Thai Environmental Engineering Journal Vol. 37 No. 3 (2023) : 9-18
www.eeat.or.th

Evaluation of Green Roof Performance in Slowing Down Stormwater Runoff in Urban Catchment, The Case of Samut Prakan, Thailand

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Abstract

Urbanization implies a reduction of vegetation leading to an increase of bare lands coverage and the expansion of impervious surfaces. Such circumstances are significantly influence the hydrological cycle, reduce evapotranspiration losses, and accumulate surface runoff, raising the risk of floods, particularly in rapidly developing urban areas. Green roofs are considered as one of the most suitable Green Infrastructure (GI) for densely urbanized areas because they can incorporate into new construction or added to existing buildings during renovation or reroofing without further land consumption. This study aims to evaluate the effectiveness of green roofs in helping to slow down water runoff in response to flood risks in Samut Prakan municipal area. The hydrological model EPASWMM 5.1 was created with rain estimated based on historical data and the green roof installation scenarios. 12 green roof scenarios, consisting of 4 main scenarios, are categorized based on the rainfall events (average extreme rainfall, 10-year return period, 20-year return period, 50-year return period). The simulation results show that green roofs significantly reduce surface runoff and peak flow. Specifically, extensive green roofs in Samut Prakan achieved runoff reduction rates of 14.6% to 54.51%, and peak flow reduction rates of 7.43% to 19.6%. Considering the runoff reduction rate, green roof can provide more hydrological benefit than that of traditional storm management system. While the performance of green roofs in tropical climates may be less effective compared to those in arid and temperate zones, the results of this study are consistent with previous research and provide valuable insights for optimizing green roof design and implementation in tropical country as Thailand.

Keywords : green roof; stormwater; urban flooding; SWMM

Introduction

Severe consequences and threats that cities are now facing as a result of climate change, posing a great risk to human life and entire urban systems. Rising global average temperature is associated with widespread changes in weather patterns. Extreme weather events such as sea level rise, heat wave and large storms are likely to become more frequent or more intense. In conjunction with urbanization, population increase, centralization, and high-density development, floods continue to be a biggest concern. Urbanization implies a reduction of vegetation leading to an increase of bare lands coverage and the expansion of impervious surfaces. Such circumstances are significantly influence the hydrological cycle, reduce evapotranspiration losses, and accumulate surface runoff, raising the risk of floods, particularly in rapidly developing urban areas [1, 2]. To alleviate damage and disruption, most cities must, therefore, manage surface water runoff in urban areas to minimize a population's exposure to flooding hazards. Traditionally, stormwater management approaches towards flood risk management have focused on capturing and conveying runoff within piped systems [3, 4]. However, in most cases such strategies have been constrained by the expense and complexities of expanding subterranean infrastructure, the high cost of infrastructure maintenance and the pressure to adopt sustainable stormwater management practices.

This situation has resulted in increasing interest in the use of alternate interventions, such as green infrastructure (GI), a generic term for drainage interventions by mimicking natural hydrologic processes through different techniques depending on urban context (4).

Although the maintenance of green areas and recovery or restoration of degraded vegetation areas is one of the best options to manage storm water runoff in an environmentally sound, these types of GI are limited by urban space availability. In this way, the adoption of green roofs is postulated as an alternative to deal with this problem [5, 6]. Green roofs (GR) are considered as one of the most suitable GI for densely urbanized areas because they can incorporate into new construction or added to existing buildings during renovation or reroofing without further land consumption. Previous studies have revealed that adoption of GR can be effective at reducing stormwater runoff and flooding in urban area [7-9]. According to its performance, the adoption of green roofs is increasing in popularity and has attracted the attention of many researchers. However, the majority of the research on green roofs has been concentrated in two main climatic groups, the temperate and continental, only a few studies were found to be conducted for tropical climatic zones [10, 11]. While there is an urgent need for the prioritization of urban flood risk management particularly in tropical regions, such as Thailand, there remain many potential barriers for the adoption of GR and other low impact development technologies (LIDs). Some of the most important factors that prevent the widespread adoption of GR in Thailand are the lack of scientific data and design guidelines to support the implementation. Summarizing the studies GR applications for managing urban stormwater in different climatic zones, Akther, M. et. al., (2018) concluded that the means and medians of the stormwater retention rate are between 56.04% - 78.10%. The medians of the stormwater retention rate among the climatic groups, tropical, dry arid and semi-arid, temperate, continental, and polar were statistically significantly different [12]. With a different climatic condition from those on the temperate zone, adaptation of GR in tropical regions requires relevant and reliable research to measure the application of GR in local conditions as well as how to adapt the design to the climatic features [13, 14].

In this regard, this study aims to evaluate the effectiveness of green roofs in helping to slow down water runoff in response to flood risks in Samut Prakan municipal area. The hydrological model EPASWMM 5.1 was created with rain estimated based on historical data and the green roof installation scenarios. The outputs from this research identify reasonable GR strategies that could be implemented within the study area. Indeed, the research explore how green roof intervention can be implemented to manage flooding across a range of rainfall events.

Methodology

Study area

Samut Prakan City Municipality located in a low-lying area of Pak Nam Subdistrict, of Samut Prakan Province. The study area is approximately 7.33 square kilometer with average annual rainfall of 1,100 - 1,500 mm. Located at the mouth of the Chao Phraya river, the municipality surrounds by many streams and canals, and has been recognized as a flood prone area due to its annual flooding and geography. Being the administrative, economic and transportation centers of the Samut Prakan, Pak Nam Subdistrict has experienced rapid urbanization, which has led to considerable increases in both population and building density. The high proportion of impervious surfaces, combing with extreme rainfall and its geographic factors significantly increases the risk of floods in the municipal area.

The land use density in Samut Prakan Municipality is concentrated along the Chao Phraya River and main roads. The increase in buildings is mostly for residential and commercial purposes. As illustrated in Table 1, land uses are classified into four categories: roofs, other impervious surfaces, roads and streams. The analysis of land use data reveals that 86.53% of Samut Prakan municipality is covered with impervious surfaces which are 28.19% roofs and 58.33% other impervious surfaces. For pervious surfaces, the total area was 13.48% divided into green area (5.85%) and streams (7.64%).

Table 1 Land use characteristics of study area

Land use	Area	
	sqkm.	%
Roofs	2.07	28.19
Other impervious surfaces	4.28	58.33
Total impervious surfaces	**6.35**	**86.52**
Green area	0.43	5.85
Streams	0.56	7.64
Total pervious surfaces	**0.99**	**13.48**
Total areas	7.33	100

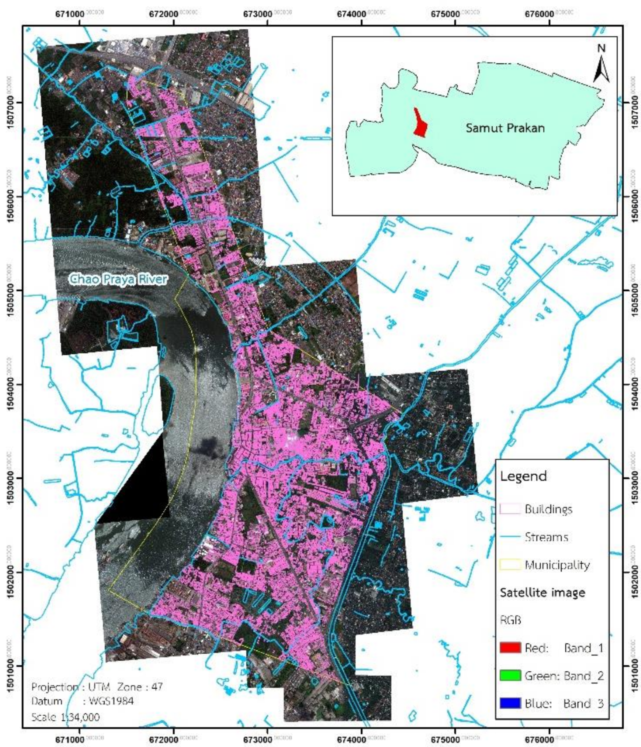

Figure 1 Map showing digital image, buildings and streams of Samut Prakan municipality.

Data uses

In order to achieve the research objectives, the study area was divided into 48 sub-catchments (Fig.2) according to Digital Elevation Model (DEM), the rainwater pipe network and land use. Geographic information system (GIS) was applied to analyze water flow direction and slope. The flow direction was verified by Samut Prakan municipality and fields measurements. Rainfall data from the Meteorological Department and the Bangkok Drainage Department were used to analyze the 10-year, 20-year and 50-year cycles of rainfall recurrence using Gumbel's method. Rooftop attributes were collected from Samut Prakan Office of Public Works and Town & Country Planning, and categorized by observed aerial photos and field study. Conduit data, such as length, diameter, and type of conduits, were suggested by Samut Prakan municipality. Parameters in SWMM's LID control (Table 2), consisting of surface layers, soil layers, and drainage mat, were estimated from SWMM user manuals [16] and Ekmekcioğlu, et. al.,

(2021) [3]. The Green-Ampt method is used to estimate infiltration losses. The dynamic wave theory is used for flow routing computation and Manning’s equation is applied to calculate runoff [17]. The capacity of a sub-catchment and its flow coefficient were determined by the land cover of each sub-catchment. Overland flow will pass through the outlet, and the model's validation was simulated by comparing it to observed data obtained from the floodgate within the study area.

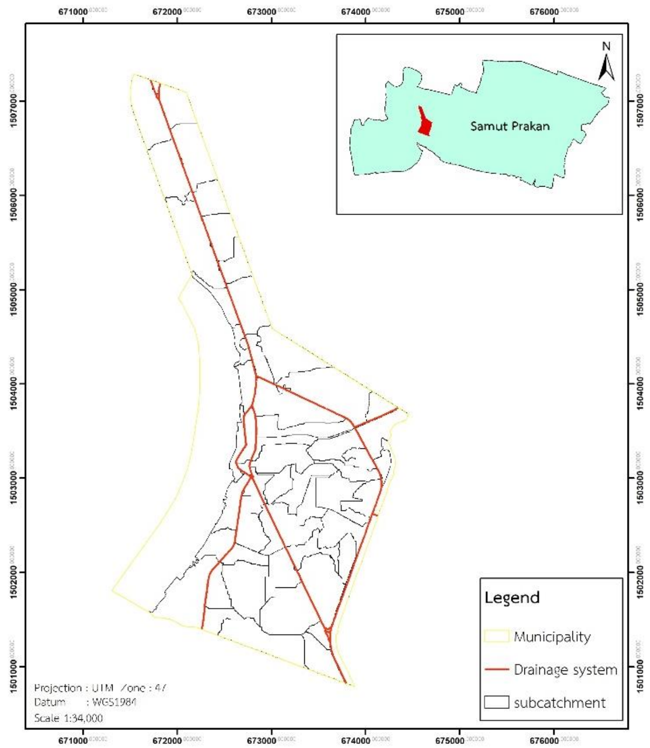

Figure 2 Subcatchment of study area generated by DEM, rain water pipe network and land use

Table 2 Parameters of LID control

Layer	Data	Value
Surface	Berm Height (mm)	300
	Vegetation Volume Fraction	0.1
	Surface Roughness (Manning's n)	0.24
	Surface Slope (%)	2
Soil	Thickness (mm)	150
	Porosity	0.463
	Field Capacity	0.232
	Wilting Point	0.116
	Conductivity (mm/hr)	3.302
	Conductivity Slope	60
	Suction Head (mm)	134.62
Drainage Mat	Thickness (mm)	75
	Void Fraction	0.5
	Roughness (Manning's n)	0.1

Data source: Rossman, L.A. (2015); Ekmekcioğlu, et. al. (2021); Liu, et. al. (2020).

SWMM model

In this study, the effectiveness of the green roof was evaluated through mathematical model EPASWMM 5.1. The EPA Storm Water Management model (SWMM) is a dynamic rainfall-runoff-routing simulation used to simulate both single-event and continuous rainfall-runoff quantities and quality from primarily urban areas [16]. The water component of the SWMM works by calculating the amount of rainfall in the sub-catchment and then transforming it into runoff. The Low Impact Development (LID) is a stormwater management approach that uses plants, soil, and natural processes to manage runoff. This approach involves creating areas that absorb, slow down, or store rainwater to alleviate the problems of flash flooding or standing water in urban areas with impervious surfaces.

There are 12 scenarios, consisting of 4 main scenarios that are categorized based on the rainfall events (average extreme rainfall, 10-year return period, 20-year return period, 50-year return period). Each scenario was further divides into three cases based on the percentage of green roof area: (1) 0% green roof and (2) 50% green roof and (3) 100% green roof. The reference scenario assumed no green roof. Green roof can be assigned in LID control modules within selected sub-catchment by defining the corresponding area coverage. The conversion green roof response is analyzed by runoff volume reduction and peak flow reduction which is calculated with the relative percentage different between outflow and the conversion in green roof and rainfall event.

Results and Discussions

The runoff reduction of green roof was simulated under three difference green roof coverages (0% GR 50%GR, 100%GR) and four different return period of rainfall (average extreme rainfall, 10-year, 20-year, 50-year rainfall events). The results indicated that green roofs significantly reduce surface runoff and peak flow. Table 3 shows the runoff reduction rate of different green roof coverages in various rainfall events. In extreme rainfall, a 50% GR can reduce rainfall runoff 14.6% and 21.71% for a 100% GR. For different rainfall return period, runoff reduction increased with an increasing rainfall period and green roof coverage. The runoff reduction rate increased from 18.40% to 27.01% in 10-year rainfall event, compared to a 50-year rainfall event after replacing 50% green roof coverage. For replacing with a 100% green roof coverage, runoff reduction rate is 37.18%, 44.22%, and 54.51% in 10-year, 20-year, and 50-year of rainfall events, respectively.

The results demonstrate that extensive green roofs in Samut Prakan achieved runoff reduction rates ranging from 14.6% to 54.51%. This finding suggests that green roofs in urban settings can reduce peak discharge. However, compared to other studies conducted in tropical climates, the extensive green roof system in this study seems to be less effective at reducing peak flow. For example, Sim., et. al. (2016) found a significant difference in the average runoff retention between extensive green roofs in semi-arid climates (75.2%) and maritime climates (43.4%) [18]. Mentens., et al. (2006) found that green roofs can provide a peak reduction of almost 50% [19]. Kasmin., et. al. (2014) reported that a similarly configured green roof in a Malaysian climate could reduce runoff by 84% [20]. Liu and Chui (2019) reported that, in the case of Sydney, green roofs can reduce peak runoff by 45-55% for different return periods [21]. Overall, the results of this study are consistent with previous researches in that the performance of green roofs in tropical climates is less effectively compared to those in arid and temperate zones.

In addition, there appears to be only a slight change in the runoff coefficient of the green roof as the rainfall intensity increases. As the rainfall return period increases from 10 to 50 years, the runoff coefficient of a 50% green roof increases from 82.55% to 83.98%, and from 67.11% to 68.47% for a 100% green roof. This change is consistent with previous research findings. Liu., et. al. (2020) found that the green roof retention capacity decreased as the precipitation intensity increased. Specifically, the runoff coefficient increasing from 57.41% to 72.19% when the precipitation intensity changed from a 2-year storm to a 100-year storm [22]. However, the slight change observed in this study, compared to Liu., et.al.(2020), could be due to the differences in characteristics of the simulation parameters that are partly influence by local conditions such as slope, green roof ratio, and rainfall intensity.

Table 3 Runoff reduction rate (%)

Green roof coverage	Runoff reduction rate (%)			
	Extreme Rainfall	Return period (Year)		
		10	20	50
Green roof 0%	-	-	-	-
Green roofs 50%	14.60	18.40	21.91	27.01
Green roofs 100%	31.71	37.18	44.22	54.51

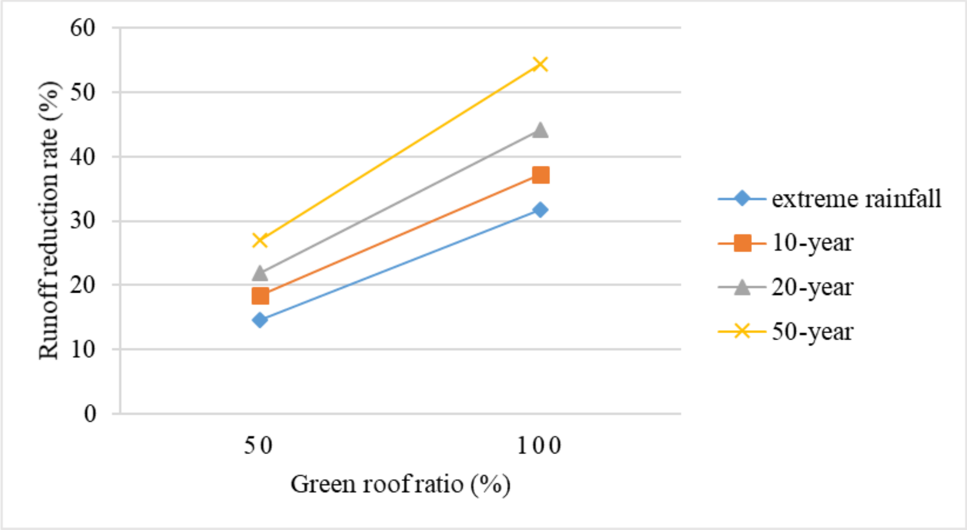

Figure 3 The impact of rainfall return period and green roof ratio on runoff reduction rate

Figure 4 shows the specific changes in runoff depth and runoff volume reduction. Under the same rainfall event, runoff depth decreased when green roof coverage area increased while runoff volume reduction increased when green roof increased. For the same green roof ratio, runoff depth and runoff volume reduction increased when rainfall increased. The correlation between runoff reduction and green roof ratio tends to be linear. The more green roof coverage ratio, the more reduction rate.

The results indicate that as rainfall return periods increased, the average runoff and runoff reduction also increased. However, the rate of average runoff reduction for the same green roof ratio decreased at different rainfall return periods. Though some previous research suggests that runoff reduction decreases with increasing rainfall return periods, this is not always the case. For instance, Liu and Chui (2019) found that the amount of annual average runoff dramatically increased through the increasing rainfall recurrence interval for a certain period of time [20]. This can be attributed to the fact that in this case, green roofs have sufficient capacity to hold rainwater even during peak precipitation, particularly for small return period [21]. Indeed, runoff reduction is site-specific and greatly influenced by several factors particularly, rainfall characteristics and soil storage [3].

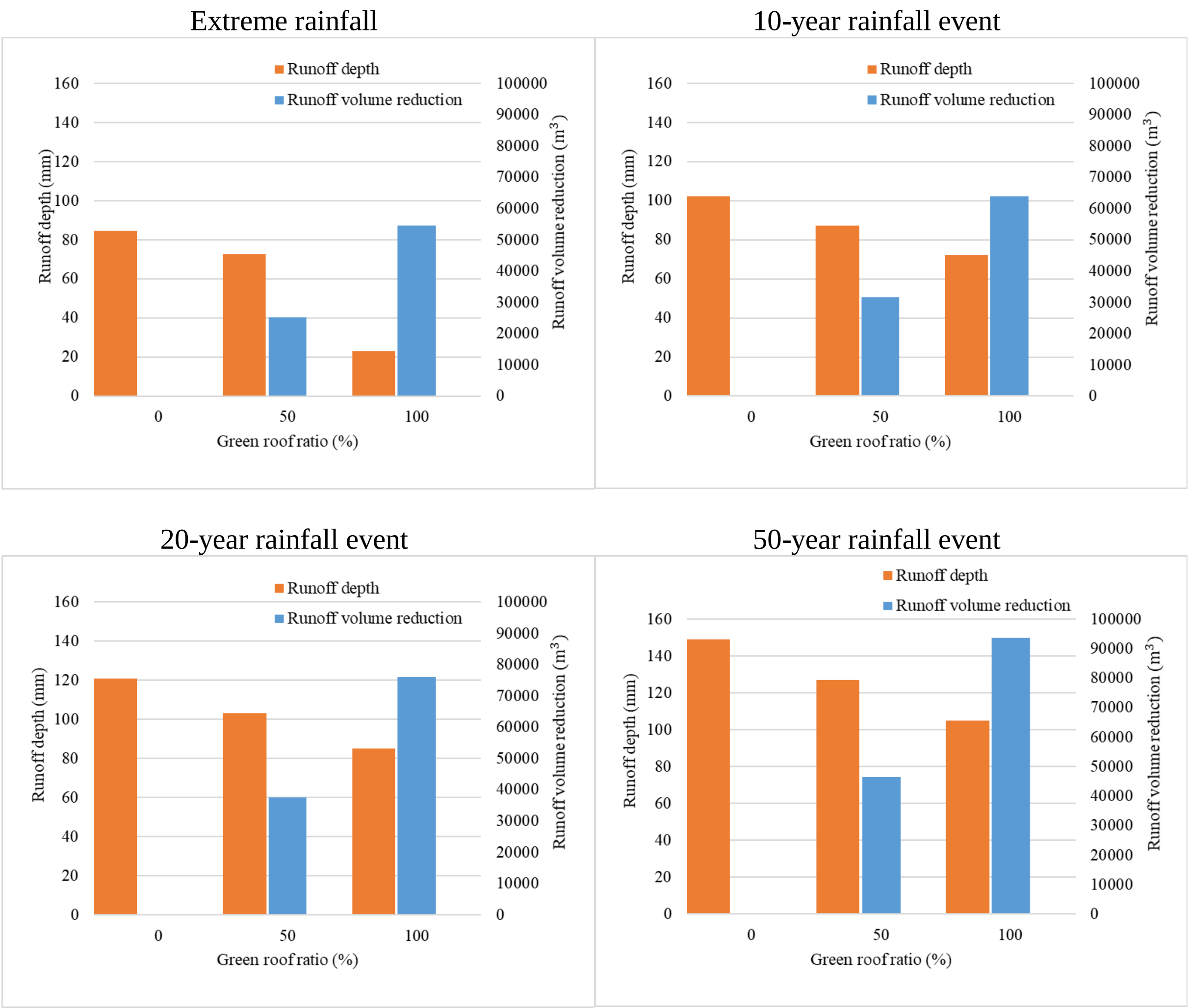

Figure 4 Variation of runoff depth and runoff volume reduction

Figure 5 and 6 shows the changes in peak flow and peak flow reduction rate during the different rainfall event and green roof ratio. Under the same rainfall scenario, peak flow decreased with increasing green roof while peak flow reduction rate increased with increasing green roof. It can be demonstrated that the increasing in area of green roof can reduce more peak flow. For the different rainfall, the peak flow increased with increasing of rainfall and the peak flow reduction decreased with increasing of rainfall. The peak flow of a 20-year rainfall event is 11.08 cms, which is an increase from 10.02 cms for a 10-year rainfall event. The peak flow of a 50-year rainfall event increased further to 16.28 cms. Notably, the increase in peak flow between the 10-year and 20-year rainfall events was smaller than the increase observed during the 50-year rainfall event. This may suggest that the green roof is approaching its capacity, although this can depend on the specific design and capacity of the green roof.

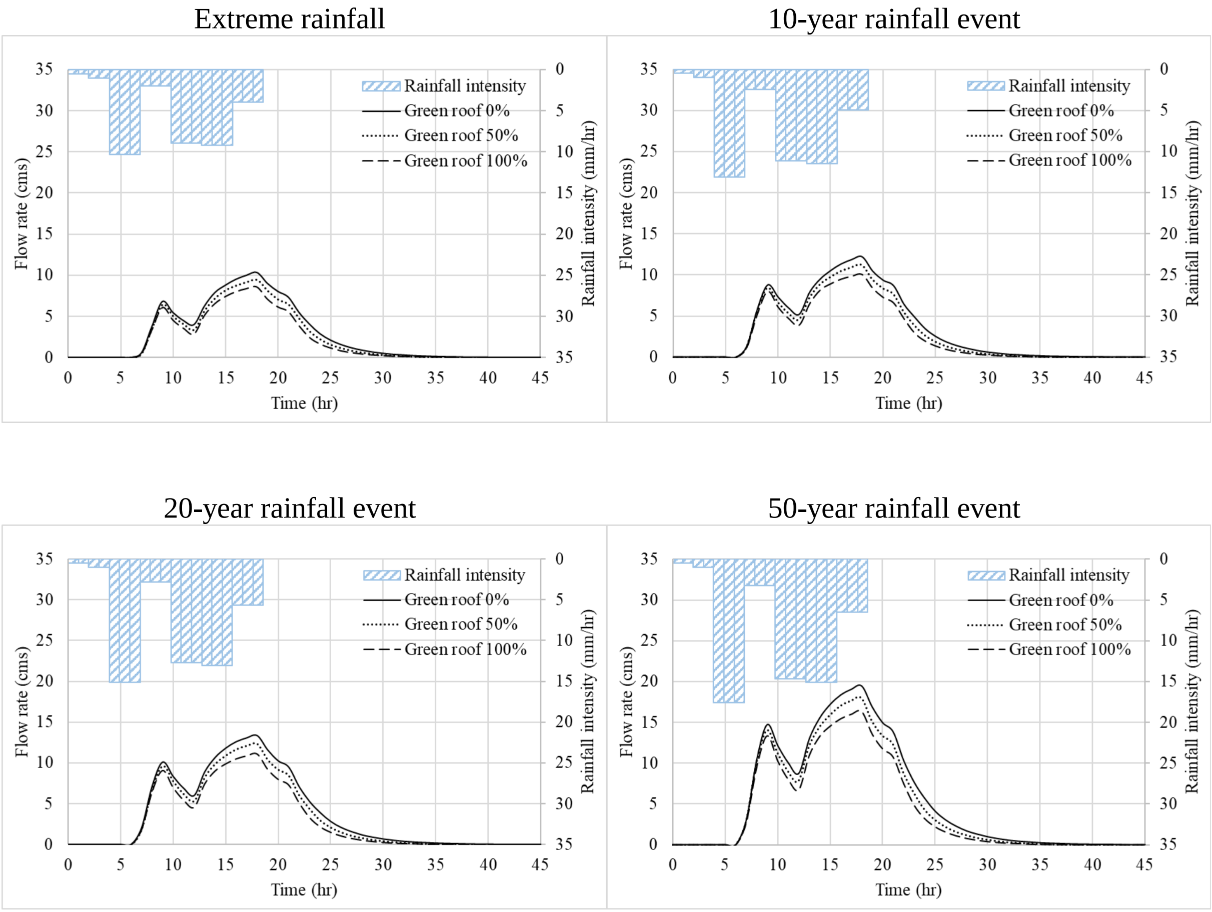

Figure 5 The hydrographs simulated based on the percentage of green roof area at assigned rainfall event return period (Extreme rainfall, 10-year, 20-year, and 50-year return period)

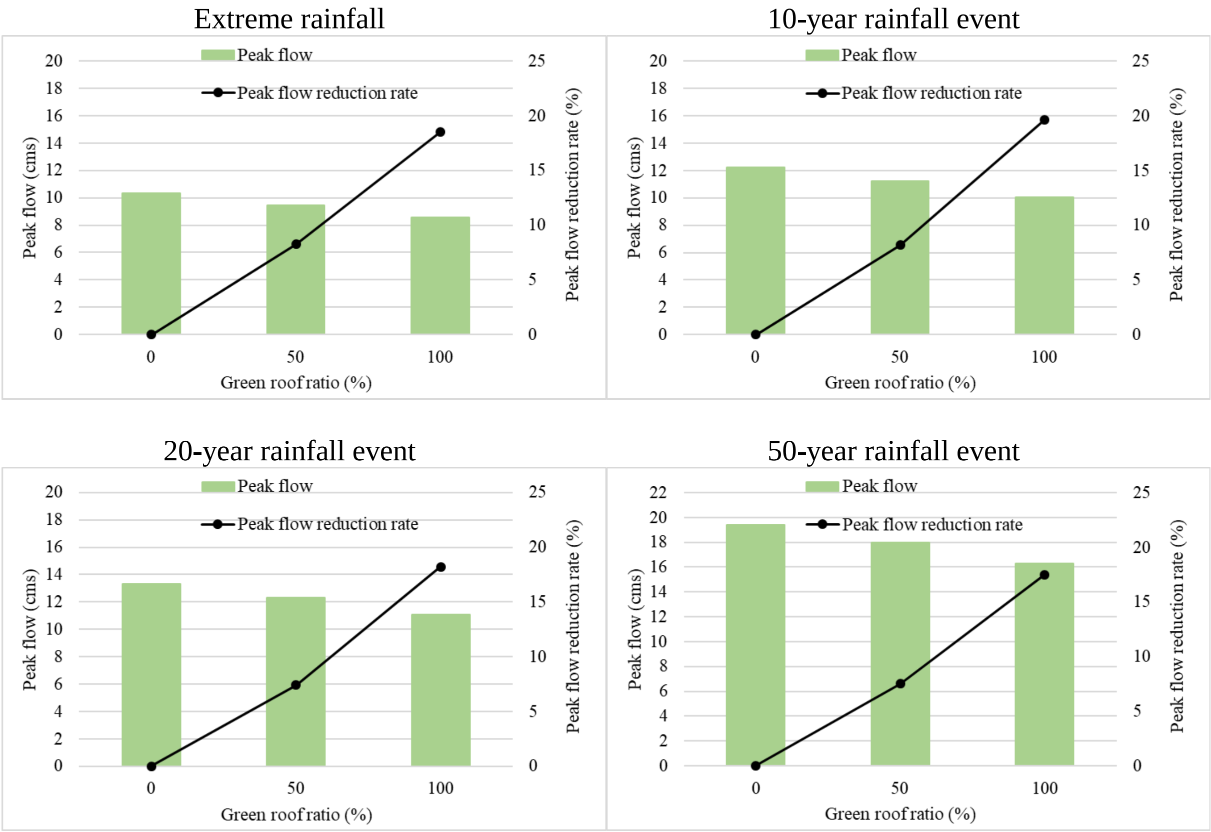

Figure 6 Variation of peak flow and peak flow reduction rate

Conclusion

This study aims to evaluate the effectiveness of green roofs in helping to slow down water runoff in response to flood risks in Samut Prakan municipal area. SWMM were used to investigate the efficiency of green roof. The study area was divided into 48 sub-catchments based on GIS data and analyzed using rainfall event data and changes in green roof area. The rainfall event used average extreme rainfall, 10-year, 20-year, and 50-year return period. The green roof coverage area ratio was varied from 0% to 50% to 100%. The impact of green roof on the runoff reduction shows that the runoff volume reduction was increased while the runoff depth decreased under different condition. For the peak flow and peak flow reduction, the peak flow was decreased and the peak flow reduction rate was increased when increasing the green roof coverage. In addition, the runoff coefficient slightly changes when rainfall intensity increases. The results suggest that an increase in green roof coverage is associated with a reduction in runoff and peak flow. This widens the range of available solutions for managing floods and mitigates the constraints of traditional structural stormwater management systems. It provides important knowledge for considering flood management policies and implementing measures for building construction and land development in the future.

Acknowledgement

The paper was originally presented at the 12 International Conference on Environmental Engineering, Science and Management. I would to thanks for Faculty of Science and Technology, Thammasat university for the scholarship and Samut Prakan municipality for the data support and guidance.

References

[1] Ajjur, S.B. and Al-Ghamdi, S.G. 2022. Exploring urban growth–climate change–flood risk nexus in fast growing cities. Scientific Reports. 12(1): 1-11.

[2] Koc, K. and Işik, Z. 2020. A multi-agent-based model for sustainable governance of urban flood risk mitigation measures. Natural Hazards. 104(1): 1079-1110.

[3] Ekmekcioğlu, Ö., Yilmaz, M., Özger, M. and Tosunoğlu, F. 2021. Investigation of the low impact development strategies for highly urbanized area via auto-calibrated Storm Water Management Model (SWMM). Water Science & Technology. 2021. 84(9): 2194-2213.

[4] Webber, J.L., Fletcher, T. D., Cunningham, L., Fu, G., Butler, D. and Burns, M. J. 2019. Is green infrastructure a viable strategy for managing urban surface water flooding? Urban Water. 17(7): 1-11.

[5] Berndtsson, J. C. 2010. Green roof performance towards management of run-off water quantity and quality: a review. Ecological Engineering. 36(4): 351-360.

[6] Feitosa, R. C. and Wilkinson, S. 2016. Modelling green roof stormwater response for different soil depths. Landscape and Urban Planning. 153(2016): 170-179.

[7] Li, Y. and Babcock, R. 2014. Green roof hydrologic performance and modeling: a review. Water Science & Technology. 69(4): 727-738.

[8] Kohler, M., Schmidt, M., Grimme, F.W. and Laar, M. 2002. Green roofs in temperate climates and in the hot-humid tropics – far beyond the aesthetics. Environmental Management and Health. 13(4): 382-391.

[9] Yoon J. 2013. Urban design mitifation tools for heavy rainfall hazard: Focusing on the flooding hazard area in Gamjeon-1 Dong, Busan. Dong-a University Master's Thesis.

[10] Viola, F., Hellies, M. and Deidda, R. 2017. Retention performance of green roofs in representative climates worldwide. Hydrology. 553(2017): 763-772.

[11] Penkova, I.F.G., Zimmerman, J.K. and Gonzalez, G. 2020. Green roofs in the tropics: design considerations and vegetation dynamics. Heliyon. 6(8): 1-8.

[12] Akther, A., He, J., Chu, A., Huang, J. and Duin, B.V. 2018. A Review of Green Roof Applications for Managing Urban Stormwater in Different Climatic Zones. Sustainability. 10(8): 2864.

[13] Williams, N.S.G., Rayner, J.P. and Raynor, K.J. 2010. Green roofs for a wide brown land: Opportunities and barriers for rooftop greening in Australia. Urban Forestry & Urban Greening. 9(2010): 245-251.

[14] Isa, N.F., Kasmin, H., Yahya, N. and Rahim, M.A. 2020. Green roof performance under malaysia tropical climates: a review. Indonesian. Electrical Engineering and Computer Science. 18(2): 614-62.

[15] Shin, E. and Kim, H. 2015. Analysing Green Roof Effects in an Urban Environment: A Case of Bangbae-dong, Seoul. Asian Architecture and Building Engineering. 14(2): 315-322.

[16] Rossman, L.A. 2015. Storm Water Management Model User's Manual Version 5.1; USEPA: Washington, DC, USA.

[17] Palla, A. and Gnecco, I. 2015. Hydrologic modeling of Low Impact Development systems at the urban catchment scale. Hydrology. 528(2015): 361-368.

[18] Sim, A.W., et. al. 2016. Retention performance of green roofs in three different climate regions. Hydrology. 542(2016): 115-124.

[19] Mentens, J., Raes, D. and Hermy, M. 2006. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? Landscape and Urban Planning. 77(3): 217-226.

[20] Kasmin, H., Stovin, V.R. and Hathway, E.A. 2010. Towards a generic rainfall-runoff model for green roofs. Water Science & Technology. 62(4): 898-905.

[21] Liu, X. and Chui, T.F.M. 2019. Evaluation of Green Roof Performance in Mitigating the Impact of Extreme Storms. Water. 11(4): 815.

[22] Liu, L., Sun. L, Niu. J. and Riley, W.J. 2020. Modeling Green Roof Potential to Mitigate Urban Flooding in a Chinese City. Water. 12(8): 2082.