Research Article

Future scenarios modeling of urban stormwater management response to impacts of climate change and urbanization†

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ABSTRACT

Future scenario modeling was used to investigate the effectiveness of urban stormwater infrastructure and its response to potential future changes. The changes of urban stormwater, both in-flow quantity and water quality, in response to climate change and urbanization were examined and tested in two highly developed urban catchments using the US Environmental Protection Agency's Storm Water Management Model. Similar responses were observed in the two catchments, despite their differences in size and land use. Flow quantity and water quality appeared to be more sensitive to urbanization factors than to climatic change. With respect to factors attributable to urbanization, urban intensification (land use plus population density) had more of an effect than land-use changes alone. Low-impact development, as a key adaptation measure, could be effective in mitigating the adverse impacts of future changes on urban stormwater. The methodology developed in this study may be useful for urban stormwater planning and testing such plans against future urbanization and climate change scenarios.

Abbreviations: C-R, commercial-residential; COD, chemical oxygen demand; GCM, general circulation model; I-R, industrial-residential; LID, low impact development; RCP, representative concentration pathway; SSP, shared socio-economic pathway; SWMM, Storm Water Management Model; TN, total nitrogen; TP, total phosphorus; TSS, total suspended solids

Keywords: Climate change, Scenario, Shared socio-economic pathway, Stormwater management, Urbanization

1. Introduction

Climate change is predicted to cause changes (e.g., rising sea level and higher temperature) across the globe [1]. More specifically, climate change has serious implications for urban stormwater management in view of possible higher rainfall intensity and frequency of heavy storm [2]. To develop adaptation and/or mitigation strategies, many researchers have focused on evaluation of the impacts of climate change, especially on rainfall and runoff, using general circulation models (GCMs) and integrated assessment models based on alternative future scenarios [3]. Such changes in precipitation characteristics could inform future development plans for stormwater management [4]. In addition to climate change, the characteristics of storm runoff are also affected by geography and land-surface features [5]. It has been observed that peak runoff increases sharply with urbanization, higher fraction of impervious surface and channelized flow [6]. The negative consequences for the urban hydrologic cycle include higher risks of urban flooding [7], deterioration of water quality in many recipient water bodies [8], and damage to the urban ecological environment through bank/bed erosion [9].

Typically, urban stormwater management includes construction of engineered infrastructure to address the core objective of flood control [10]. Because conventional drainage systems are focused primarily on flood protection, most are not designed with sustainable development in mind [11]. Over the last decade, modern urban stormwater management has emerged, informed by principles such as low impact development (LID) [5]. LID is an innovative approach to urban stormwater management that does not rely on conventional end-of-pipe structural methods but instead uniformly or strategically integrates stormwater controls throughout the urban landscape [12]. LID techniques, which may include constructed wetlands, bioretention, and green roofs, more closely mimic the watershed's natural ecological and hydrological functions -- the water balance between runoff, infiltration, storage, groundwater recharge, and evapotranspiration as well as improving stormwater quality through physical, chemical and biological processes [13].

However, urbanization's effects are seldom considered in climate change impact assessments, and few studies of stormwater management acknowledge the importance and impact of both urbanization and climate change [14]. Most studies reported in the literature focus on either climate change or urbanization (not both) as the driver in simulations of future scenarios of the flow quantity and/or quality of urban stormwater [15]. Recently, there are suggestions that assessment of an urban storm management system should consider more realistic scenarios and account for the impacts of changes in both climate and urbanization [16]. Zahmatkesh et al. analyzed the effects of climate change on storm frequency and intensity in large watersheds based on GCMs and examined the effectiveness of LID practices to mitigate adverse effects on stormwater runoff [17]. However, the authors did not take urbanization into overall consideration. Although Wang et al. evaluated the impacts of urbanization and climate change on bioretention using future scenario modeling in Singapore, few studies of LID have been carried out considering the combined impacts of climate change and urban development [18]. Therefore, it is critical to assess the performance of LID practices applied to different urban catchments.

In addition, there is still lack of consistency in research findings when it comes to future scenarios based on different levels of urban development. Abdul-Aziz and Al-Amin investigated the sensitivities of stormwater quantity and quality in a coastal urban watershed (the Miami River Basin of Florida) based on certain climate change scenarios and changing land use, and found that runoff quantity exhibited high sensitivity, which also varied seasonally [19]. Willuweit et al. stimulated the effects of climate change and economic and urban planning scenarios on urban runoff patterns in Dublin, Ireland, and found that climate change is likely to reduce runoff, while urbanization is likely to increase it, and that decentralized practices have a critical role in sustainable urban stormwater management [20]. The mentioned studies were based on large urban watersheds. In contrast, Borris et al. considered both climate change and socio-economic factors in their assessment of stormwater quality in the relatively small-scale urban and suburban catchments of Östersund, Sweden [21]. There is consensus that more studies are needed of different urban catchments and different development scenarios.

The objectives of this study were (1) to examine the potential impacts of climate change on stormwater runoff (flow quantity and water quality); (2) to evaluate the potential impacts of changes in urbanization on stormwater runoff (flow quantity and water quality) in different urban catchments with different development scenarios (urban intensification and/or land-use changes); and (3) to assess the performance of LID practices applied to different urban catchments through future scenario modeling. The methodology developed in this study can be used to plan LID practices as adaptation strategies for stormwater management in local urban catchment.

2. Materials and methods

Stormwater in two urban catchments was examined in terms of flow quantity and water quality, under the effects of urbanization, climate change, and LID measures. The framework of the investigation is shown in Fig. 1. This study considered three main factors: climate change, degree of urbanization, and catchment characteristics and management strategies. Climate change may affect storm characteristics such as frequency, duration and intensity (design storm). Storm runoff is driven by the design storm and modified by land surface characteristics (terrain, soil type, cover and imperviousness), which were affected by land use (commercial, industrial or residential activities, which change with urbanization) and catchment management strategies (e.g. LID). The Stormwater Management Model (SWMM) is a catchment model that uses the design storm, catchment characteristics and stormwater management strategies to calculate runoff and route of the flow through the various sub-catchments. The outputs from SWMM are runoff flow rate and water quality.

2.1. Test Catchments

Two urban catchments in Singapore were selected as test catchments (Table 1). Outram Park (Singapore) is designated a mixed commercial-residential (C-R) area. It occupies 71 ha with a large fraction of impervious surfaces and mostly commercial and residential land use. Jurong West is a mixed industrial-residential (I-R) district. It has an area of 787 ha, with a large fraction of impervious surfaces and residential and industrial land use. Though distinctly different in size, the two catchments are similar in degree of urbanization and fraction of impervious land surface. The baseline scenario represents the present climate condition, land-use patterns, and other relevant urbanization factors, and serves as a benchmark for comparison with future scenarios. A storm event with a recurrence interval of ten years and duration of 90 min (about 110 mm of rainfall within the 90 min) was selected as the design storm.

2.2. Future scenarios

The future scenarios selected were based on a matrix of radiative forcing levels and socio-economic factors [22]. Representative concentration pathways (RCPs), as measures of the anthropogenic forcing of the climate systems, were used to explore the range of potential future greenhouse emissions, and RCPs were selected to define radiative forcing levels [23]. The ensembles of climate databases for Singapore were extracted from the climate change database portal of the World Bank Group. RCPs 2.6, 4.5, 6.0 and 8.5 were selected to reflect climatic changes from low to high level, and 16 ensembles of databases reflecting the percentage changes in rainfall intensity were chosen for each RCP. Table 2 is a summary of the changes in rainfall intensities in these four RCPs. The period from 2040 to 2059, corresponding to Singapore's concept plan, was selected for simulation.

Sets of variations in socio-economic factors in these test catchments, including economic activities, population, land use, technology, and urbanization policies, were considered as shared socio-economic pathways (SSPs) that will impact urban stormwater directly or indirectly [24]. To elucidate the impacts of urbanization and the sustainability of urban development, three SSPs (SSP1, SSP2, and SSP3) were adopted to present high-, median-, and low-sustainability scenarios. For these three SSPs, the storyline and narrative of the main features of urbanization were developed [25]. Following the selected storylines, detailed parameters of SSPs were chosen and combined with the master plan of Singapore to represent urban sustainable development level. The parameters include: (1) pollutant loads due to increased density of urban population (applicable to the mixed C-R catchment), (2) sizes of the residential, open space and other areas (applicable to the I-R catchment), (3) pollutant loads generated from street surface runoff caused by increased urban development, and (4) LID measures as sustainable stormwater management.

2.2.1. SSP1

SSP1 describes urban catchments sustainable development progresses at a rational but fast pace [25]. Generally rapid technological development is assumed, with changes towards environmentally friendly processes, and investments in high levels of education, coinciding with slower population growth. Well-planned urban development, employment opportunities, adequate infrastructure, and readily available dwellings for residents in the urban catchments are also assumed. To reduce adverse impacts on urban stormwater, a number of LID measures are applied in this scenario, similar to the vision of Public Utility Board, Singapore. However, human settlements inevitably become denser, as there is limited space for urban development in Singapore. Detailed parameters of SSPs corresponding to limited land space, high-intensity land use, and city-center features may be assumed to be static, with no significant changes in land-use patterns. The pollutant loads from residential and commercial land use are assumed to vary by --10 to 20% due to higher urban intensity in C-R. In I-R, due to greater land area (open space and other areas) for development, more space may become residential. These would be reflected in the change in the size changes of residential, open space and other areas; the relative ratios and patterns remain but with certain variations. For example, residential areas might be assumed to increase by --10 to 20% and the open space and other areas adjust correspondingly. It was also assumed that LID measures would occupy 5--10% of the total land area in both C-R and I-R urban catchments.

2.2.2. SSP3

This SSP, with demanding challenges for adaptation and/or mitigation, represents a society/economy in which the focus is to maintain living standards for a rapidly growing population [25]. There is relatively slow sustainable development, driven by moderate economic growth, small or infrequent investments in technology, education and human capital. The parameters include: (1) pollutant from commercial and residential land use increase by 5--35% in C-R; (2) residential area increase by 5--35 % in the form of high-rise buildings and more land surface; (3) other land use areas are reduced correspondingly in I-R. Pollutant loads from the street surface will increase by 50%, since uncontrolled quality degradation by storm runoff is recognized as a major non-point source in both test catchments [21]. Change in pollutant loads from street surfaces is highly uncertain, and was treated by introducing a ±15% range of variation of pollutant generation (i.e., 35--65%). The SSP3 scenario posits no new LID measure.

2.2.3. SSP2

This scenario represents an intermediate case between SSP1 and SSP3. It is built on the projection of the trends in population growth, economic growth, and technological change of the last few decades [25]. The parameters include --2.5 to 27.5% deviation in increased pollutant generation from residential and commercial land uses, and intermediate changes in residential land use in C-R and I-R catchments. Pollutant loads from street surfaces are assumed to increase by 10--40% in both catchments [21]. LID measures in the form of total impervious surface will change by 0--5% in this scenario.

Whether there are existing areas being redeveloped in C-R or new areas being developed in I-R, urban development is highly uncertain. This fact was treated by 12 random model setups with various degrees of change in pollutant loads, land-use, and LID measures. Table 3 shows the features and urbanization factors of the SSPs selected for the test catchments.

2.3. Hydrological model

SWMM version 5.1 as the simulation engine for physical hydrological processes in the catchments was used in this study. SWMM was developed by the US Environmental Protection Agency. The SWMM package has been widely used for catchment planning, design and analysis related to stormwater runoff in urban areas, and to simulate the hydrological response of different urban catchments under various scenarios. The Horton method for infiltration was used in this study, and kinematic wave routing to solve the one-dimensional dynamic waves for runoff routing. The outcomes of the simulation based on selected design storms include hydraulic parameters such as peak runoff, and water quality parameters such as total suspended solids (TSS), chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP). The selected design storm had a recurrence interval of ten years and duration of 90 min. Bioretention was selected as a representative LID measure implemented in the test catchments. The detailed parameters for both test urban catchments simulated in this study are shown in Table 3. The future scenarios were based on a combination of the RCPs and SSPs, and the selected drivers were presented in a matrix. A total of 2304 model runs (16 databases × 4 RCPs × 3 SSPs × 12 random SSPs) were conducted for each test catchment. For each simulation, peak runoff, TSS, COD, TN and TP loads were extracted and compared with those for the baseline scenario. The parameters for the baseline scenario are shown in Table 4. Statistical techniques based on variance and normal distribution were used to check the significance of the findings.

3. Results and Discussion

3.1. Peak runoff and pollutant loads

Peak runoff and loads of TSS and TN are shown in Figs. 2 and 3 for the four scenarios (base scenario, SSP1-RCPs, SSP2-RCPs, and SSP3-RCPs), simulated in both test catchments. In these boxplots, the base of the box denotes the first quartile (Q1, 25 %), the line in the central part of the box indicates the median (50 %), and the roof marks the third quartile (Q3, 75 %). The variability of flow quantity and water quality is high, as indicated by the upper and lower ends of the whiskers. COD and TP (not shown) are highly correlated with TSS (correlation coefficient >0.85; $p < 0.001$); their boxplot shapes are almost identical to those of TSS.

The peak runoff and pollution loads for different scenarios in both test catchments show similar trends. With reference to the base scenario, the median flow quantity decreases significantly in SSP1-RCPs, and increases significantly in SSP3-RCPs. Comparison of the average peak runoff and pollution generation to the base scenario are summarized in Table 5. The key findings are discussed below.

For SSP1-RCPs, the peak runoff and pollution loads were clearly smaller than those in the base scenario, especially in the I-R catchment, as a result of the relatively small changes in urbanization and the use of various well-designed LID measures incorporated in this scenario. For SSP2-RCPs, the peak runoff increased slightly in both test catchments as rainfall intensity increased and land use changed (e.g., converting open space and other areas into residential areas in I-R). However, there was performance differing in terms of quality (i.e., quality deteriorated in C-R, and improved in I-R) as pollutant load density increased following land-use change (more residential area and impervious surface) in C-R. In the case of SSP3-RCPs, the peak runoff and pollutant loads increased significantly in both catchments as a result of climate change (higher rainfall intensity) and increased urbanization but no new LID measures.

The I-R catchment is almost 11 times as large as the C-R catchment. However, peak runoff and water pollution parameters were only 4.8 times as high in I-R as in C-R. Consequently, one would expect greater benefits from land-use changes and LID measures in the C-R. In addition, due to the smaller C-R catchment in the downtown area, one should follow the path of urbanization development with greater emphasis on sustainability (SSP1). In the case of the larger I-R catchment, one could adopt an urbanization plan with emphasis on high or medium degree of sustainability (SSP1 or SSP2), since peak runoff decreased and water quality deteriorated in both scenarios.

3.2. Relative effects of climate change and urbanization

In this study, RCPs and SSPs were incorporated as two major factors that introduced uncertainty in flow quantity and water quality in the future scenarios. Cumulative uncertainty in flow quantity, and water quality for RCPs and SSPs are examined separately and the findings are shown in Figs. 4 and 5 for C-R and I-R, respectively. The trends in COD and TN (not shown) were similar to TSS. One may note in Figs. 4 and 5 that changes in urbanization produced significantly higher variability in flow quantity and water quality than changes in RCPs, especially in water quality.

To assess the relative influence on each RCP with respect to changes in SSP, matrices with a fixed RCP and different SSPs, and vice versa, were applied. Specifically, parameters used in SSP2-RCPs (i.e., SSP2 held constant while RCP was varied (four variants) and RCP6.0-SSPs (i.e., RCP6.0 held constant while SSP was varied (three variants)) were selected. The findings are presented in Figs. 6 and 7 for flow quantity and water quality in the C-R and I-R catchments, respectively. The results of the statistical analyses based on normal distribution, and the effects of different RCPs and SSPs on flow quantity and water quality are summarized in Table 6. Changing SSPs produced significantly higher variability. The best performance in terms of flow quantity and water quality was observed in SSP1-RCP6.0, and the worst in SSP3-RCP6.0. The performance based on SSP2-RCPs is similar in the two test catchments.

Hence, one may conclude that flow quantity and water quality are more sensitive to changes in land use, degree of urbanization (intensity of land use), and LID measures than to climate change. Other work focusing on stormwater quantity or quality has produced similar findings [21,26]. Thus, it appears that the pace and degree of urbanization is a factor of crucial importance in evaluating socio-economic impact in the development of an urban catchment, underlining the importance of considering changes in land use in developing a rational plan for sustainable urbanization.

3.3. Performance of LID measures in future scenarios

LID measures were applied in both test catchments to counter the adverse effects of urbanization and climate change, and to improve runoff water quality. Although the performance of LID is strongly dependent on environmental conditions, certain LID measures, such as source management, could cap or reduce the peak runoff and reduce pollutant loads. Taking bioretention as an example, Ahiablame et al. reported peak-flow reduction of 32--99% [27]. Ahiablame and Shakya reported that LID measures can be used to attenuate flood risks in an urban watershed [28]. Guan et al. reported that LID measures appeared to be effective in controlling flow quantity and water quality of runoff and mitigating the negative impacts of rapid urbanization [29].

To assess the performance of LID measures in future scenarios, the influences of LID measures applied to SSPs-RCPs were simulated and compared with the findings for the same SSPs-RCPs in the same catchments but omitting all LID measures (Fig. 8). It can be seen in Fig. 8 that the median peak runoff, TSS and TN are lower, and the values corresponding to the third and first quartiles are about four times as large in those SSPs-RCPs with LID measures, compared to those without LID. This observation underlines the importance of LID measures for the development of an urban catchment.

4. Conclusions

This study evaluated the combined effects of climate change and urbanization on urban stormwater in

Singapore using future scenario modeling of urban stormwater in terms of quantity and quality. Several future scenarios were selected based on a framework of representative concentration pathways and shared socio-economic reference pathways. The following conclusions may be drawn:

1) Studies predict increasing rainfall in Singapore as a result of climate change. Urbanization, characterized by population increase, greater economic activity, and land-use changes, may increase the fraction of impervious area and thus exacerbate pollution loads. These changes will directly influence the flow quantity and water quality of storm runoff.
2) Relevant factors attributable to climate change, development strategies and urbanization should be incorporated in the catchment model to produce realistic simulations. The findings can then be used to conduct scenario analysis and assess the effectiveness of urban stormwater infrastructure and management strategies under various scenarios.
3) Despite their very different size, the two test catchments studied generally exhibited similar results and trends for all scenarios. However, C-R showed relatively larger changes in flow quantity and water quality of storm runoff for different RCPs-SSPs. This is expected as urbanization tends to lead to higher pollution loads. On the other hand, I-R might have more flexibility and options in urbanization strategy because there is more space available for development.
4) Runoff flow quantity and water quality appears to be more sensitive to changes in urbanization than to factors attributable to climate change. Adopting an appropriate sustainability strategy will provide better control of runoff flow quantity and water quality. LID measures which retain runoff at the source will reduce peak runoff and result in better water quality.

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Fig. 1. The overall framework of this study.

Fig. 2. a) Simulated peak runoff, b) simulated TSS, and c) simulated TN from mixed C-R based on four scenarios (base scenario, SSP1-RCPs, SSP2-RCPs, and SSP3-RCPs).

Fig. 3. a) Simulated peak runoff, b) simulated TSS, and c) simulated TN from mixed I-R based on four scenarios (base scenario, SSP1-RCPs, SSP2-RCPs, and SSP3-RCPs).

Fig. 4. a) Simulated peak of runoff, b) simulated TSS, and c) simulated TN from mixed C-R based on four scenarios (base scenario, RCPs, SSPs, and RCPs-SSPs).

Fig. 5. a) Simulated peak runoff, b) simulated TSS, and c) simulated TN from mixed I-R based on four scenarios (base scenario, RCPs, SSPs, and RCPs-SSPs).

Fig. 6. Effects of RCP and SSP on a) peak runoff, b) TSS, and c) TN for mixed C-R.

Fig.7. Effects of RCP and SSP on a) peak runoff, b) TSS, and c) TN for mixed I-R.

Fig. 8. Effects of two RCPs-SSPs (RCPs-SSPs and RCPs-SSPs without LID) with respect to a) peak runoff, b) TSS, and c) TN from mixed C-R simulated from mixed I-R.

Table 1 Characteristics of Outran Park and Jurong West in Singapore.

Land use	Outran Park	Jurong West
Residential areas (ha)	19 (13.8%)	343 (23.3%)
Commercial areas (ha)	52 (37.7%)	5 (0.3%)
Industrial areas (ha)	0	439 (29.8%)
Streets (ha)	22 (15.9%)	185 (12.6%)
Open space (ha)	41 (29.7%)	472 (32.1%)
Other areas (ha)	4 (2.9%)	28 (1.9%)
Total area (ha)	138	1472

Source from Urban Redevelopment Authority, Singapore (www.ura.gov.sg, accessed 15 April 2016).

Table 2 Changes of rainfall intensities for four RCPs.

	Minimum	Average	Maximum
RCP 2.6 （N = 16）	5.2%	9.4%	15.1%
RCP 4.5 （N = 16）	5.5%	10.5%	18.9%
RCP 6.0 （N = 16）	6.5%	11.0%	21.8%
RCP 8.5 （N = 16）	6.7%	12.6%	26.1%

Source from climate change knowledge portal of the World Bank Group for Singapore (http://sdwebx.worldbank.org/climateportal, accessed 5 May 2016).

Table 3 Characteristics of SSP1, SSP2, and SSP3, as well as detail parameters of SSPs for mixed C-R and/or I-R.

	SSP 1	SSP 2	SSP 3
Sustainability [a]	High	Median	Low
Population growth [a]	Low	Median	High
Economic [a]	High	Median	Low

Technology [a]	High	Median	Low
Education [a]	High	Median	Low
Changes of pollutant loads from residential and commercial land uses (mixed C-R) [b]	--10 to 20%	--2.5 to 27.5%	5 to 35%
Changes of size for land uses (mixed I-R) [b]	Residential areas may be increased by --10 to 20% and open space and other areas may be declined correspondingly	Residential areas may be increased by --2.5 to 27.5% and open space and other areas may be declined correspondingly	Residential areas may be increased by 5% to 35% and open space and other areas may be declined correspondingly
Changes of pollutant loads from street [b]	No change	10 to 40%	35 to 65%
The area of LID measures applied for total residential, commercial, industrial land uses and street [b]	5 to 10%	0 to 5%	No more

[a] Source of sustainability, population growth, economic, technology and education [25, 30, 31].

[b] Source of information [21].

Table 4 Parameters of imperviousness, quality and LID for different land uses in SWMM.

Parameter	Land use	Residential area	Commercial area	Industrial area	Street	Open space & other area
Features of	Impervious rate (%)	70	70	70	95	30

land uses	Depth of depression storage on pervious area (mm)	5	5	5	0.05	30
Quality [a]	TSS (mg/L)	50	50	50	50	50
	COD (mg/L)	100	100	100	100	100
	TN (mg/L)	3.20	3.20	3.20	3.20	3.20
	TP (mg/L)	0.24	0.24	0.24	0.24	0.24
Maximum possible buildup [b]	TSS (kg/ha)	13.50	29.78	24.61	30.38	16.27
	COD (kg/ha)	1.454	11.43	5.72	11.63	0.19
	TN (kg/ha)	0.05	0.18	0.78	0.18	1.28
	TP (kg/ha)	0.30	0.30	0.30	0.30	0.30
Rate constant [b]	TSS	0.40	0.40	0.40	0.40	0.40
	COD	0.40	0.40	0.40	0.40	0.40
	TN	0.40	0.40	0.40	0.40	0.40
	TP	0.40	0.40	0.40	0.40	0.40
Wash-off coefficient [b]	TSS	0.0023	0.5063	0.94	0.51	0.006
	COD	2.6395	2.2098	0.4153	2.21	0.015
	TN	0.035	1.695	0.5533	1.70	0.007
	TP	0.01	0.01	0.01	0.01	0.006
Runoff exponent in wash-off function [b]	TSS	1.8423	0.50	0.3753	0.50	1.20
	COD	0.102	0.11	0.5234	0.11	1.20
	TN	0.002	0.30	0.50	0.30	1.20
	TP	1.60	1.60	1.60	1.60	1.20
Surface of LID [c]	Berm height (mm)	150.00	150.00	150.00	150.00	--
	Vegetation volume fraction	0.10	0.10	0.10	0.10	--
	Surface roughness	0.10	0.10	0.10	0.10	--
	Surface slope (%)	1.00	1.00	1.00	1.00	--

Soil of LID [c]	Thickness of soil (mm)	1200	1200	1200	1200	--
	Porosity	0.50	0.50	0.50	0.50	--
	Field capacity	0.20	0.20	0.20	0.20	--
	Wilting point	0.10	0.10	0.10	0.10	--
	Conductivity (mm/h)	250	250	250	250	--
	Conductivity slope	10.0	10.0	10.0	10.0	--
	Suction head (mm)	87.5	87.5	87.5	87.5	--
Storage of LID [c]	Thickness of storage (mm)	500	500	500	500	--
	Void ratio （voids/solids）	0.75	0.75	0.75	0.75	--
	Seepage rate (mm/h)	750	750	750	750	--
	Clogging factor	0	0	0	0	--
Drain of LID [c]	Flow coefficient of drain	0.50	0.50	0.50	0.50	--
	Flow exponent of drain	0.50	0.50	0.50	0.50	--
	Offset height of drain (mm)	150	150	150	150	--

[a] Parameters of quality are from Public Utilities Board, Singapore (www.pub.gov.sg, accessed 27 March 2016).

[b] Parameters of maximum possible buildup, rate constant, wash-off coefficient, and runoff exponent in wash-off function of TSS, COD, TN and TP [32].

[c] Parameters of surface, soil, storage, and drain [33].

Table 5 Comparisons of average peak of runoff and pollutions generation among the various scenario.

		Base scenario	SSP1-RCPs	SSP2-RCPs	SSP3-RCPs
Mixed C-R	Peak of runoff (m^3/s)	48.07	45.77 (--4.8%)	50.56 (5.2%)	53.29 (10.9%)
	TSS (kg)	6,380	5098 (--20.1%)	7364 (15.4%)	9317 (46.0%)

	COD (kg)	12,896	10,283 (--20.3%)	14 874 (15.3%)	18 835 (46.1%)
	TN (kg)	531	422 (--20.6%)	605 (13.9%)	785 (47.9%)
	TP (kg)	44.26	35.32 (--20.2%)	51.06 (15.4%)	64.62 (46.0%)
Mixed I-R	Peak of runoff (m^3/s)	368.17	263.09 (--28.5%)	375.27 (1.9%)	411.18 (11.7%)
	TSS (kg)	65 248	45 429 (--30.4%)	59 628 (--8.6%)	78 831 (20.8%)
	COD (kg)	130 379	90 744 (--30.4%)	119 036 (--8.7%)	157 367 (20.7%)
	TN (kg)	4761	3231 (--32.1%)	4257 (--10.6%)	5875 (23.4%)
	TP (kg)	446.14	310.07 (--30.5%)	407.77 (--8.6%)	538.94 (20.8%)

Table 6 Relative effects for average quantity and quality from different RCP and SSP.

		Base scenario	RCP8.5-SSP2	RCP6.0-SSP2	RCP4.5-SSP2	RCP2.6-SSP2	SSP1-RCP6.0	SSP2-RCP6.0	SSP3-RCP6.0
Mixed C-R	Peak of runoff (m^3/s)	48.07	51.33	50.62	50.39	49.88	45.83	50.62	53.36
	TSS (kg)	6380	7477	7373	7340	7265	5104	7373	9329
	COD (kg)	12 896	15 038	14 844	14 742	14 605	10 291	14 844	18 788
	TN (kg)	531	614	605	603	597	404	605	786
	TP (kg)	44.26	51.88	51.16	50.93	50.41	35.41	51.16	64.73
Mixed I-R	Peak of runoff (m^3/s)	368.17	381.03	375.75	374.07	370.23	263.43	375.75	411.71
	TSS (kg)	65 248	60 543	59 705	59 438	58 827	45 487	59 705	78 932
	COD (kg)	130 379	120 861	119 180	118 647	117 427	90 798	119 180	157 462
	TN (kg)	4761	4322	4262	4243	4199.49	3235	4262	5882
	TP (kg)	446.14	413.97	408.24	406.41	402.24	311.02	408.24	539.37

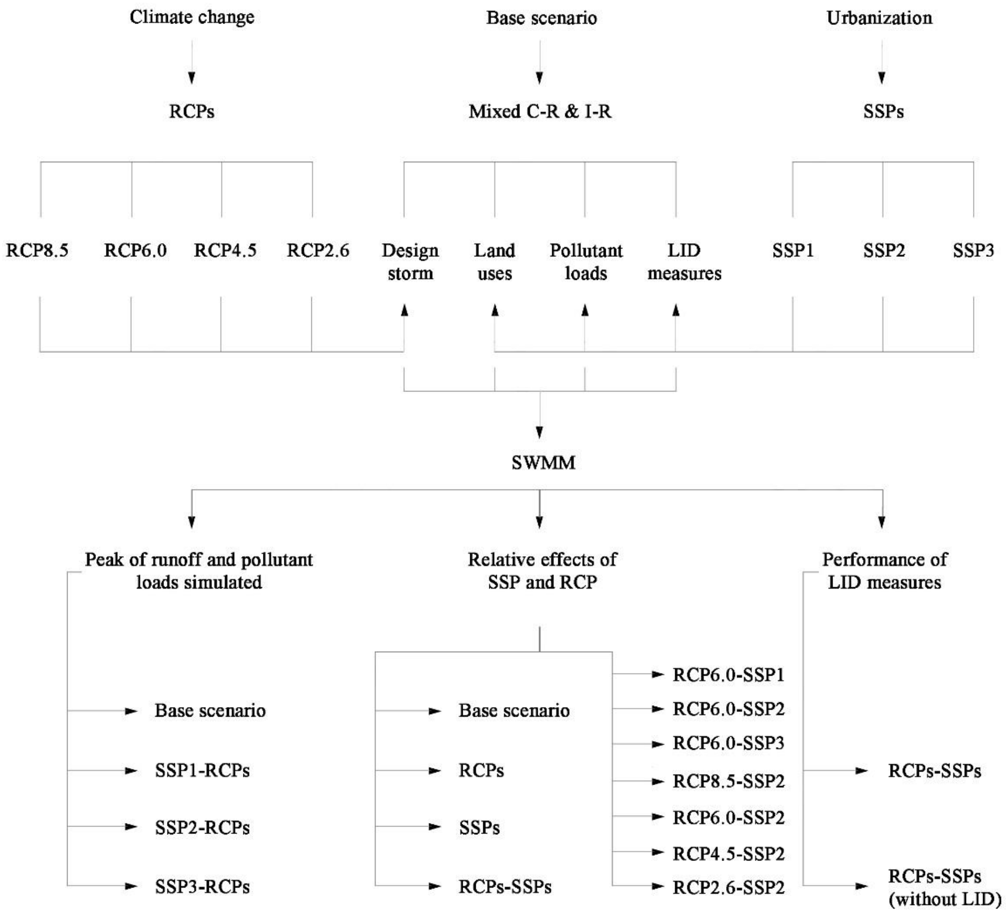
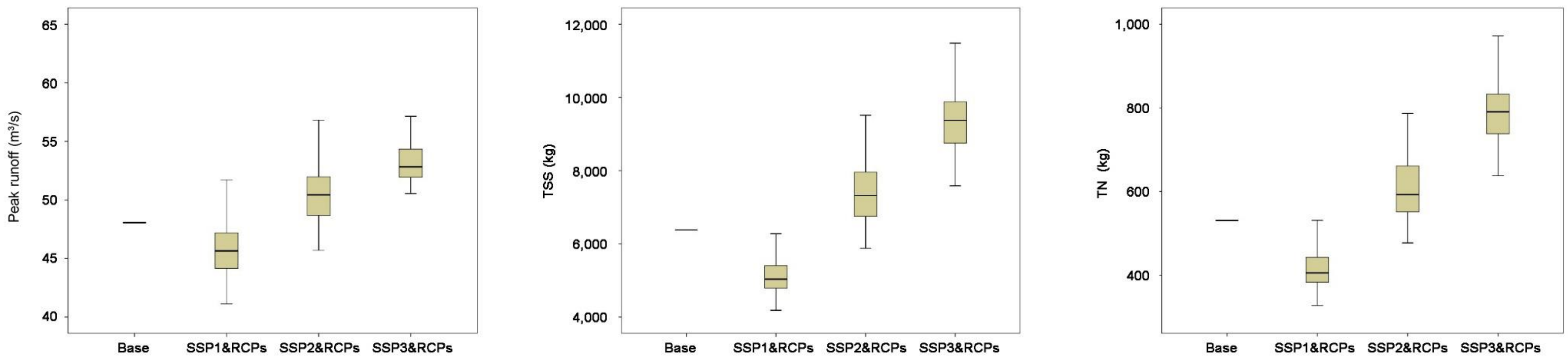

Climate change
Base scenario
Urbanization
RCPs
Mixed C-R & I-R
SSPs
RCP8.5
RCP6.0
RCP4.5
RCP2.6
Design storm
Land uses
Pollutant loads
LID measures
SSP1
SSP2
SSP3
SWMM
Peak of runoff and pollutant loads simulated
Relative effects of SSP and RCP
Performance of LID measures
Base scenario
SSP1-RCPs
SSP2-RCPs
SSP3-RCPs
Base scenario
RCPs
SSPs
RCPs-SSPs
RCP6.0-SSP1
RCP6.0-SSP2
RCP6.0-SSP3
RCP8.5-SSP2
RCP6.0-SSP2
RCP4.5-SSP2
RCP2.6-SSP2
RCPs-SSPs
RCPs-SSPs (without LID)

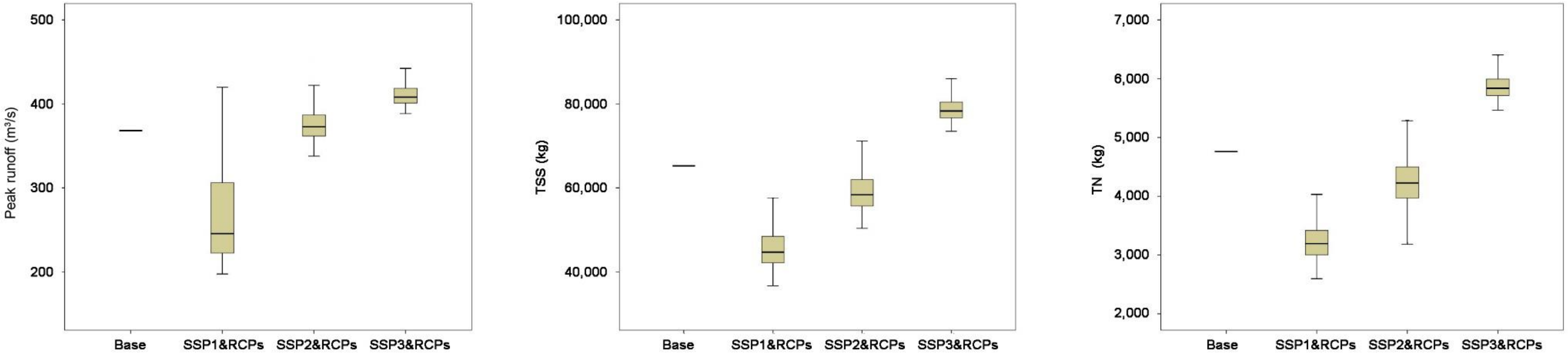
Fig. 1.



65
60
55
50
45
40
Peak runoff (m³/s)
Base
SSP1&RCPs
SSP2&RCPs
SSP3&RCPs
12,000
10,000
8,000
6,000
4,000
TSS (kg)
Base
SSP1&RCPs
SSP2&RCPs
SSP3&RCPs
1,000
800
600
400
TN (kg)
Base
SSP1&RCPs
SSP2&RCPs
SSP3&RCPs

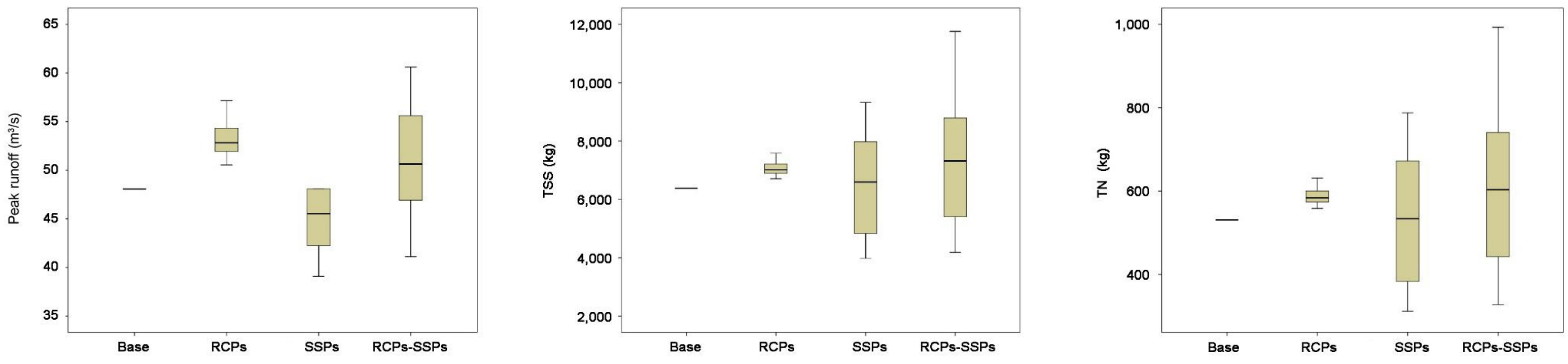
a) **b)** **c)**

Fig. 2.


500
400
300
200
Peak runoff (m³/s)
Base
SSP1&RCPs
SSP2&RCPs
SSP3&RCPs
100,000
80,000
60,000
40,000
TSS (kg)
Base
SSP1&RCPs
SSP2&RCPs
SSP3&RCPs
7,000
6,000
5,000
4,000
3,000
2,000
TN (kg)
Base
SSP1&RCPs
SSP2&RCPs
SSP3&RCPs

a) b) c)

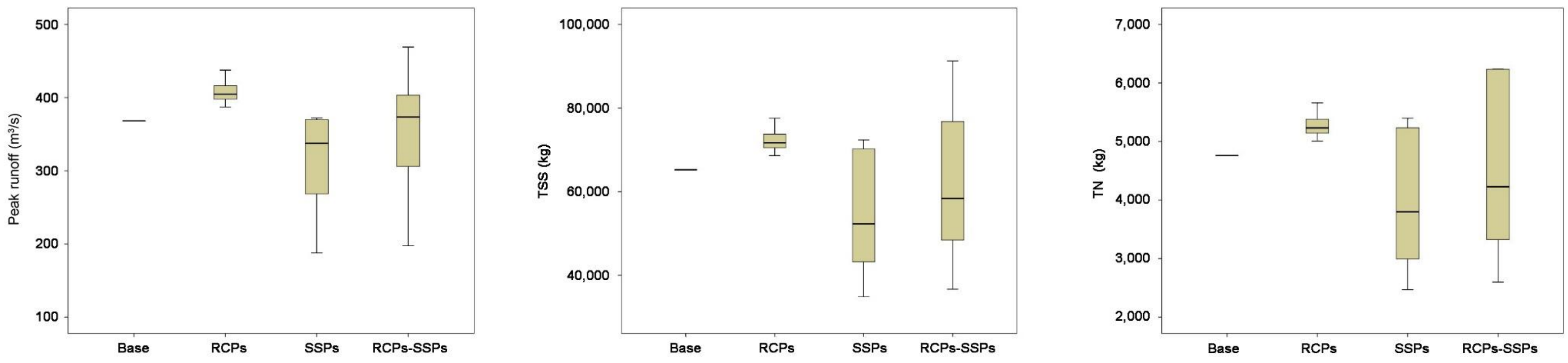
Fig. 3.



Peak runoff (m³/s)
65
60
55
50
45
40
35
Base
RCPs
SSPs
RCPs-SSPs
TSS (kg)
12,000
10,000
8,000
6,000
4,000
2,000
Base
RCPs
SSPs
RCPs-SSPs
TN (kg)
1,000
800
600
400
Base
RCPs
SSPs
RCPs-SSPs

a) b) c)

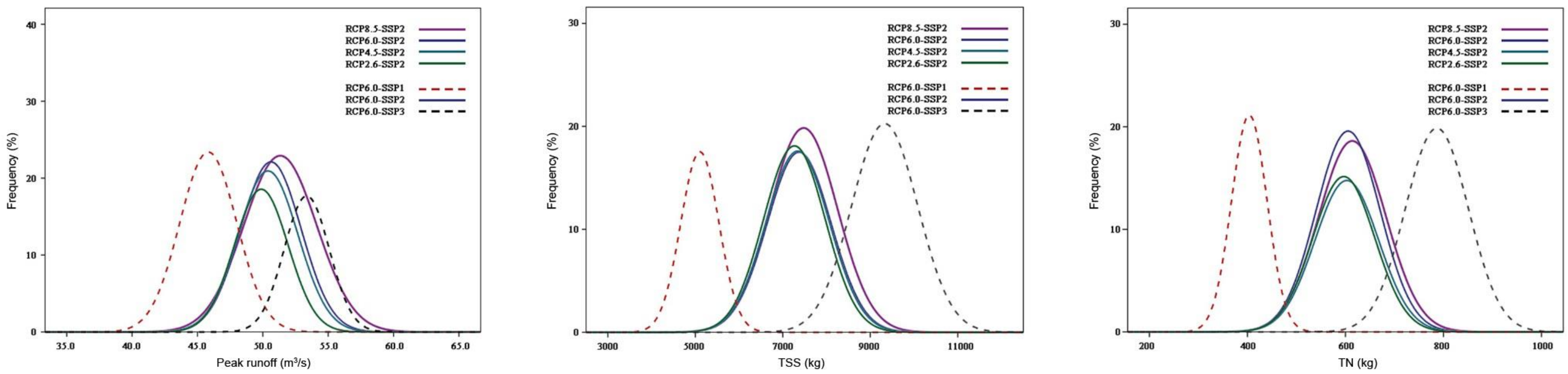
Fig. 4.



Peak runoff (m³/s)
500
400
300
200
100
Base
RCPs
SSPs
RCPs-SSPs
TSS (kg)
100,000
80,000
60,000
40,000
Base
RCPs
SSPs
RCPs-SSPs
TN (kg)
7,000
6,000
5,000
4,000
3,000
2,000
Base
RCPs
SSPs
RCPs-SSPs

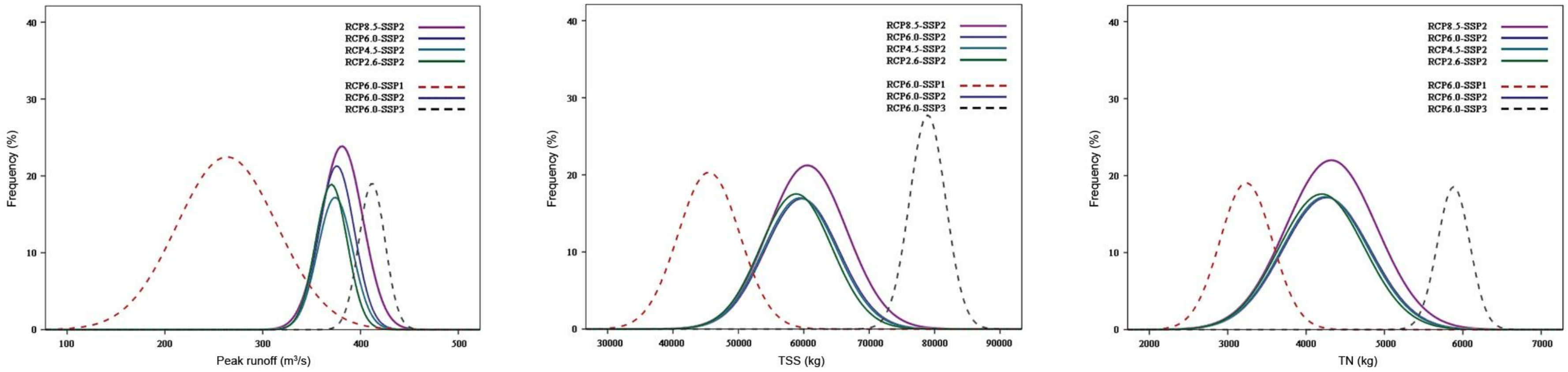
a) b) c)

Fig.5.


RCP8.5-SSP2
RCP6.0-SSP2
RCP4.5-SSP2
RCP2.6-SSP2
RCP6.0-SSP1
RCP6.0-SSP2
RCP6.0-SSP3
Frequency (%)
Peak runoff (m³/s)
TSS (kg)
TN (kg)

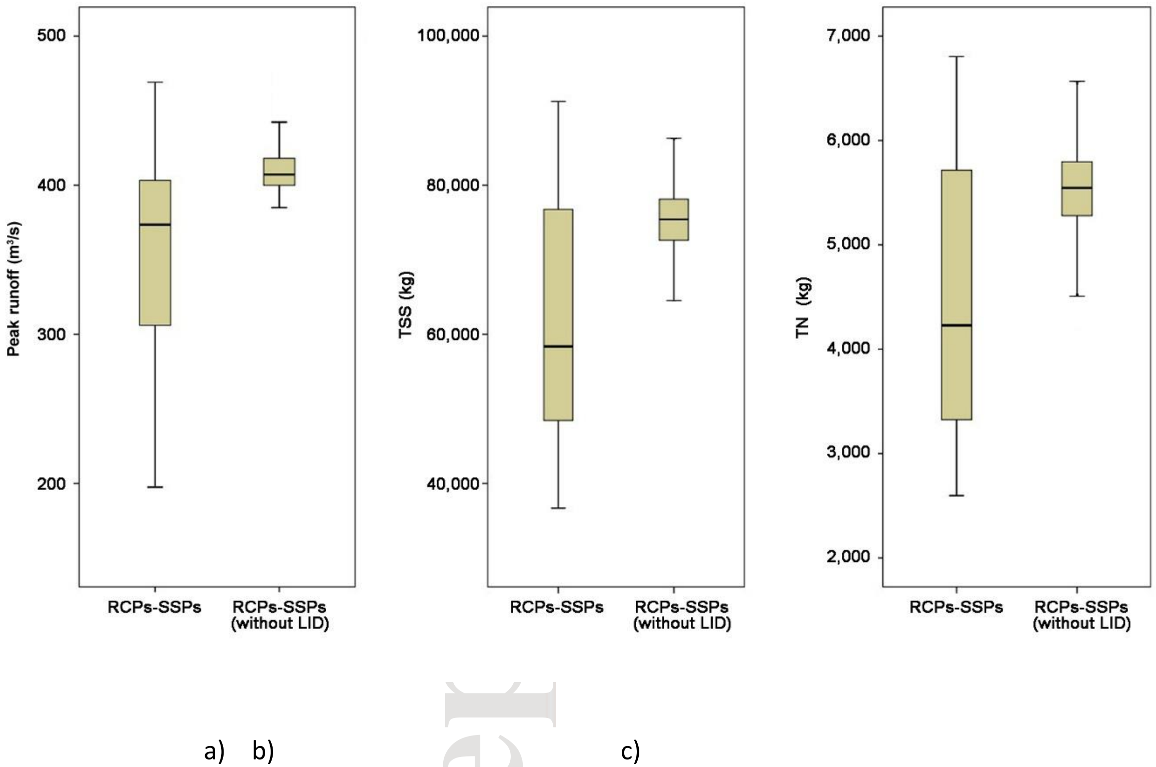
a) **b)** **c)**

Fig. 6.


RCP8.5-SSP2
RCP6.0-SSP2
RCP4.5-SSP2
RCP2.6-SSP2
RCP6.0-SSP1
RCP6.0-SSP2
RCP6.0-SSP3
Frequency (%)
Peak runoff (m³/s)
TSS (kg)
TN (kg)

a) b) c)

Fig.7.



Peak runoff (m³/s)
500
400
300
200
RCPs-SSPs
RCPs-SSPs (without LID)
TSS (kg)
100,000
80,000
60,000
40,000
RCPs-SSPs
RCPs-SSPs (without LID)
TN (kg)
7,000
6,000
5,000
4,000
3,000
2,000
RCPs-SSPs
RCPs-SSPs (without LID)
a) b) c)

Fig. 8.