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Efficiency of Low Impact Development on Urban Stormwater in Phnom Penh Capital of Cambodia

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Abstract: *Cambodia is at an early stage of development, with 21% of people presently living in cities. Phnom Penh, the capital and largest city of Cambodia, is under urbanization pressure with a population of 2.1 million and the annual growth rate of 3.2% in 2019. In this regard, aging infrastructure needs an upgrade or replacement with a new design considering a percentage, as high as possible, of permeable surfaces in urban areas. Low Impact Development (LID), including green infrastructure, should be taken into account in planning and design approaches to mitigate land development impacts on the environment. This study aims to evaluate the efficiency of LID scenarios on surface runoff reduction, peak flow reduction, and pollutant removal under rainfall patterns using PCSWMM model in Boeng Trabek sewerage system, Phnom Penh. Flow monitoring and water quality sampling during three rainfall events were conducted in a main conduit for testing model performance. Six types of LIDs (Infiltration trenches, bioretention, porous pavements, rain garden, green roof, and rain barrels) were implemented in an applicable proportion of existing sub-catchments. For every selected rainfall event, LIDs could reduce in average 48% of surface runoff, 35% of peak flow and increase infiltration rate to 90%. For water quality (COD, NO3, PO4, and TSS), the average sub-catchment's washoff removal and outlet's total pollutant removal is 55%. In summary, the implementation of LIDs has a significant impact on runoff reduction, peak flow reduction, and pollutant removal. The results provide concrete evidence for relevant stakeholders to consider Low Impact Development technique for sustainable development and to achieve smart cities.*

Keywords: Boeng Trabek catchment; Low impact development; PCSWMM; Phnom Penh; Stormwater

1. INTRODUCTION

Urbanization and climate change are becoming a significant threat to urban storm water management. According to Word Bank, Cambodia is at an early stage of urbanization, with 21 percent of people living in cities, and 36 percent of its resident will live in urban areas by 2050 [1]. Cambodia is one of the developing countries in Southeast Asia, with the economic growth of 7.5% in 2018 [2]. Recently, Phnom Penh City is facing severe and frequent inundations because of insufficient technical structures and management of stormwater during heavy intense rainfalls. Simultaneously, the speed of urbanization has outpaced the ability of governments to build essential that make life in cities safe, rewarding, and healthy, particularly in low-income infrastructures countries [3]. From the aspect of urban development, the increase in activities of residence area, industry and transportation has led to a rapid increase in urban population density and associated changes in land cover characteristics [4]. Urban drainage facilities in the Phnom Penh Capital City with functions of draining stormwater and domestic wastewater have been gradually improved in sequence in this recent year with the city development. Even though, the amount of stormwater has outpaced the capacity of drainage facilities as well due to old age and poor maintenance. Subsequently, the city experiences flooding and poor environmental conditions coming from overflowing of storm water and wastewater within the lowland areas. This problem is a serious constraint to the improvement of environment of residential area as well as social and economic development, not only of Phnom Penh capital city but the whole country in general [5]. Thus, it will be difficult to drain out

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logged water of the system in time and become aggravating urban flooding [6].

Aging infrastructure that are being upgraded or replaced with high proportion of impervious surfaces in urban areas cause more surface runoff. This problem is triggered in urbanized areas where the infiltration into groundwater is limited and blocked by paved surfaces with high imperviousness, resulting in more runoff. This runoff contains vast amounts of pollutants, including heavy metals, hydrocarbons and microbiological organisms that affect the quality of receiving aquatic environments, sometimes permanently [7]. Contaminated floodwater lead citizen health to the risk of exposure to harmful effects of microorganism in the water [8]. By increasing environmental and social pressures resulting from the adverse impacts of urbanization, urban flood, and other anthropogenic activities, a new approach in urban water management must be found to tackle increasingly complex traditional problems and to get more sustainable use and proper management of urban water [9].

The installation of effective water management facilities is essential for sustainable urban water management [10]. The Green Infrastructure (GI)/Low Impact Development (LID) controls is modeled in PCSWMM including bioretention cells, rain gardens, green roofs, infiltration trenches, permeable pavements, rain barrels, rooftop disconnections, and vegetative swales. LID practice effectively reduces pollutant loads and stormwater runoff by improving surface and subsurface water cycle, and retention [11]. This engineering technique is designed to be environmental friendly [12]. The practice of LID has a long-term effect along with minimal management after installation, and especially it is extraordinary for use in urban areas.

Therefore, this study aims to evaluate the efficiency of Low Impact Development scenario on urban stormwater in Trabek Catchment using Personal Computer Storm Water Management Model (PCSWMM). The study will provide concrete evidence to all stakeholders and show the importance of LID practice in reducing vast amount of pollutant, peak flow, and runoff during the rainfall event.

2. METHODOLOGY

2.1. Study area and data collection

Phnom Penh is the capital city of the Kingdom of Cambodia and is located at the western side of the confluence of the Mekong River and Tonle Sap (see Fig. 1). It is the political, economic and cultural center of the country and had the population of about 2.1 million (the annual growth rate is 3.2%) and its area is 678.46 km^2 [13]. Boeng Trabek catchment is one of the 27 sub-catchments in Phnom Penh cwith boundary’s area of 5.49 km^2. Previous research showed household wastewater and stormwater discharge volumes into this wetland is about 20 million m^3 with rainfall intensity of 1081 mm in 2002 [14].

The combined sewer system in this wetland consists of a series of pipes, culverts, and open channels. The study area has 3.048 km of open channels and 5.478 km of pipeline (Figure 1). According to Japan International Cooperation Agency (JICA) study in 2011 “The Project for Flood Protection and Drainage Improvement in Phnom Penh Capital City (Phase III)”, the average annual rainfall is approximately 1,400 mm, precipitation and rainy days from December to April are around 50 mm/month and 5 days/month respectively, while those from May to November are more than 100 mm/month and 15 days/month, respectively [5].

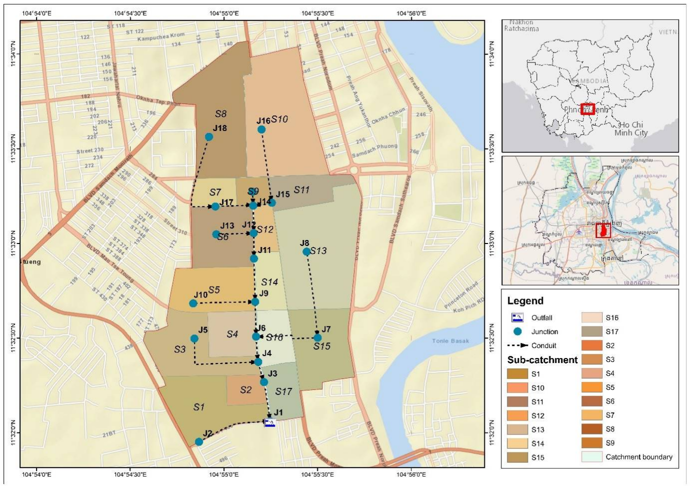

Fig. 1. Boeng Trabek mian drainage network and its hydraulic features, locate in Phnom Penh, the capital city of Cambodia.

Flow measurement is conducted by u sing Velocity/Area method to get observed flow during rainfall events, either during the dry day to get observed initial flow in the selected points. The primary purpose of this measurement is to get peak flow from the sampling point during rainfall events. Data is collected every 10 min for the first 60 min, every 30 min between 60 and 180 min.

For the important note, the observed flow was collected from the beginning of rainfall event, peak rainfall, and after rainfall event. Flow monitoring and water quality sampling were taken at the middle of conduit 17th (conduit 17th connected from J3 to J1) near the outlet of the catchment, locates behind Boeng Trabek Primary School. Water quality sampling were collected every 20 min for the first 60 min, every 30 min between 60 and 180 min. The samples were collected, treated, and analyzed at Industrial Laboratory Center of Cambodia (ILCC) within 24 hours. All the storm runoff samples were analyzed for Total Suspended Solids/Total Solid (TSS), Chemical Oxygen Demand (COD), Phosphate (PO4) and Nitrate (NO3) using standard methods by (ILCC).

2.2. Conceptual model and processing

PCSWMM/SWMM is a physically based, discrete-time simulation model [15]. The flexible set of these hydraulic model is that, it has full capabilities of rainfall-runoff routing and external inflows through the drainage system network of pipes, channels, storage/treatment units and diversion structures [16]. By dividing the selected catchment into different sub-catchments, each surface is considered as a non-linear reservoir and receive inflow from rainfall and any designated sewer networks in each sub-catchment. As the inflow has mentioned, the outflow of this model processing includes infiltration, evaporation, and surface runoff. Otherwise, this model can estimate the production of pollutant loads associated with stormwater runoff and with different land use [17].

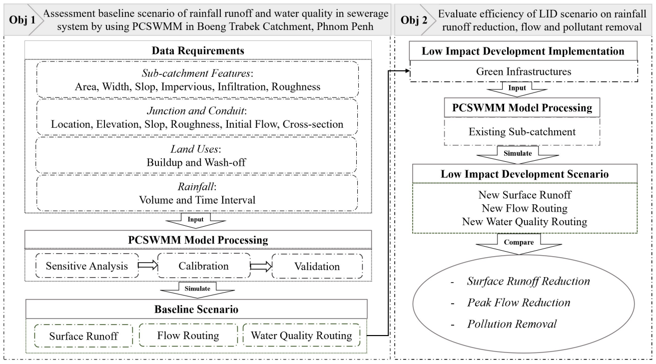

Fig. 2. Research framework of Low Impact Development application in Boeng Trabek Catchment, Phnom Penh of Cambodia

Before the model processing, a detailed investigation of the drainage system has been conducted to get basic data requirements. The observed data (channel flow and water quality) during rainfall events are necessary in process of model calibration and validation. After getting an acceptable baseline result, LID facilities will be projected to the existing sub-catchments (See Fig. 2).

2.3. Sensitivity analysis and model calibration

A sensitivity analysis was used to detect the most sensitive parameters that positively correlated with runoff. Sensitivity-based Radio Tuning Calibration (SRTC) of PCSWMM was used in model calibration and validation, which provides fast processing. The calibration and validation are performed by using the SRTC tool in PCSWMM (Version 2017). This tool allows the user to select the parameters in PCSWMM entity layers (sub-catchments, junctions, aquifers) with an allowable tolerance to be initially defined. For evaluating the calibration, long-term continuous PCSWMM simulation results were compared to the observed runoff. The accuracy of the model verified based on the evaluation criteria of root mean square error (RMSE), mean absolute error (MAE) and Nash- Sutcliffe coefficient [18]. The integral square error (ISE) integrates the square of the error over time. Integral square error rating metrics varying from "Excellent" to "Poor" depending on the ISE value calculated (Table 1) [19].

Table 1 Integral square error (ISE) rating

Rating	ISE Value
Excellent	< 3.0
Very good	3.0 - 6.0
Good	6.0 - 10.0
Fair	10.0 - 25.0
Poor	> 25.0

2.4. Low impact development scenario

Six LID practices, which are bio-retention, infiltration trenches, rain garden, permeable pavement, green roofs, and rain barrels, are selected to simulate in this study. Area of each LID types is determined based on the area of open space, road shoulder, parking space, and roof building in each sub-catchment, which is digitized by the integrated Google Earth and PSWMM model. Open space considered in this study includes public administration, pagoda, park, school, etc. The combination of road shoulder and parking space were calculated by the total shoulder length of each sub-catchment and shoulder width. The occupied area LIDs of each sub-catchment are shown in Table 2. In this study area, some sub-catchments are not applicable for all LID types.

For placing LIDs in sub-catchments, two approaches are considered: (1) placing one or more LIDs in an existing sub-catchment that will displace an equal amount of non-LID area from the sub-catchment, and (2) creating a new sub-catchment devoted entirely to a single LID and routing adjacent sub-catchment runoff onto this LID sub-catchment. The method of placing LIDs in the existing sub-catchment is applied with the different proportion mentioned in Table 2. In this approach, the difference of LIDs is placed into a sub-catchment and treated each portion of the runoff generated from the non-LID fraction of the sub-catchment [20]. By adding LID to an existing sub-catchment, the sub-catchments percentage of impervious was recalculated to take into account the LID's area and re-simulation. The impervious sub-catchment is the percentage of area in a sub-catchment where there is no infiltration versus the total non-LID area.

3. RESULTS AND DISCUSSION

3.1. Flow calibration and validation

Calibrating a hydrologic model is essential to take into consideration rainfall variability to the modeling process. Validation is a process to verify calibrated results to other observed data. Model validation was conducted to get reliable output, and three rainy events of observation data were managed

Table 2 Proposed occupied LIDs area, used for evaluating its effectiveness in Boeng Trabek catchment

LID types	Bio-retention	Infiltration trenches	Rain gardens	Permeable pavement	Green roofs	Rain barrels
Implemented places	10% open space	15% open space	10% open space	25% road shoulder & parking space	5% roof building	20% roof building
Sub-catchments	Occupied LIDs area (square meter)					
S1	627	940	×	5381	61983	15496
S2	×	378	252	1172	15709	3927
S3	×	×	×	5479	62471	15618
S4	62	92	×	3001	2401	600
S5	×	×	×	4361	50345	12586
S6	×	×	×	5489	48322	12080
S7	×	×	×	2137	14569	3642
S8	×	299	199	10565	82069	20517
S9	1131	1696	×	1597	8735	2184
S10	×	1305	870	8879	115354	28839
S11	286	429	×	3109	27183	6796
S12	×	×	×	1946	11405	2851
S13	3818	5728	×	11308	102019	25505
S14	×	×	×	2664	19588	4897
S15	×	6151	4101	3496	55811	13953
S16	×	×	×	2328	25149	6287
S17	670	1004	×	3281	20052	5013

Note: × Not applicable

to verify model accuracy. The percentage of the differences between observed data and simulated data was calculated to evaluate model application. The flow measured in conduits C17 of Boeng Trabek sewer system was selected for calibration and validation process by SRTC tool in PCSWMM model.

The sensitive parameters considered for calibration were: (i) width of each sub-catchment; (ii). the percentage of impervious area in each sub-catchment; and (iii). sub-catchment surface slope. A rainfall event on 28 September 2018 used for the calibration process and the next events on 22 September 2018 and 24 September 2018 were used to complete the validation process (Table 3). The reason for choosing one event for calibration and two events for validation is that this study is simulated in a single event and to avoid having different optimal parameters for the further scenario prediction.

Sensitivity-based Radio Tuning Calibration (SRTC) of PCSWMM was used in model calibration because this tool provides fast calibration. In this study, the percentage of uncertainty were selected for sub-catchment input parameter. The Nash Sutcliffe Efficiency (NSE) was selected to assess model accuracy, NSE represents a better fit when its value about 0.60 - 0.70. In this research study, the value of NSEs is higher than 0.60 for both calibration and validation during the rainfall events on 22nd 24th and 28th, which shows acceptable accuracy of the model setup (Table 3). R-squared (R^2) values of three events of the simulated flow and observed flow were 0.76, 0.86, and 0.92 while the perfect fit would equal to 1. The calibration and validation results indicated that the model structure and parameter matched the runoff-producing pattern and the calibration model was suitable. The process worked well, but it was difficult to explicitly compare one calibration against others since RMSE will vary depending on the length of time series. Thus, the RMSE values of both calibrations are acceptable even they are highly different.

Table 3 Summary of flow simulation, flow calibration and flow validation

Rainfall-runoff event	28/09/18 *	24/09/18**	22/09/18**
Observed rainfall (mm)	13.6	12.22	10.2
Observed peak flow (m^3/s)	8.23	7.51	8.72
Simulated Peak flow (m^3/s)	8.75	8.86	8.69
NSE	0.71	0.64	0.76
R^2	0.76	0.86	0.92
RMSE	4.61	3.34	0.97
ISE	4.57	5.11	2.62
ISE Rating	Very Good	Very Good	Excellent

* calibration ** validation

3.2. Water quality calibration

Water quality calibration and validation are performed after obtained an acceptable of flow verification. Three buildup

Table 4 Evaluation of the accuracy of the water-quality module simulation

Date	Water Quality Parameters	Concentra-tion (mg/l)	Calibration	Observation	R²	NSE	RMSE	ISE	ISE Rating
28-09-18	COD	Max	130.40	136.00	0.93	0.66	22.00	7.84	Good
		Min	89.05	80.00					
		Mean	111.60	108.90					
	NO_3	Max	0.34	0.28	0.91	0.67	0.04	9.09	Good
		Min	0.11	0.15					
		Mean	0.15	0.17					
	PO_4	Max	2.93	2.95	0.72	0.62	0.25	3.5	Very good
		Min	2.20	2.32					
		Mean	2.61	2.66					
	TSS	Max	197.40	195.00	0.70	0.54	30.50	10.5	Fair
		Min	111.30	102.00					
		Mean	163.50	151.00					

equations (power, exponential, and saturation) and three wash-off equations (exponential, rating curve, and event mean concentration) are provided in model. In this study, simulating the buildup and wash-off of pollutants was done using exponential equations.

For the first step, the general range of the buildup and washoff parameters were obtained from previous studies [21], following which the initial values of the parameters were input into the model. In calibration process (trial and error), the buildup and washoff parameters were adjusted and changed within the range of the established values. For the second step, the sensitive parameters were manually adjusted for all the pollutants and washoff that contributed to the outlet until the PCSWMM model matched the observed values. While the simulated values were approximately equal to the measured values in an acceptable range, the model was further calibrated by adjusting the less sensitive parameters. Through a two-step adjustment process, the calibration of the four pollutants and washoff was completed and result is showed in Table 4.

3.3. Efficiency of LID on hydrology

3.3.1. Conduit's peak flow reduction

The single event-based on 28 September 2018 is used to evaluate the performance of the LID facilities on peak flow reduction in each conduit. Figure 3 shows the representative reduction rate by clustered column, which consists of peak flow in each conduit before and after LID facilities was implemented in each sub-catchment.

The performance of LID facilities on peak flow is assessed by the percentage of reduction rate. Peak flow is determined by maximum flow in each conduit during rainfall period. As a result, peak flow reduction rate ranges from 24% to 45% in each conduit. The lowest reduction rate is 24% in conduit C10 (The discharge reduces from 0.44 m^3/s to 0.58 m^3/s). The highest reduction rate is 45% in conduit C12. The reduction ranged from 0.64 m^3/s to 1.15 m^3/s, depending on the area of LID facilities occupation.

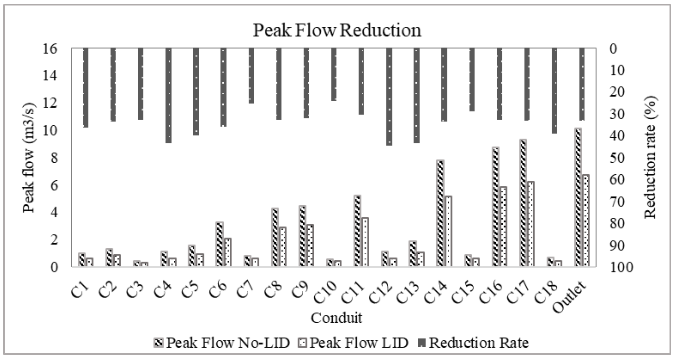

Fig. 3. Peak flow reduction of each conduit

3.3.2. Sub-catchment's surface runoff reduction

The reduction rate of surface runoff after LID facilities was implemented, represented by clustered column in Fig. 4. As a result, sub-catchment surface runoff reduction ranges from 23% to 58%. The lowest surface runoff reduction is 23% in sub-catchment S4, which decreased from 13.4 mm to 10.3 mm. The highest reduction rate is 58% in sub-catchment S15, which decreased from 13.5 mm 5.6 mm, depending on the area of LID facilities occupation.

3.3.3. Sub-catchment's Infiltration Variation

Fig. 5 shows the representative reduction rate by clustered column, which consists of infiltration in each sub-catchment before and after LID facilities were implemented. As a result, sub-catchment infiltration increased almost 79% to 95 %. The lowest infiltration increase is 79% in sub-catchment S6, which increased from 0.26 mm to 1.24 mm. The highest increasing rate is 90% in sub-catchment S17, which increased from 0.13 mm 3.12 mm, depending on the area of LID facilities occupation.

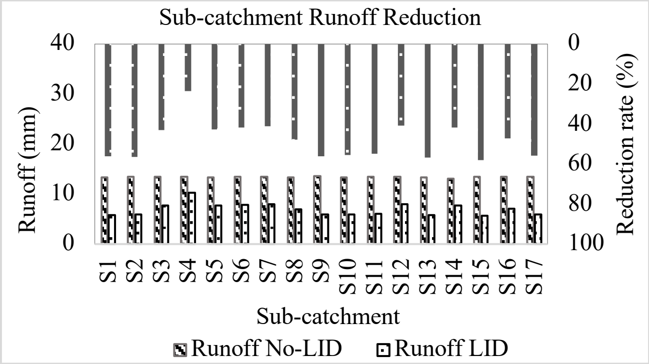

Fig. 4. Surface runoff reduction of each sub-catchment

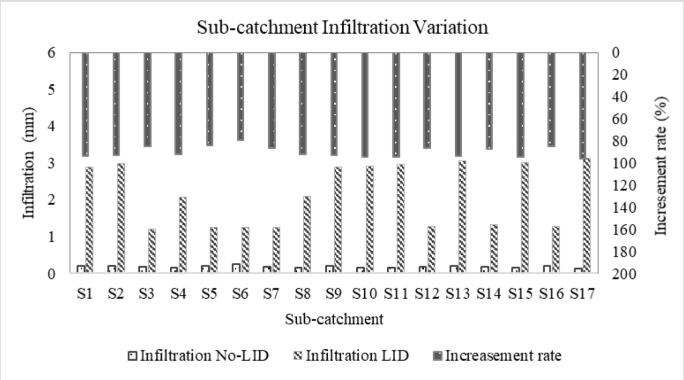

Fig. 5. Infiltration variation of each sub-catchment

After description of the performance of LID practices on each hydrological property which are the conduit's peak flow, sub-catchment's runoff, and, it could be observed that the implementation of LID facilities also positively effected sub-catchment's infiltration. The implementation of LID facilities plays a vital role in minimizing environmental impact, by reducing in average 48% of surface runoff from each sub-cathment, 35% of peak flow from each conduit, and increase in average 90% of infiltration from each sub-catchment. From this result, we can conclude that LID has significant positive impact on hydrological performance of the sewerage system by reducing amount of rainfall water going to conveyance system, which could be good solution for storm water surcharge.

3.4. Efficiency of LID on water quality

3.4.1. Sub-catchment's washoff reduction

To investigate the comprehensive characteristic of sub-catchment washoff removal before and after the implementation of LID, the signal event-based was analyzed to evaluate the performance of the LID facilities on washoff removal. Figure 6 shows the representative washoff reduction rate of each selected water quality parameters (COD, NO3, PO4, and TSS) by clustered column, which consists of washoff in each sub-catchment before and after LID facilities were implemented. As the result, washoff removal ranges from 32% to 63% for COD, 24% to 60% for NO3, 31% to 63% for PO4, and 32% to 64% for TSS in each sub-catchment.

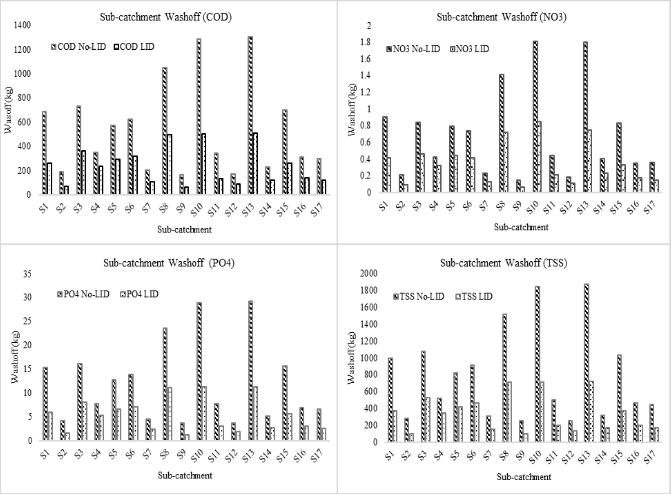

Fig. 6. Washoff removal of each sub-catchment

The maximum washoff removal of the four water quality parameters occurred in sub-catchment S15. The maximum removal of COD, NO3, PO4, TSS, decreased from 703 kg to 259 kg, 0.84 kg to 0.33 kg, 15 kg to 5.74 kg, and 1035 kg to 376 kg respectively. The minimum washoff removal of these four water quality parameters occurred in sub-catchment S4. The minimum washoff removal of COD, NO3, PO4, TSS, decreased from 353 kg to 239 kg, 0.42 kg to 0.32 kg, 7.85 kg to 5.38 kg, and 518 kg to 350 kg, respectively. On average, the effectiveness of LID practices on wasoff removal from sub-catchment is 53 % for these quality parameters.

3.4.2. Conduit's pollutant reduction

Fig. 7 shows the representative reduction rate by clustered column, which consists of pollutant load in each conduit before and after LID facilities were implemented.

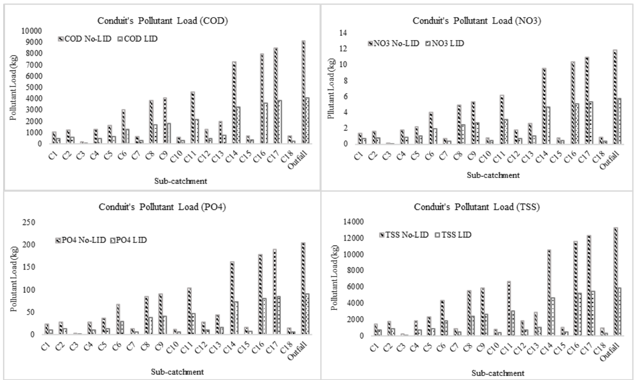

Fig. 7. Pollutant removal of each conduit

As the result, pollutant removal ranges from 48% to 62% for COD, 45% to 61% for NO3, 49% to 62% for PO4, and 49% to 62% for TSS in each conduit. The maximum pollutant removal of these four water quality parameters occurred in conduit C13. The maximum pollutant removal of COD, NO3, PO4, TSS, decreased from 1982 kg to 759 kg, 2.6 kg to 1.0 kg, 44.7 kg to 16.9 kg, and 2873 kg to 2085 kg, respectively. The minimum washoff removal of COD, NO3, PO4, TSS, decreased from 621 kg to321 kg, 0.74 kg to 0.41 kg, 13.82 kg to 7.11 kg, and 914 kg to 465 kg, respectively. On average, the effectiveness of LID practices on pollutant removal of each conduit is 55 % for these water quality parameters.

3.4.3. Outlet's total pollutant load removal

As mention earlier, pollutant removal in each conduit varies depending on the area of LID occupation in each sub-catchment. In this section, the modeled pollutant removal by LID installing in each sub-catchment using rainfall event 13.6 mm (28 September 2018) is summarized in Table 5. As a result, outfall total pollutant load from LID facilities could remove 55% of COD, 51.57% of NO3, 55.56% of PO4, and 56.07% of TSS. In average, effectiveness of LID practice on total pollutant load removal at outlet is 55% for these water quality parameters.

Table 5 Summarized outlet loading of the Boeng Trabek catchment and its removal after LIDs placing

Parameters	**Scenario**	**Loading (kg)**	**% Removal**
Total COD (kg)	No LID	9161.84	55.44
	LID	4082.79	
Total NO3 (kg)	No LID	11.89	51.57
	LID	5.76	
Total PO4 (kg)	No LID	204.81	55.56
	LID	91.02	
Total TSS (kg)	No LID	13324.36	56.07
	LID	5853.25	

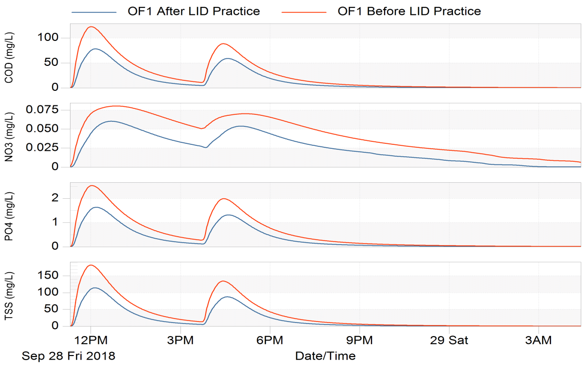

Fig. 8. The graphical comparison of water quality concentration at outlet before and after implementation of LIDs in Boeng Trabek catchment

As a result, outfall total pollutant load from LID facilities could remove 55% of COD, 51.57% of NO3, 55.56% of PO4, and 56.07% of TSS. In average, effectiveness of LID practice on total pollutant load removal at outlet is 55% for these water quality parameters.

4. CONCLUSIONS

PCSWMM model is used to evaluate the efficiency of LID scenario on surface runoff reduction, peak flow reduction, and pollutant removal, under rainfall pattern in Boeng Trabek catchment, Phnom Penh city. Single event and short-term simulation were used in this study for both quantity and quality in the hightlt urbanized sarea. The performance of PCSWMM modeling in the baseline scenario of the sewerage system was investigaed before the implementation of further scenarios. Flow measurements and water quality sampling during rainfall events were used to calibrate and validate model in the main conduit for testing the model performance. From the calibration and validation process, it could be observed that the most sensitive parameters that influences the hydrology and hydraulic model were sub- catchment widths, mean ground slope and manning's roughness coefficient. The results showed that flow simulation and water quality simulation were "very good fit" between the observed and simulated in different rainfall events. The calibration and validation results indicated that the model structure and parameter was suitable.

The effectiveness of LID practices can be determined by evaluating hydrological function and pollutant removal capabilities. Six types of LIDs (Infiltration trenches, bioretention, porous pavements, rain garden, green roof and rain barrels) are implemented in applicable proportion for each sub-catchment. During the rainfall event 28/09/18 (13 mm), LIDs could reduce in average 48% of surface runoff, 35% of peak flow and increase infiltration rate 90%. For water quality (COD, NO3, PO4, and TSS), the results show that the average washoff removal from catchment and total pollutant load removal from outlet is 55%. The implementation of LIDs has a significant impact on runoff reduction, peak flow reduction, and pollutant removal. The implementation of LIDs has a significant impact on runoff reduction, peak flow reduction, and pollutant removal.

According to the results of this study, LIDs have proven effective at reducing a high proportion of flood discharge. It has been considered as tools for reducing increasingly severe flooding events. But LID alone will not completely mitigate the current big flood event. Besides LID, flood storage measures such as dry ponds or underground storage are required to meet flood control requirements. The results provide concrete evidence for relevant stakeholders (Phnom Penh Capital Hall, Ministry of Public Works and Transport, prominent property development companies and all relevant stakeholders) to consider Low Impact Development technique for sustainable development and to achieve smart cities.

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