Evaluation of Stormwater BMPs Performances for Flood Volume Reduction in Bengaluru City, Karnataka, India

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Abstract

Urbanization causes hydrological change and increases stormwater runoff volume, leading to flooding, erosion, siltation and the degradation of natural drainage system. Best management practices (BMPs) as an alternative approach to better natural flow regime by using decentralized designs to control stormwater runoff at the source, rather than at a centralized location in the watershed. BMP such as permeable pavement can be retrofitted in residential street, infiltration trench can be retrofitted in roadside stormwater drain, rain barrel storage can be retrofitted in building roofs and bioretention cell can be retrofitted in park. The present paper describes a modelling approach to incorporate four types of BMPs in the study site and estimates the impacts of BMPs on flood volume and peak flow reduction. Results depict that use of these four BMPs leads to significant stormwater control for reducing the risk of flooding in the study site.

Keywords - *Best Management Practices (BMPs), Urban Stormwater Management, Sustainable Solution*

I. INTRODUCTION

Land use change in the form of urbanization, has profound impacts on the runoff characteristics and consequently on the aquatic environments of the urban streams [1], [2]. Storm water management is a common concern in urbanizing watersheds where development-related increases in impervious areas result in increases of flood flows. Floods occur in urbanized watersheds with greater magnitude and frequency, presenting greater challenges for mitigating flood damage and water quality impacts. The concept of Best Management Practices (BMPs) encompasses a wide variety of appropriate technologies and activities intended to minimize the effect of watershed development on flow regimes without altering existing impervious coverage. Examples of BMPs that achieve storm flow reduction and peak reduction include infiltration trenches, porous pavement, grass swales, green roof, rainwater barrel storage and bioretention cells etc.

The primary method to control urban stormwater discharges onsite is to use of best management practices (BMPs). The US Environmental Protection Agency (USEPA) defines BMPs as an engineered and constructed system that is designed to provide water quantity and quality control of storm water [3]. The purpose of BMPs is to restore the site's pre-development hydrologic condition [4]. The analysis of BMP performance usually focuses on water quality aspects such as pollutant loads and concentrations. Recently, volume based reduction has been the focus of site hydrology management and stormwater pollutant load control [5].

The application of BMPs can provide a solution for on-site management of post-construction stormwater runoff. Storm water BMP is one of the simplified approaches in mitigating urban flooding [6]. Stormwater best management practices utilizing detention and infiltration are widely used to reduce the negative impacts of urban stormwater runoff associated with increased impervious surfaces and have become essential tools of urban stormwater management [7], [8]. Infiltration best management practice guidance for storm water management in USA is being practiced to limit urban flood runoff [9].

Simulation based on realistic model provides an approach to predicting the hydrological performances of future BMP practices. In stormwater management practice, models are often used to simulate runoff generated from the watersheds and to evaluate the effectiveness of certain BMP structures [10]-[12]. The most widely used models include the Hydrological Modelling System (HEC-HMS), EPA System for Urban Stormwater Treatment and Analysis INtegration (SUSTAIN), EPA Stormwater Management Model (SWMM), Model for Urban Stormwater Improvement Conceptualization (MUSIC), and Soil and Water Assessment Tool (SWAT). Of all the hydrological models, SWMM is considered one of the most promising models for representing the profoundly different hydrological characteristics of BMPs in undeveloped and developed urban lands [13], [14]. Therefore, PCSWMM was used in the present study to simulate hydrological performances of BMP practice.

The present study seeks to explore how effectively, the designed BMPs can reduce onsite runoff discharging from study site. The objectives of the study are to 1) Present hydrological simulation approaches for typical BMPs in a highly urbanized area 2) Evaluate peak flow attenuation and volume reduction performance of BMPs using PCSWMM

II. METHODOLOGY

A. Study Site

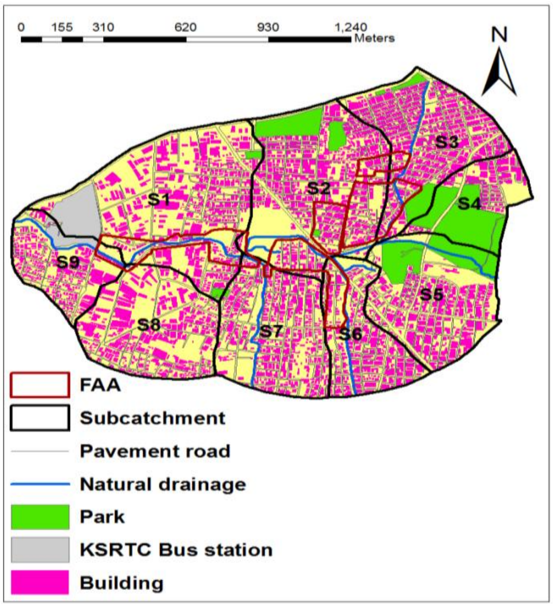

Fig 1: Land use map of the study area

The study site is a flood affected area (FAA), located in Bengaluru city, India shown in Fig.1. The site includes five FAAs. The study area has a total area of 200ha and moderately sloped at nearly 5%. Soils are characterized as HSG-A (Hydrologic Soil Group) with a high infiltration rate. The study site is a highly urbanized area with imperviousness percentage of 73.94%. The local flood events are reported in the study area [15], [16]. There is an alternative solution to retain existing developed impervious surface system and to manage stormwater runoff [17]. To reduce the impact of water logging, a sustainable BMPs approach have been proposed and modelled in the study area.

B. Hydrologic Model

PCSWMM, a GIS version of the EPA Storm Water Management Model (EPA SWMM) was chosen to develop hydrological model of the study area and to evaluate the effects of BMP on flood reduction in the study [17]-[19]. PCSWMM consists of a dynamic rainfall-runoff model and a hydraulic model for piped systems. It is used for simulation of runoff quantity from primarily urban areas. In the model, BMP controls are represented by a combination of vertical layers whose properties (such as thickness, void volume, infiltration rate etc.) are defined on a per-unit-area basis. These BMP controls can then be placed within selected subcatchment at any desired sizes (or areal coverage). The PCSWMM model has been widely used to evaluate the effects of stormwater management based on conventional drainage systems [20] or BMP designs [13].

Table 1: SWMM parameter values of study area

Parameter	Typical
Area	200 ha
Imperviousness	74%
Slope	5.0 %
Manning's roughness coefficient on impervious area [28]	0.013
Manning's roughness coefficient on pervious area [28]	0.1
Depression storage on impervious area [29]	0.56 mm
Depression storage on pervious area [29]	2.54 mm
Weighted average Curve Number for hydrologic soil group-A [30]	86

The study area total of 200ha was simplified to 9 subareas (size vary from 12ha to 39ha) based on hydrologic characteristics, before development of BMP, for simulation (Fig.1). A nonlinear reservoir approach was used to simulate the rainfall-runoff process, which includes infiltration, depression storage, evaporation and surface runoff. Since the infiltration features of BMPs were the objectives, the Curve Number method was applied to simulate the infiltration in the model [21]. The BMP performance can be evaluated under an individual storm event. September 9th 2017 rainfall event of 15min. interval data is obtained from Karnataka State Natural Disaster Management Centre (KSNDMC) Bengaluru and was selected to model the scenarios for BMP performance. It was assumed that the evaporation was taken as negligible. Hence, the runoff from catchment was either infiltrated, stored on the surface, or flowed overland. Model parameters and their values are listed in Table 1.

Effective storage depth of bioretention cell
= {storage depth of surface layer}
+ {Thickness of soil layer x (porosity–field capacity)}
+ {Height of storage layer x void ratio} ---------- (1)

Effective storage depth of permeable pavement
= {Thickness of pavement layer x void ratio}
+ {Height of storage layer x void ratio} -------- (2)

Effective storage depth of infiltration trench
= {Height of storage layer x void ratio} ------ (3)

Effective storage depth of rainwater harvesting
= Storage barrel height ------------------------ (4)

Table 2: Parameter values of BMP's designs

Layer	Parameter	Permeable pavement	Rain water harvesting	Infiltration trench	Bioretention cell
Surface	Storage depth (mm)	-	-	-	100
	Manning's roughness coefficient	0.014	-	0.014	-
Pavement	Thickness (mm)	150	-	-	-
	Void ratio	0.2	-	-	-
	Permeability (mm/hr)	100	-	-	-
Soil	Thickness (mm)	-	-	-	500
	Porosity	-	-	-	0.4
	Field capacity	-	-	-	0.232
	Wilting point	-	-	-	0.116
	Conductivity	-	-	-	30
	Conductivity slope	-	-	-	10
	Suction head	-	-	-	88.9
Storage	Height (mm)	300	1000	1500	200
	Void ratio	0.4	-	0.5	0.5
	Conductivity (mm/hr)	2	-	2	2
	Effective storage depth (mm)	150	1000	750	284

Table 3: Surface areal coverage percentage of BMPs in study site

Subarea No.	BMPs total area (%)			
	Rain barrel storage	Permeable pavement	Infiltration trench	Bioretention cell
S1	0.58	11.08	0.20	0.24
S2	0.64	15.52	0.28	1.86
S3	0.81	20.08	0.37	1.42
S4	0.32	*	0.18	10.59
S5	0.56	*	0.32	4.02
S6	0.70	20.96	0.39	**
S7	0.64	18.96	0.35	**
S8	0.69	11.34	0.21	**
S9	0.62	11.21	0.21	**
The entire site	0.63	12.48	0.28	1.62

* Subcatchment has slope more than 5% and in that case permeable pavement cannot be applied
** Subcatchment does not have suitable locations to incorporate bioretention cell

Scenarios that are pre-BMP and post-BMP developed condition were modelled to test the application of BMP for managing stormwater in the study area. The pre-BMP scenarios represent conditions when no BMP was installed in the area. The pre-BMP scenarios represent conditions when no BMP was installed in the area. The post-BMP scenarios represent conditions when the BMP such as permeable pavement, infiltration trench, rain barrel storage and bioretention cell were installed as part of the study area. Each BMP consists of surface layer and storage layer with overflow components. The BMPs are implemented in study area depending upon the suitable site availability. Thus the surface runoff from impervious surface can flow into and be stored in the BMPs on-site or excess runoff flows out via overflow components. In the model, BMPs are depicted as several vertical layers and its properties (Table 2) are defined on a per unit area basis. The effective storage depth of each BMP was calculated according to equations from (1) to (4). The parameter values of BMPs were designed according to the recommendations by Rossman method [19]. These BMPs can then be placed within selected subcatchment at any desired sizes on aerial coverage basis (Table 3).

III. RESULTS AND DISCUSSIONS

For the analysis of runoff control performance of the BMPs options, BMP scenarios were designed and then simulated using PCSWMM to evaluate the expected runoff volume and peak flow control effectiveness. The simulation outcome predicted by SWMM model for pre BMP development scenario is 166.6ML of runoff with peak discharge of 35.76m^3/sec. Again SWMM model was rerun with the individual BMP and combined BMPs scenario in place with the simulation outcome is shown in figure 2. It is clear from the figure 2 that, a considerable damping down of peak flow and runoff volume in response to the pre BMP development is predicted with the post BMP development. The patterns of peak flow and runoff hydrograph for rain barrel storage and infiltration trench are very similar in response to the pre BMP development hydrograph. The permeable pavement, bioretention cell and combined BMP scenario exhibits a much greater variability than rain barrel storage and infiltration trench scenario particularly during the earlier part of the storm event. This reflects the infiltrative mechanism associated with the porous surfacing and underlying storage of sub base. By comparison the porous pavement and Combined BMP scenario is able to store and infiltrating larger proportion of the incident rainfall. Each BMP scenario becomes more stable to rainfall fluctuations after the peak rainfall intensity, probably as a result of saturation of the BMP storage capacity.

For the study, the target for evaluating BMP performance is runoff quantity which includes total stormwater runoff volume and the peak flow rate. The percentage of runoff volume reduction and peak flow reduction for all post BMP development scenarios (four individual BMP scenarios and one combined scenario) are shown separately in the figure 3 which illustrates the performance effectiveness of runoff control facilities. Performance of the simulated post BMP development scenarios indicates that substantial reductions in total runoff volumes and peak flow can be achieved.

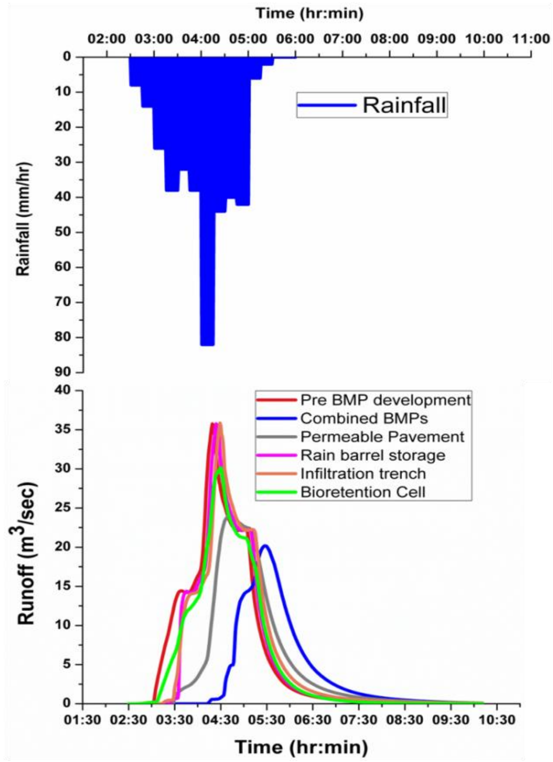

Fig 2: Runoff hydrograph generation at pre BMP and Post BMP development scenarios

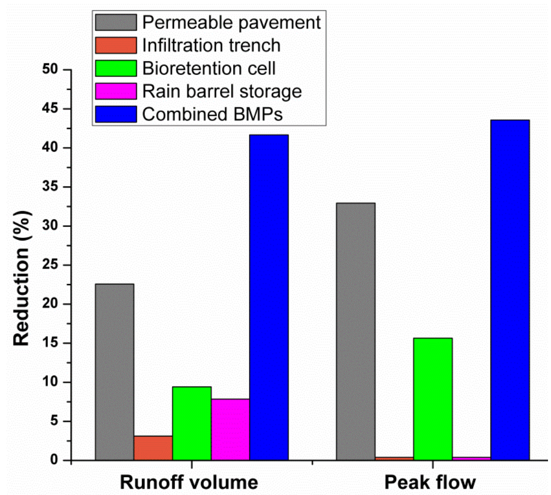

Fig 3: Performance effectiveness of post BMP development scenario

It can be seen from figure 3 that under permeable pavement scenario, infiltration trench scenario, bioretention cell scenario and rain barrel storage scenario runoff volume reduced by 23%, 3%, 9% and 8% respectively compared to those under combined BMP scenario. By comparison within the individual BMP scenarios, for total runoff, under pavement scenario 20%, 12% and 11% more volume reduction would be achieved compared to that under infiltration trench scenario, bioretention cell scenario and rain barrel storage scenario respectively. The result shows that under permeable pavement scenario, infiltration trench scenario, bioretention cell scenario and rain barrel storage scenario peak flow reduced by 33%, 0.4%, 16% and 0.4% respectively compared to those under combined BMP scenario. For peak flow, under permeable pavement scenario 17% more peak flow reduction would be achieved compared to that under bioretention cell scenario. infiltration trench and rain barrel storage scenario has a quite considerable runoff volume control i.e. 3% and 8% respectively but both of these BMPs has no peak flow control, this is because of comparatively very less BMP area of less than 1%. As a result of this, only limited stormwater can be stored and infiltrated by the storage layer of the BMP system.

The result indicates that combined BMP scenario could effectively reduce the runoff volume as well as peak flow. Under the combined BMPs scenario the runoff volume of 42% reduction and peak flow of 44% reduction is much larger when compared to the Individual BMP scenarios. The result shows that individual BMP scenario performances on controlling runoff volume and peak flow are frequently inadequate in themselves as the sole solution to runoff impairment in urban catchment, especially for extreme event conditions. The use of retrofitted permeable pavement together with limited rain barrel storage, infiltration trench and bioretention cell called combine BMP scenario have been successful in reducing total runoff volume and peak flow in the catchment modelling. The result clearly shows that by properly designing and implementing the BMPs for the study area, significant higher runoff volume and peak flow reductions could be realized.

The BMP performance in terms of runoff volume reduction is compared with the different literature from the international stormwater BMP database (www.bmpdatabase.org). The BMP database results are based on the experimentally monitored results. For validating the results, an exact impervious drainage area runoff into the particular BMP are utilized. The model result 78% after implementing permeable pavement is similar to the results of international stormwater BMP database literatures [22], [23]. The model results 62% after implementing infiltration trench are consistent with the results of international stormwater BMP database literatures [24] [25]. The model result 69% after implementing bioretention is comparable with the results of international stormwater BMP database literatures [26], [27]. The rain barrel storage results are not validated due to the lack of data in the international stormwater BMP database.

IV. CONCLUSIONS

The present study analyses the impacts of BMP designs on urban flooding in an urbanizing catchment in Bengaluru, where the BMP structural designs can be considered in combine with the conventional drainage system for stormwater management. The performances of BMP's design are substantially affected by their properties and structure e.g., the percentage of area installed with BMP structures; the percentage of the drainage area of BMP structures and the effective storage capacity of BMP structures. The study concludes that the BMP efficiency is very effective for the combined BMP for catchment scale instead individual BMP implementation. to retain 100% runoff of catchment, storage volume of BMP can be increased. The permeable pavement scenario results are found to be reasonably well for a single storm event.

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REFERENCES

[1] A. K. Misra, "Impact of urbanization on the hydrology of Ganga Basin (India)", Water Resources Management, Vol.25 No.2, pp.705-719, 2011. DOI:10.1007/s11269-010-9722-9.

[2] R. C. Nagy, B. G. Lockaby, L. Kalin and C. Anderson, Effects of Urbanization on Stream Hydrology And Water Quality: The Florida Gulf Coast, Hydrological Processes, vol.26 No.13, pp. 2019-2030, 2012. DOI:10.1002/hyp.8336

[3] USEPA (United States Environmental Protection Agency), Preliminary Data Summary of Urban Storm Water Best Management Practices, Office of Water (4303). Washignton: EPA-821-R-99-012, 1999.

[4] USEPA (United States Environmental Protection Agency), Low Impact Development (LID): A Literature Review, Washington, DC: USEPA, 2000 http://water.epa.gov/polwaste/green/upload/lid.pdf

[5] A. Poresky, C. Bracken, E. Strecker, and J. Clary, International Stormwater Best Management Practices (BMP) Database Technical Summary: Volume Reduction, GeoSyntec Consultants & Wright Water Engineers, Inc., 2011

[6] Gabriele Freni & Elisa oliveri, "Mitigation of Urban Flooding: A Simplified Approach for Distributed Stromwater Management Practices Selection as Planning, Urban water journal," vol.4, pp. 215-226, 2005.

[7] C. H. Emerson and R. G. Traver, Multiyear And Seasonal Variation of Infiltration From Storm-Water Best Management Practices, Journal of Irrigation and Drainage Engineering, vol.134 No.5, pp.598-605., 2008. DOI:10.1061/(ASCE)0733-9437(2008)

[8] E. S. Williams and W. R. Wise, Hydrologic Impacts of Alternative Approaches to Storm Water Management And Land Development, Journal of the American Water Resources Association, vol.42 No.2, pp.443-455, 2006. DOI:10.1111/j.1752-1688.2006.tb03849.x

[9] Rose Mary Seymour, Tim Carter, Seth Wenger, Deborah Stewart and Michelle Richburg, 2007 "Infiltration best management Practices in the Runoff limits Mannual". ETOWH habitat conservation plan

[10] H.F. Jia, Y.W. Lu, S.L. Yu, Y.R. Chen, "Planning of LID-BMPs for urban runoff control: the case of Beijing Olympic

Village," Purification Technol. Vol.84, pp.112–119, Sep.2012.
[11] H.F. Jia,, H.R. Yao, S.L Yu,. "Advances in LID BMPs research and practice for urban runoff control in China," Front. Environ. Sci. Eng. Vol.7, pp.709–720, 2013.
[12] W. Liu, W. Chen, C. Peng, "Assessing the effectiveness of greeninfrastructures on urban flooding reduction: a community scale study," Ecol. Modell. vol.291, pp.6–14, 2014.
[13] A. H. Elliott and S.A. Trowsdale, "A review of models for low impact urban stormwater drainage," Enviornmental modeling & Software, vol.22 no.3 pp.394-405, 2007
[14] S.H. Lai, A. Ab Ghami, N. A. Zakaria, C. S. Leow, C.K. Chang, M.F. Yosof, "Application of SWMM for urban stormwater management: A case study with Modelling" 2009.
[15] T.V. Ramachandra and Pradeep P. Mujumdar, "Urban Floods: Case Study of Bangalore", Journal of the National Institute of Disaster Management, Vol.3 No.2 pp.1-97, 2009.
[16] BBMP (Bruhat Bengaluru Mahanagara Palike), "Preparations of revised detailed project report for remodeling of primary and secondary storm water drains in four major catchment areas in core Bangalore city," Govt. of Karnataka, Jan 2011.
[17] Azadeh Akhavan Bloorchiana, Laurent Ahiablameb, Abdolreza Osoulic, Jianpeng Zhoud, "Modeling BMP and vegetative cover performance for highway stormwater runoff reduction," International Conference on Sustainable Design, Engineering and Construction, Procedia Engineering vol.145, pp. 274 – 280, 2016.
[18] Yan-wei SUN, Qing-yun LI, Lei LIU, Cun-dong XU and Zhong-pei LIU, "Hydrological simulation approaches for bmps and lid practices in highly urbanized area and development of hydrological performance indicator system" Water Science and Engineering, 7(2): 143-154, 2014, doi:10.3882/j.issn.1674-2370.2014.02.003
[19] L.A. Rossman, 2010. "Storm Water Management Model User's Manual - Version 5.0,". USEPA. EPA/600/R-05/040
[20] C. Zoppou, "Review of urban storm water models," Environ. Modell. Softw. Vol.16, 195-231, 2001.
[21] USEPA (United States Environmental Protection Agency), "Stormwater Management Model User's Mannual," EPA/600/R-05/040, 2010.
[22] B. Brattebo and D. Booth. "Long term stormwater quantity and quality performance of permeable pavement systems," Water Research, 37(18): 4369-4376, 2003.
[23] J. Gilbert, and J. Clausen. "Stormwater runoff quality and quantity from asphalt, paver and crushed stone driveways in Connecticut," Water Research. Vol.40, pp: 826-832, 2006.
[24] Abdolreza Osouli, Azadeh Akhavan Bloorchian, Sina Nassiri and Scott L. Marlow, "Effect of Sediment Accumulation on Best Management Practice (BMP) Stormwater Runoff Volume Reduction Performance for Roadways," Water, Vol.980 No.9 pp:3-13, December 2017. doi: 10.3390/w9120980
[25] BWM (Bureau of Watershed Management), "Pennsylvania stormwater Best Management Practices Manual," Department of Environmental Protection, vol. 34, document number: 363-0300-002, December 2006.
[26] M.E. Dietz, and J.C. Clausen, "A field evaluation of rain garden flow and pollutant treatment," Water Air and Soil Pollution. Vol. 167. No. 2. pp. 201-208, 2005.
[27] J. Ryan Winston, Jay D. Dorsey, William F. Hunt, "Quantifying volume reduction and peak flow mitigation for three bioretention cells in clay soils in northeast Ohio," Science of the Total Environment, vol.553 pp.83-95 DOI: 10.1016/j.scitotenv.2016.02.081, 2016.
[28] E.T. Engman., "Roughness coefficients for routing surface runoff," Journal of Irrigation and Drainage Engineering. Vol. 112 No.1, pp: 39-53, 1986.
[29] Paula Rees and Jerry Schoen. "PCSWMM Evaluation," Water Resources Research Centre. University of Massachusetts. Project#08-08/319, July 2009.
[30] NRCS (Natural Resources Conservation Service), "Urban hydrology for small watershed," United states Department of Agriculture, Technical Release 55, Second Edition, June 1986. 210-VI-TR-55