed stone or gravel layer used in bio-retention cells, porous pavement systems, and infiltration trenches as a bottom storage/drainage layer.

RESULTS AND DISCUSSION

The simulation results are presented for the storm event observed during March 06−09, 2010. The change in surface runoff generated over the watershed and change in TSS concentrations with LID BMP implementation and with no LID BMP implementation are observed and compared. Effects of LID BMP implementation on runoff volume and peak flow rate and pollutant buildup and washoff for TSS are predicted.

Figure 2 shows the predicted flow rate versus time at the outfall of the Sazlidere Watershed with LID BMP implementation and with no LID BMP implementation. As it can be seen from this figure, for the case with LID BMPs, peak of the hydrograph decreases from approximately 7.5 m³/s to 6.5 m³/s. Furthermore, the total amount of surface water generated over the watershed decreases 17.5%.

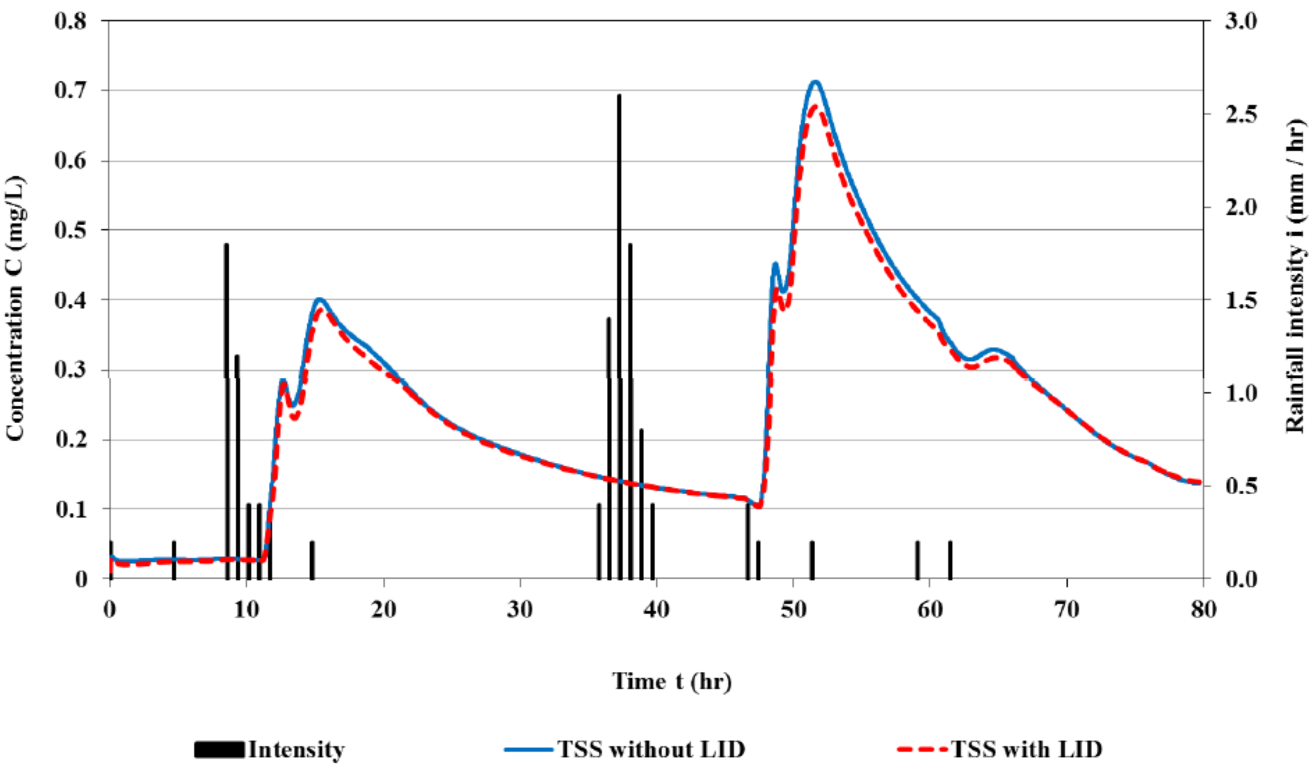

Fig. 2 Predicted flow rate versus time at the outfall of the Sazlidere Watershed with LID BMPs and with no LID BMPs during storm event observed between March 06-09, 2010.

Table 1. Properties of surface, pavement, soil and storage layers for LID implementation (Rossman, 2010)

Surface Layer	Value	Pavement Layer	Value	Soil Layer	Value	Storage Layer	Value
Storage Depth (mm)	500	Thickness (mm)	120	Thickness (mm)	100	Height (mm)	600
Vegetation Volume (Fraction)	0.2	Void Ratio (voids/solids)	0.17	Porosity (volume fraction)	0.5	Void Ratio (voids/solids)	0.75
Surface Roughness (Manning'sN)	0.24	Impervious Surface Fraction(fraction) (0 for continuous porous pavement systems)	0	Field Capacity (volume fraction)	0.2	Infiltration Rate (mm/hr)	10
Surface Slope (Percent)	1	Permeability (mm/hr)	100	Wilting Point (volume fraction)	0.1	Clogging Factor	0
Swale Side Slope (Run/Rise)	5	Clogging Factor (Use a value of 0 to ignore clogging)	0	Conductivity (mm/hr)	0.8		
				Conductivity Slope	10		
				Suction Head (mm)	240		

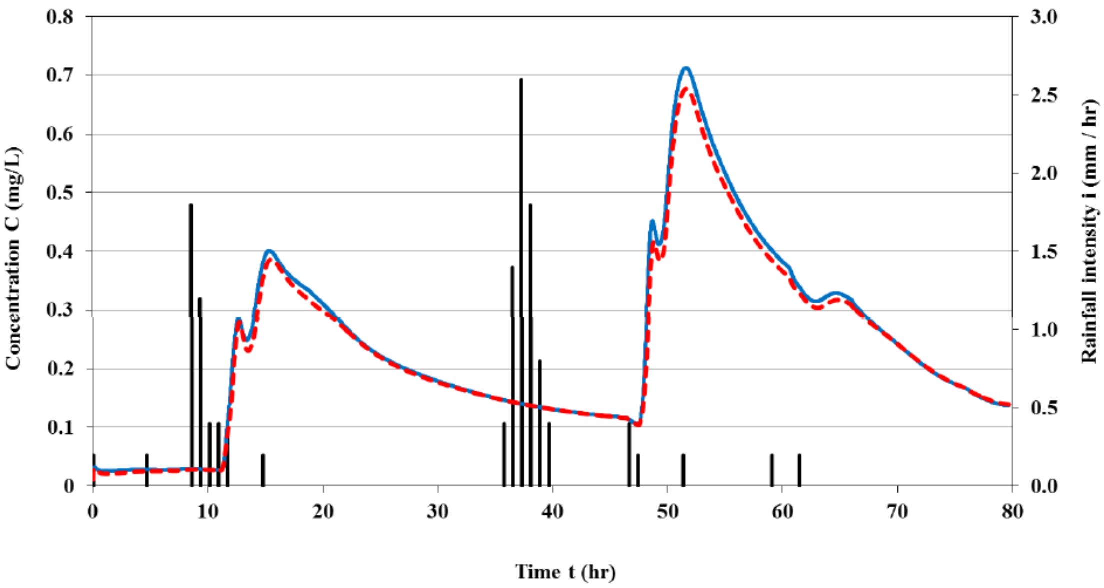

Fig. 3 Predicted TSS concentration versus time at the outfall of the Sazlidere Watershed with LID BMPs and with no LID BMPs during storm event observed between March 06-09, 2010.

Table 2. Volume of water and amount of pollutant loading calculated in EPA SWMM model

	Before LID BMP Implementation	After LID BMP Implementation
Volume of water collected (m^3)	252 766	218 808
Amount of TSS buildup (kg)	120.04	99.24

CONCLUSION

A calibrated hydrodynamic model and a water quality model is established for Sazlidere Watershed in EPA SWMM. Then, change in flow rate and TSS concentration are predicted with no LID BMP implementation. In addition, the total amount of water and TSS buildup collected on the watershed are also calculated. After implementing LID type of storm water BMPs, such as retention basins, vegetative swales and permeable pavement, we re-run the model and compare the difference between flow rate and TSS concentration with LID BMPs and with no LID BMPs. Moreover, we obtain total amount of water and TSS buildup collected on the watershed after LID BMP implementation and compare the results. We found that LID BMP implementation in the Sazlidere Watershed results in a decrease in the peak of the hydrograph and pollutograph (TSS) and total amount of surface water and TSS over the catchment.

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