Flooding Control and Hydro-Energy Assessment for Urban Stormwater Drainage Systems under Climate Change: Framework Development and Case Study

Huan-Feng Duan[1] • Xichao Gao [1,2]

Abstract:

Flooding issue and energy shortage have become the common concerns impeding the urban development under climate change scenarios. Exploiting potential hydro-energy from urban stormwater drainage system (USDS) has multiple beneficial perspectives for controlling flooding, relieving energy shortage and mitigating the greenhouse gases emission, which has not yet been systematically investigated in previous works. In this paper, a systematical analysis framework is developed to design the flooding risk control measures and to assess the feasibility and capacity of the hydro-energy development in USDS. The GCMs and HBV models, integrated within the SWMM computation platform, are adopted to simulate the hydrological and hydraulic processes during rainfall events, with the results used to manage the flooding situation and evaluate the energy generation capacity under the influences of both historical and future climate changes. The framework is then applied to a practical case in Tung Chung town of Hong Kong. The analysis result shows that, in the studied area, it is significant and worthwhile to develop the hydro-energy in USDS, which is evidenced to be beneficial to the energy generation and the flooding risk control as well as water resources management in the urban drainage system. The

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developed method and obtained results of this study may provide a new perspective and technical guide for effective USDS management and operation.

Keywords: Climate change · Detention tank · Flooding control · Hydro-energy · Urban stormwater drainage system (USDS)

1. Introduction

The survival of mankind on the earth has become more and more crucial due to many natural and artificial influence factors, such as climate change (global warming), natural disasters (flooding and earthquake), and resources deficits (water and energy) (Rojas et al., 2013; Madsen et al., 2014; Shadman et al., 2016). As the consequences of these influence factors, many issues such as urban flooding, extreme weather and water/energy shortage have become more and more frequent and serious in the world (Nie et al., 2009; Schaeffer et al., 2012; Huong and Pathirana, 2013; Bartos and Chester, 2015; Fortier and Mailhot, 2015; DeNooyer et al., 2016; Fernández-Blanco et al., 2017; Sahin et al., 2017). Therefore, it is necessary and important for the mankind to take advantages of the beneficial characteristics of these impact factors, and meanwhile, to handle well their conflicts in terms of their detrimental influences to the global system.

On one hand, various observations and occurrences have evidenced that climate change worldwide may cause great of impacts on the living systems on the earth, including warming atmosphere and ocean, diminishing snow and ice, and rising sea level (IPCC, 2014). The analysis results in the literature have also demonstrated that a global warming climate might decrease the temperature difference between the poles and the equator which may lead to the decrease of the number of storms, and meanwhile, it could also increase the intensity and frequency of extreme storms because of the increased water evaporation into the atmosphere due to the overall temperature increase (NASA, 2018). Specifically, the study by Chen (2013) based on 16 simulations from the CMIP5 (the Couple Model Inter-comparison Project 5 Phase) in different regions of China has indicated the trend of more and more extreme rainfall events resulted from the significantly increased annual precipitation by the end of the 21st century under a global warming scenario. Besides, the duration and intensity of extreme storms (i.e., the number of heavy rainfall days) are also supposed to increase significantly, which will cause severer stormwater volumes and peak flows, and thus aggravate urban flood risks in these regions. Moreover, due to the rapid urbanization worldwide, the greatly increased emission of anthropogenic waste heat has caused the fast change of surface heat budget which may result in increasing rainfall intensity (Aikawa et al., 2009; Huong and Pathirana, 2013). Under this situation, the urban drainage systems, which were designed originally to meet historically common climate conditions, will become incapable or inefficient to solve the urban drainage problems. As a result, flooding disasters and the associated issues may occur frequently in current urban regions such as traffic interruption, economic loss, pollution and health issues. From this perspective, it is crucial to investigate the hydrological process and flooding issues in urban drainage systems under the global climate change and the local atmospheric variation.

On the other hand, water and energy shortage has become more and more serious, which is another critical challenge in the world. Under such background, renewable resources become a preferable choice to against the adverse situations resulted from the water and energy wastage, such as ecological damage and pollution. To this end, hydropower is one of these renewable energy forms, which plays more and more important role in the energy utilization (Huang and Yan, 2009; Chang et al., 2010; Dursun and Gokcol, 2011; Xingang et al., 2012; Zarfl et al., 2015). On this point, the small hydropower (SHP) has become more and more popular and useful to urban energy systems, which takes use of the stormwater control facilities to generate energy in the urban drainage system. Actually, the development of SHP is first beneficial to the control and management of flooding issues resulted from the global climate change as mentioned above, e.g., reducing the peak flowrate and velocity by flow buffering and energy dissipation (Sima and Lar, 2014; Sahin et al., 2017). Meanwhile, the application of SHP is also helpful to climate change mitigation and security of energy supply, considering the fact that one GWH of energy from SHP is equivalent to a reduction of carbon dioxide emissions of 480 tons (Shapes, 2010).

In fact, the development of hydropower converters for low head differences has been widely promoted to exploit the energy created by small waterfalls or in water supply systems (Nautiyal et al., 2010; Shapes, 2010; Ramos et al., 2013; Lydon et al., 2017). Moreover, the feasibility of small hydropower has also been explored in the urban drainage system by some research groups. European Small Hydropower Association (ESHA) has formulated a handbook for SHP in which theoretical measures and practical procedures are provided to develop micro hydropower facilities (Penche, 1998). Waze and Ahmed (2009) studied the feasibility of micro hydropower generation at Sapchari Waterfall, and it was concluded that the building of micro hydropower facilities has few effect on the ecosystem of the area. Thereafter, the energy generation and utilization in urban drainage systems have also been assessed by Romas et al. (2013) and Kamal et al. (2014). Redpath and Ward (2015) investigated the potential of low head hydro power in Northern Ireland from a perspective of economic viability with some economic indicators such as Simple Payback Periods (SPP), Net Present Values (NPV) and Benefit Cost Ratios (B/C). Zema et al. (2016) provided a simple method to evaluate costs and incomes for MHP plant design in existing irrigation systems and verify the method in an irrigation system of a WUA in Calabria. The method is easy to implement with less easy-to-survey input parameters but might cause inaccurate results because of the simplistic method used to evaluate the hydrological processes.

Furthermore, Bayazıt et al. (2017) explored plausible sites for SHP in Bilecik region by geographic information system and distributed hydrological model. The method can determine the points having hydro power potential quickly compared to other methods. But the result depends on the accuracy of digital elevation model (DEM) and need to be compared with the sites selected by observation in the region. Bousquet et al. (2017) proposed a GIS-based method to assess the potential for hydropower in wastewater systems, considering two operation type: upstream and downstream of wastewater treatment plants (WWTPs). Meanwhile, a methodological guide for the feasibility studies of the micro hydro power plants in Cameroon was established by Signe et al. (2017) based on the case study of the fall river of KEMKEN. Du et al. (2017) assessed the hydro power generation using pump as turbines in the water supply system of one individual high rise building and the head reduction effect. Despite that many previous studies have focused on the SHP development in water supply systems, irrigation systems and natural rivers, they are mainly from a perspective of economic and social viability. Moreover, most of these studies are performed for previous and/or current climate scenarios, while very few are for the framework development and evaluation of the SHP implementation and performance in urban stormwater drainage system (USDS), especially under the influences of global climate change and local system conditions.

This study aims to develop a systematical analysis framework to design and assess the feasibility and capacity of the SHP development in the USDS under the flooding control measurements of detention ponds. In the framework development, the GCMs and HBV model, integrated within the SWMM computation platform, is adopted to simulate the hydrological and hydraulic processes during rainfall events, as well as to evaluate the energy generation capacity. The developed framework is then applied and validated through a practical case study in Tung Chung town, Hong Kong. From the application, the obtained results are used to systematically analyze the possibility, feasibility, and capacity of SHP development as well as the flooding control and management in this region. Finally, the findings and practical implications of this study are discussed and summarized in the end of the paper.

2. Study Area and Data Collection

A practical urban area – Tung Chung town in Hong Kong – is adopted for the application study. Tung Chung town is located in the northwestern region of Lantau Island in Hong Kong with a resident population of 80,000 and area of 1.68 km^2, connecting Lantau Island with Chek Lap Kok airport. This area is selected for the investigation because it is a newly developed town, and its target population will be grown up to 275,000 for the future development plan, with achieving a multi-function town. The current land use and the drainage system are shown in Figure 1 below, with most of the area developed for residential and commercial use.

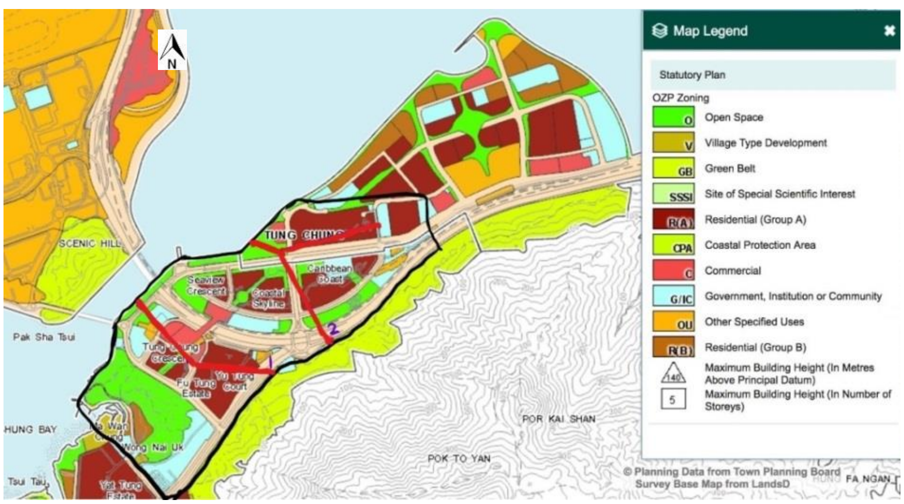


Figure 1. Land use and existing drainage system of Tung Chung town (Bold black lines represent for the studied urban area borders and Red lines for main drainage conduits).

With regard to the geographic environment, Tung Chung is a typical coastal town in Hong Kong with three sides surrounded by hilly land, and the elevation varying from 0 to 500 meters. From this perspective, this region is a low-lying land within the district. With regard to the existing drainage system of this focused region, there are two main channels that collect the stormwater and the directly drain to the sea. With regard to the climate environment, Tung Chung region lies in the humid subtropical climate zone, where summer is humid and hot while winter is dry and cool. The mean annual rainfall in this area is about 2400 mm and the average rainy days is 138 days from the official statistical record (HKO, 2017). Accordingly, the record shows that the average temperature of this region is about 21-25 0C, and the maximum temperature is around 40 0C. Other information about hourly rainfall and detailed drainage system network as well the land use of this town are available from the relevant offices of Hong Kong Government.

It is worthy of noting that urban flooding disasters and associated issues are common and have become challenging during specific seasons (e.g., summer) and under some extreme conditions (e.g., typhoon) (Yim, 1996; Yang et al., 2015). Therefore, it is necessary to evaluate first the flooding risks and controls under the above-mentioned urban development and drainage system conditions, in order to better conduct the assessment of hydro-energy generation and utilization later in this USDS, which is the scope and objective of this paper work.

3. Model and Method

As stated above, the flooding risks and associated control measurement as well as the potential of hydro-energy generation are evaluated for the focused urban drainage system in Tung Chung town of Hong Kong. Therefore, both the hydrological-hydraulic models and the water-energy nexus relation are required for this study. Specifically, the coupled model of the HBV1 for rainfall-runoff process and the SWMM for hydraulic drainage and potential flooding evolution is used for the numerical simulation for specific rainfall events under the influence of either historical or future climate change. As for the flooding control and management, the measure of detention tanks is adopted and designed to regulate the runoff process and meanwhile, to improve hydro-energy generation through water energy nexus relation. The application procedure of this proposed methodology framework can be illustrated by the flowchart in Figure 2.

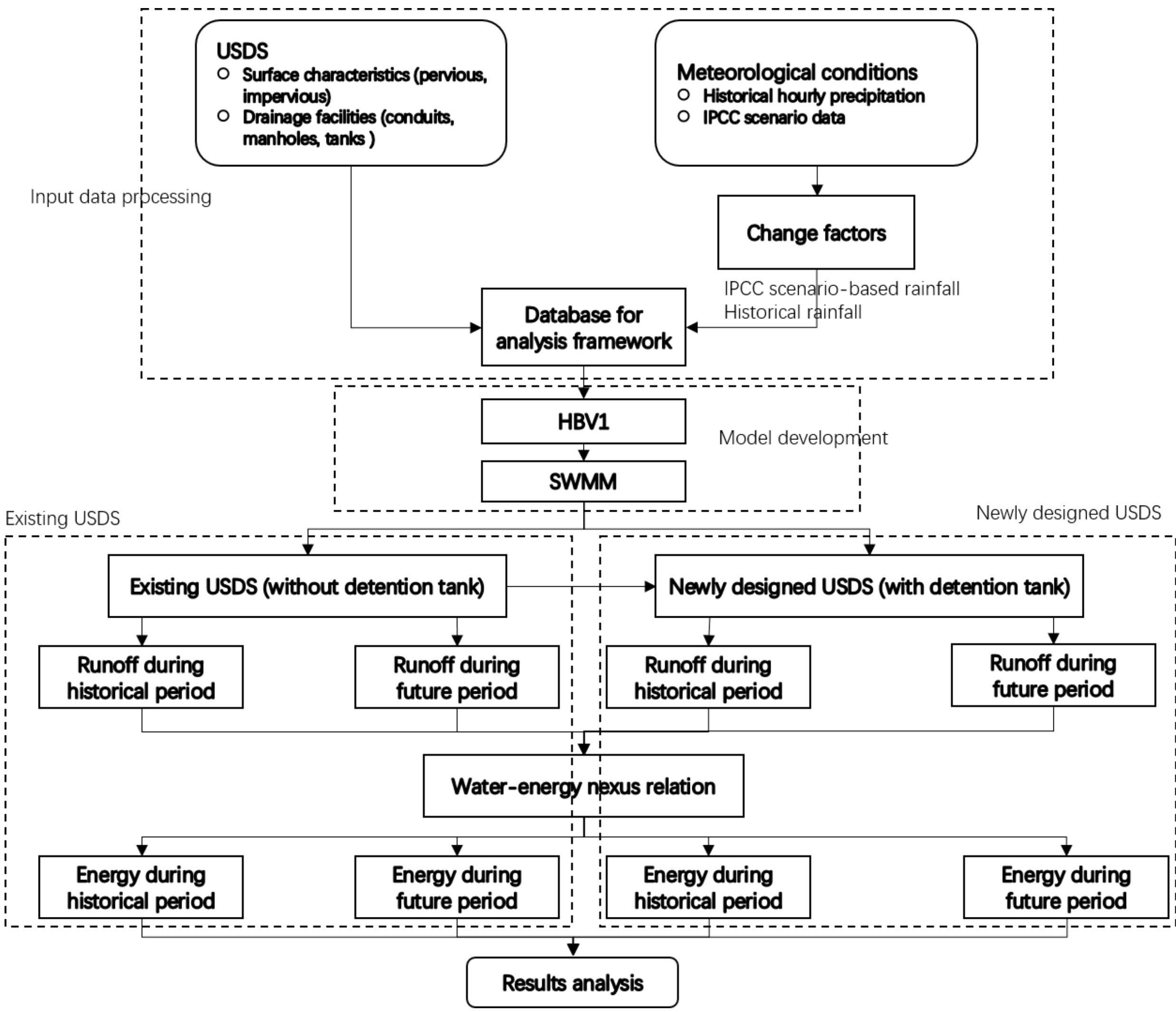


Figure 2. Flowchart and procedure of the developed method framework.

3.1. HBV Model for Rainfall-Runoff Process

The HBV model is a semi-distributed conceptual model for the rainfall-runoff simulation, which was developed by Bergström (1992). This model has advantages of simple structure and catchment division (including sub-basins, elevation and vegetation zones). Moreover, it consists of several subroutines: a precipitation and snow accumulation and melt routine, a soil moisture accounting routine, two runoff generation routines and a routing procedure (Tian et al., 2013), and thus has been applied widely by both researchers and engineers with provided good results in most cases (Kobold and Brilly, 2006). The input data of HBV model includes time series of precipitation, air temperature and PET, while the output is the runoff process.

Table 1. Main parameters of HBV1 model

Parameter	Explanation	Minimum	Maximum	Value
FC	Maximum soil moisture capacity	100	500	140
LP	Soil moisture threshold for reduction of evapotranspiration	0.3	1	0.88
BETA	Shape coefficient	1	5	1.8
CFLUX	Maximum capillary flow from upper response box to soil moisture zone	1	2	0.27
ALFA	Measure for non-linearity of low flow in quick runoff reservoir	0	1	0.06
KF	Recession coefficient for quick flow reservoir	0.01	0.5	0.13
KS	Recession coefficient for base flow reservoir	0.001	0.1	0.028
PERC	Maximum flow from upper to lower response box	0	6	3.5

In this study, the HBV model will be used to simulate the runoff process from the Lantau Island to the drainage system (see Figure 1). Because the spatial distribution of climatological and geographical characteristics of the study area are relatively evenly and the purpose of the hydrologically modeling is to offer boundaries to the hydraulic modeling, there is no sub-catchment division for the studied case with relatively small-scale drainage system for this newly developed town. Besides, the snow routine will not be used in the study considering the local temperature. It is also noted that this used HBV model has been well calibrated and verified by practical data collected under the similar scenarios for its parameters and configurations prior to its application to the systematical analysis of this study, to compensate for the deficiency of runoff data in this study area. The main parameters of the model are shown in table 1.

3.2. SWMM for Hydrologic-Hydraulic Simulation

The Storm Water Management Model (SWMM), developed by EPA-US, is a dynamic rainfall-runoff flow model used for single-event or long-term continuous simulation of runoff quantity and quality for USDS. The SWMM platform includes both hydrological and hydraulic components for the generation, transportation, evolution and management of stormwater in USDS (Tsihrintzis and Hamid, 1998; Liu et al., 2006; Jang et al., 2007; Burszta-Adamiak and Mrowiec, 2013).

In this paper, the SWMM model will be used to simulate the runoff process of stormwater in the drainage system of Tung Chung and to access the reliability of the existing drainage system under historical and future extreme precipitation conditions. Specifically, according to the present drainage system plan of the Tung Chung town from the drainage services department (DSDHK, 2017) of Hong Kong, the study area in Figure 1 is divided into 14 sub-catchments with sub-area ranging from 3.9 to 41.7 hectares and each sub-catchment is linked to the manhole junction of the drainage network. A simplified schematic of the studied system configuration by SWWM is shown in Figure 3. Because of the deficiency of runoff data in the study area of this newly developed town, the HEC-HMS results are used herein to verify the results of the SWMM model.

The Nash coefficient is used to assess the consistency of the daily runoff of the outlet simulated by SWMM and HEC-HMS. As a result, the flow hydrographs of the two models are shown in Figure 4, with the Nash coefficient of 0.98, which demonstrates the good agreement of these two model results.

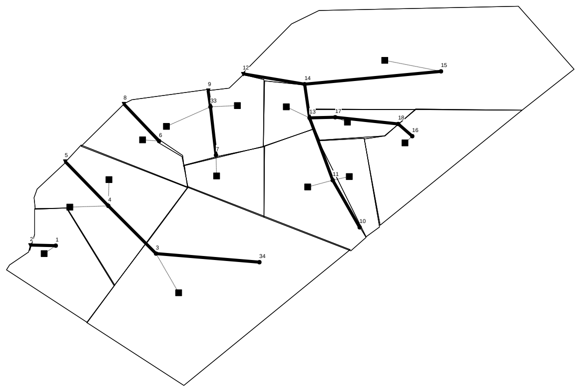


Figure 3. Simplified system configuration for SWMM (Only drainage mains shown).

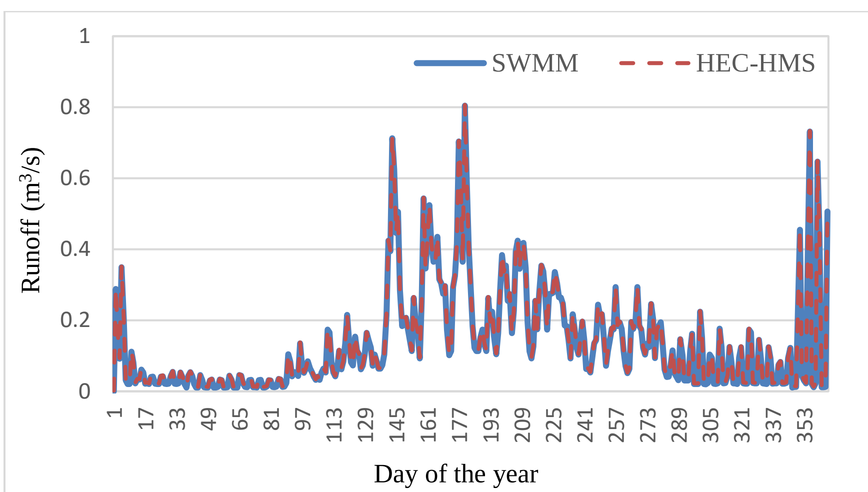


Figure 4. Flow hydrograph of SWMM and HEC-HMS for one year.

3.3. Climate Change Model

Under the new greenhouse gas (GHG) emission scenarios termed "Representative Concentration Pathways (RCPs)", the CMIP5 has simulated the historical climate of the 20th century and projected the future climate of the 21st century (Taylor et al., 2012). RCPs represent classes of mitigation scenarios that produce emission pathways following various assumed policy decisions that would influence the time evolution of the future emissions of GHGs, aerosols, ozone, and land use/land cover changes. According to a number of model simulations by the CMIP5, the investigation results by the Hong Kong Observatory (HKO, 2017) has demonstrated that, under the high greenhouse gas concentration scenario (RCP8.5), the number of extremely wet years is expected to increase from 3 during 1885-2005 to about 12 during 2006-2100. Meanwhile, annual rainfall in late 21st century is expected to rise by about 180mm when compared to the average during 1986-2005.

In this study, the BCC_CSM1.1 model from Beijing Climate Centre (Xin et al., 2013) is used for the future climate change projections in the case study of Hong Kong. Multiplicative change factors (CFs), which are obtained from the GCM through dividing future period (2070-2100) precipitation by baseline (1980-2010) precipitation under four different GHG emission scenarios (i.e., RCP2.6, RCP4.5, RCP6.0, RCP8.0), are applied to the baseline observed precipitation for predicting the future period precipitation. Specifically, this CF method assumes that the GCM produces a reasonable estimate of the relative change in the value of precipitation. This method can be applied with following procedure: (1) estimate the mean values of the GCM baseline and future climates for a selected temporal domain; (2) calculate multiplicative change factors; and (3) obtain local scaled future values by applying CFs (Anandhi et al., 2011). Mathematically,

$$
\begin{aligned}
&\overline{GCMb} = \sum_{i=1}^{Nb} GCMb_i / Nb \\
&\overline{GCMf} = \sum_{i=1}^{Nf} GCMf_i \, / \, Nf \\
&CF_{mul} = GCMf \, / \, GCMb \\
&LSf_{mul,i} = LOb_i \times CF_{mul}
\end{aligned}
\tag{1}
$$

where $GCMb$ and $GCMf$ represent the values from the GCM baseline and GCM future climate scenario respectively; $\overline{GCMb}$ and $\overline{GCMf}$ are the mean values from a GCM baseline and GCM future scenario for the designated temporal domain; Nb and Nf are the number of values in the temporal domain of the GCM baseline and GCM future scenario, respectively; CF_{mul} is the multiplicative change factor; LOb is observed value of the meteorological variable; and LSf is the variable value of future scenarios obtained from multiplicative change factors. In this study, CFs were calculated monthly for the whole period of case study.

3.4. Flood Control and Management Framework

For flooding risks assessment, the number of flooding manholes, the total flood duration and the total volume of flood water spilling from the flooding manholes is selected as assessment indicators. The observed baseline (2006-2015) hourly precipitation and the future scenarios hourly precipitation (2091-2100) obtained by above CFs to the baseline data are applied to run the HBV1 model and the SWMM model. The time resolutions of hydrological calculation and flow routing are set to be 1 hour and 1 minute respectively, and the dynamic wave method is used for the drainage flow routing.

Under the flooding circumstance, it is expected to design relevant facilities to prevent the adverse situation. In this paper, the detention tank, which is the most commonly used measure in Hong Kong, is designed in the drainage system for the flooding control and management. To obtain an optimal effect, a multi-objective optimization method developed previously by the authors (Li et al., 2015; Duan et al., 2016) is adopted and incorporated in the SWMM model for the design and application of the detention tanks in USDS. For simplicity and illustration, the design criteria and parameters from these studies are also used in this study. More details on the design method and optimization framework can refer to these previous studies.

3.5. Water-Energy Nexus for Hydro-Energy Generation

Apart from the flooding risk and management, it is necessary and important to evaluate the energy generation and utilization in stormwater drainage systems, especially under the influence of climate change (Bailey and Bass, 2009; Wazed and Ahmed, 2009; Kamal et al., 2014). According to basic physics laws, the energy available in the drainage water flow is related to two factors: head difference (also effective head) and flowrate. The relationship (nexus) between the potential energy and the drainage water characteristics can be expressed as follows:

$$P = \eta \rho g Q H \tag{2}$$

where

$$\begin{aligned}
&P = \textit{power} \\
&\eta = \textit{hydraulic efficiency of the turbine} \\
&\rho = \textit{density of water} \\
&g = \textit{gravitational cons} \\
&Q = \textit{volumetric flow} - \textit{rate} \\
&H = \textit{gross head}
\end{aligned}$$

In this study, the volumetric flowrate is obtained from the SWMM model under the specific conditions of climate change and drainage system. For case study, it is assumed that: (1) the effective head of drainage water flow for energy generation by the SHP turbine is 5.5 m, based on a comprehensive consideration of the local conditions and design criteria in this region (e.g. topography of discharge area, pipeline condition, and land use plan, etc.); and (2) the overall hydraulic efficiency of the SHP turbine is 70% by considering various forms of energy loss during energy conversion (Penche, 1998).

It is necessary to note that the objective of this study is to study the feasibility and capacity of the hydro-energy generation in the focused USDS. Therefore, only the input-output energy generation results based on above water-energy nexus relationship are examined in this case study, while the development of the details of SHP facilities (e.g., type design, test and manufacture (Chen et al., 2013) is out of the scope of this study and will be investigated in future work.

4. Results and Analysis

The developed framework and method above in this study is applied to the realistic case of Tung Chung Town in Hong Kong as depicted in Figure 1. The flooding risk under the existing drainage conditions is firstly analyzed for typical scenarios under the influence of climate change. To prevent the flooding risk, relevant measure of detention tanks is designed based on the above-mentioned optimization method and applied to this practical drainage system. On this basis of the design results, the hydro-energy generation capacity in this system is then assessed systematically for various scenarios of rainfall-runoff and drainage process under the influence of climate change.

4.1. Flood Control under Existing Drainage Condition

Since this study is aimed to evaluate the capacity of the drainage system to resist flooding in specific rainfall events, the magnitude and duration of possible flooding results, rather than the flooding frequency, are focused and extracted from the simulation model. To this end, the use of CFs to predict future period precipitation becomes reasonable for the case study. Based on the available data from HKO department for the studied system in Figure 1, the monthly CFs and seasonal CFs for the four RCPs (Xin et al., 2013) are obtained based on Eq. (1) and the results are shown in Table 2 and Table 3 respectively. In general, the results demonstrate that, compared to the baseline period, there is not clearly monotonic change trend (increase or decrease) for the precipitation of future period under both monthly and seasonal CFs (Figure 5 and Figure 6).

However, it is also observed from these two tables that the precipitation will become more seasonally distributed at the end of 21st century. In particular, for all the scenarios of the used RCPs, the precipitation of spring will experience obviously monotonic increase, and the precipitation under the RCP8.0 scenario will increase most significantly. Moreover, the precipitation under RCP2.6 scenario will increase for all the four seasons, although the increasing trend is more obvious in spring and fall. While for the RCP4.5, the RCP6.0 and the RCP8.0 scenarios, the precipitation shows a decreasing trend in the other three seasons (summer, fall, and winter) except the precipitation of fall under the RCP6.0 scenario. From the statistical results of standard deviation in Table 3, it reveals that the CFs of the RCP8.0 scenario has the largest standard deviation, meaning that the time distribution of precipitation under this RCP scenario is the most uneven while it is less distributed under the RCP2.6 scenario. To conclude, the annual precipitation in this region does not have a significant trend in the future period studied herein compared to the baseline period, but it will become more seasonally distributed. Actually, this result is consistent with the findings in the previous studies for this region (Ying and Chong-Hai, 2012; Chen, 2013).

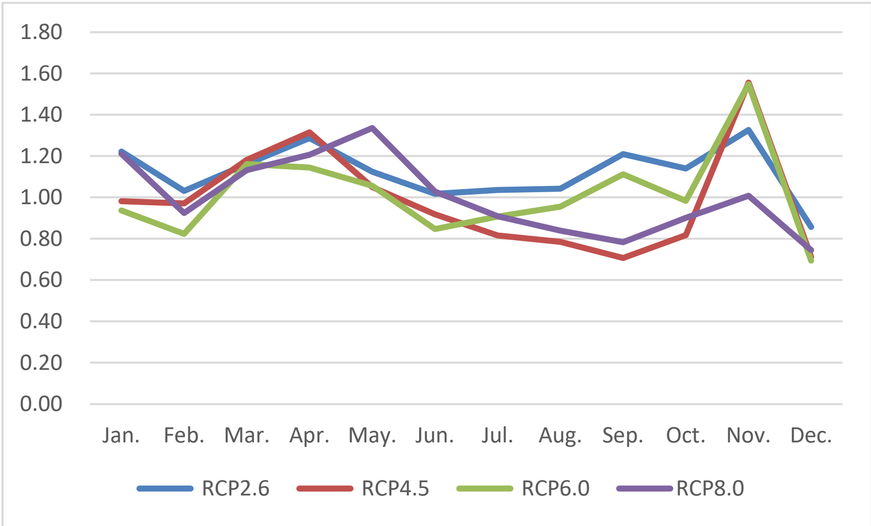


Figure 5. Monthly CFs.

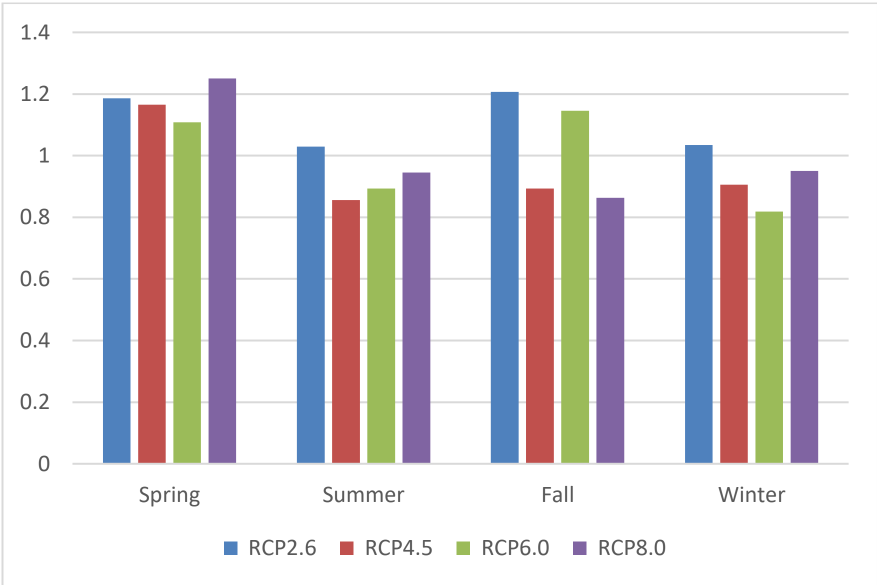


Figure 6. Seasonal CFs

Table 2. Results for monthly CFs.

Month	RCP2.6	RCP4.5	RCP6.0	RCP8.0
January	1.222262	0.981357	0.937674	1.212315
February	1.031475	0.970561	0.82372	0.924786
March	1.162282	1.181638	1.162335	1.132198
April	1.287998	1.31568	1.144819	1.206874
May	1.124212	1.050022	1.057211	1.33642
June	1.0179	0.91887	0.84754	1.02841
July	1.03691	0.816963	0.90718	0.9089
August	1.042155	0.785672	0.956482	0.840182
September	1.209712	0.70724	1.11243	0.783038
October	1.139724	0.817688	0.983206	0.901944
November	1.32675	1.556278	1.548453	1.009037
December	0.857495	0.713029	0.694476	0.745328

Table 3. Results for seasonal CFs. (Std. = standard deviation)

Season	RCP2.6	RCP4.5	RCP6.0	RCP8.0
Spring	1.186367	1.165455	1.108192	1.250828
Summer	1.029572	0.855629	0.893048	0.945474
Fall	1.206628	0.893344	1.145293	0.862762
Winter	1.034012	0.906189	0.818638	0.950162
Std.	0.082678	0.122831	0.138603	0.147635

To assess the flooding risk in this region, the rainfall-runoff simulations under the above obtained participation results are performed based on the procedure in Figure 2 for both the historical period from 2006 to 2015 (10 years) and the future period from 2091 to 2100 (10 years) under four RCP scenarios indicated above. Note that in this region (Tung Chung town), the stormwater drainage system is separated from the domestic sewage, and therefore, the latter part will not be considered in this study.

Under the existing drainage condition without detention tanks, the flooding assessment results of the three specified indicators – the number of flooding manholes, the total flood duration and the total volume of flood water – are summarized in Table 4. The results in Table indicate clearly the flooding risks for all both historical and future periods in this system without any detection tank protection. Moreover, compared to the historical flooding results, the predicted flooding risks for the future period will be potentially increased or decreased with different extents for different RCP scenarios, by referring to different change percentages in the blankets in Table 4. This result implies clearly a high dependence of the storm pattern and flooding risks on the climate change.

Table 4. Indicators of the drainage case without detention tanks (the numbers in brackets are relative changes related to the historical period).

Indicators	**historical**	**RCP2.6**	**RCP4.5**	**RCP6.0**	**RCP8.0**
No. of flooding manholes	3	3	3	3	3
Flooding duration	53.1	75.6 (42.4%)	46.6 (-12.2%)	46.6 (-12.2%)	66.5 (25.2%)
Total flood water	1369.0	1963.6 (43.3%)	1309.2 (-4.4%)	1117.1 (-18.4%)	1968.3 (43.8%)

4.2. Flood Control under Improved Drainage Condition with Detention Tanks

To improve the above-mentioned flooding situations for the future period in this region, detention tanks are designed based on the method in Duan et al. (2016) and Li et al. (2015). For illustration, the rainfall event with 50-year return period induced by above mentioned climate change of future period in this region is taken for the simulation and design. The results demonstrate that two detention tanks with dimensions of 200 m (L) × 150 m (W) × 16m (D), located at node 34 and node 10 in Fig. 2 are necessary to achieve both the elimination of flooding risks and most economic investment in this region. The size of the outlet of the first detention tank at node 34 is 2 m (H) × 1.8 m (W) and that of the second one is 1.2 m (H) × 1.0 m (W) to satisfy the capacity requirement of the system drainage. As a result, under this design condition of detention tanks, the flooding risk in this system has been totally eliminated for the specified extreme rainfall event (i.e., all the three indicators in Table 4 become zero).

4.3. Hydro-Energy Evaluation for the Studied USDS

In addition to the flooding risk reduction/elimination, another benefit of detention tanks in USDS is the energy generation and management. In this paper, the hydro-energy generation capacity based on the water-energy nexus relation in Eq. (2) is assessed for this studied system under the both cases with and without detention tanks (referred as case 1 and case 2 respectively in this study). For demonstration, the ten-year average daily runoff within the drainage system is used to evaluate the hydro-energy capacity.

By applying the method framework in Figure 2, the flow duration curves (FDCs) are obtained and plotted for both case 1 and case 2 to identify the frequency of discharge flowing into the turbine of potential SHP facility. Since a linear relationship between the energy generation and the discharge as indicated in Eq. (2), these FDCs can be used directly to obtain the frequency distribution of energy, which are plotted in Figure 7 and Figure 8 respectively. The results of Figure 7 and Figure 8 reveal very small difference of FDCs between the baseline period and the future period with different RCP scenarios for both case 1 and case 2. Specifically, the main difference occurs where the exceedance probability of flowrate is less than 20%. However, even for these main differences, the law of change for FDCs can hardly be identified.

For convenient comparison, the differences of FDCs of these two cases for both the historical period and the future period under all the scenarios are extracted and shown in Figure 9. By inspection, the main difference that the FDCs of case 1 are steeper than that of case 2 for all the scenarios occurs where the exceedance probability of flowrate is less than 40%. While for the exceedance probability greater than 40%, the FDCs of the two cases become almost coincident.

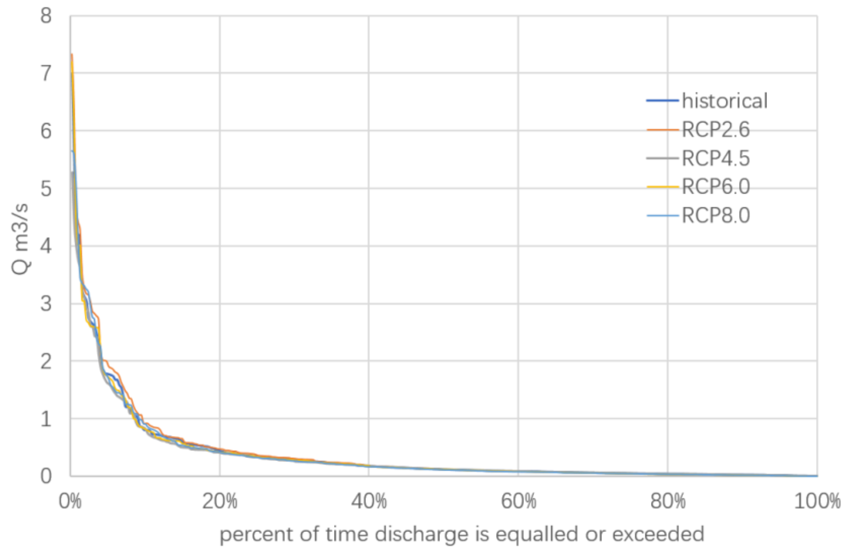


Figure 7. FDCs of case 1(without detention tanks) for the baseline and the future period.

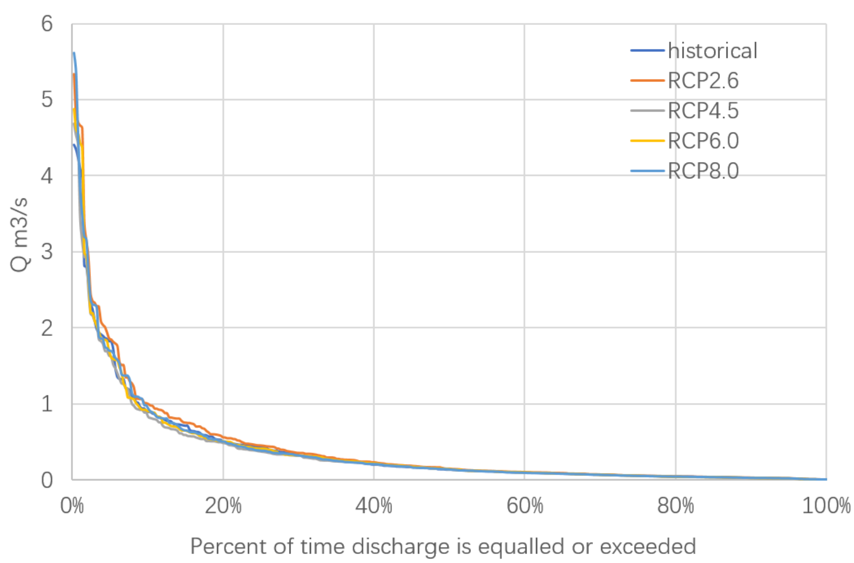
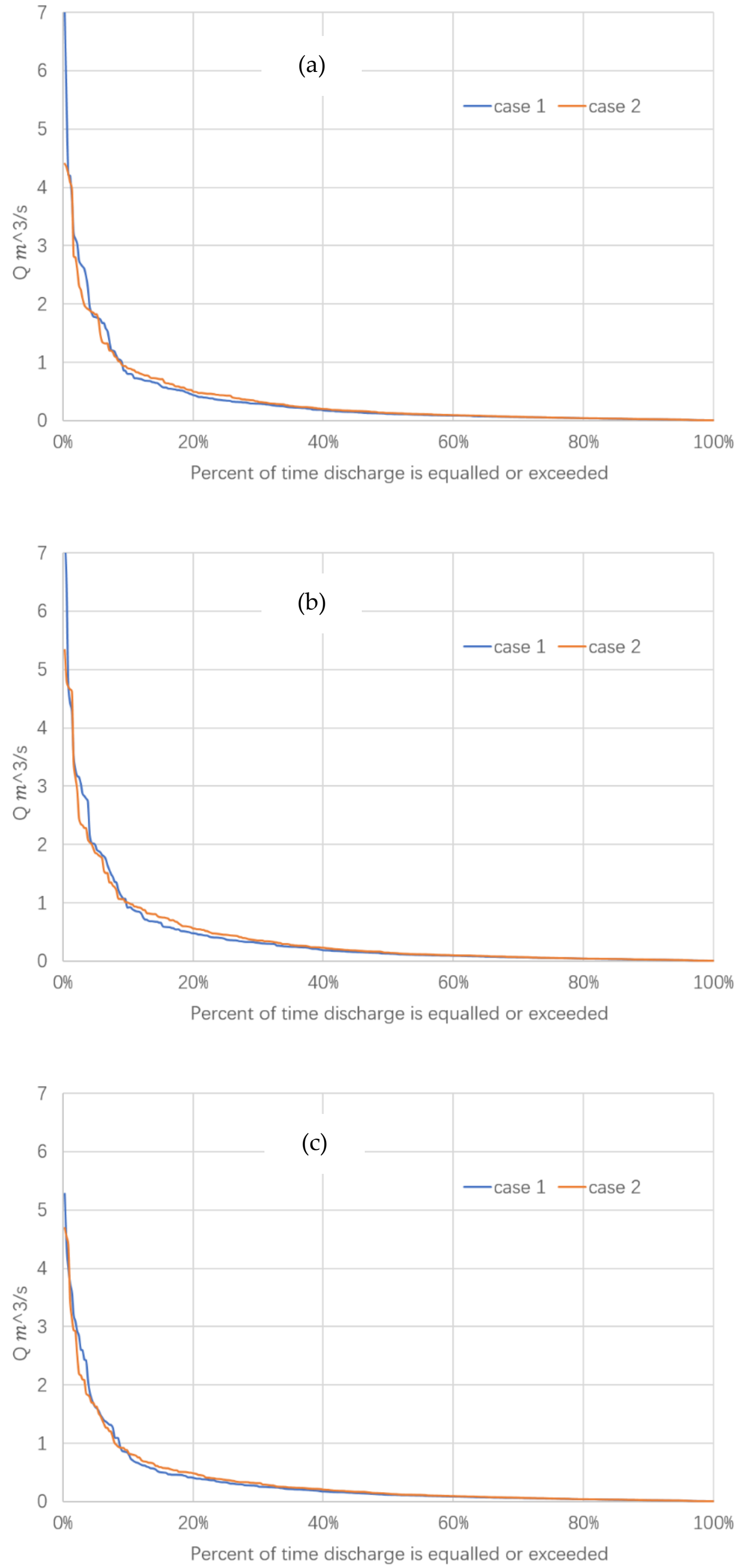
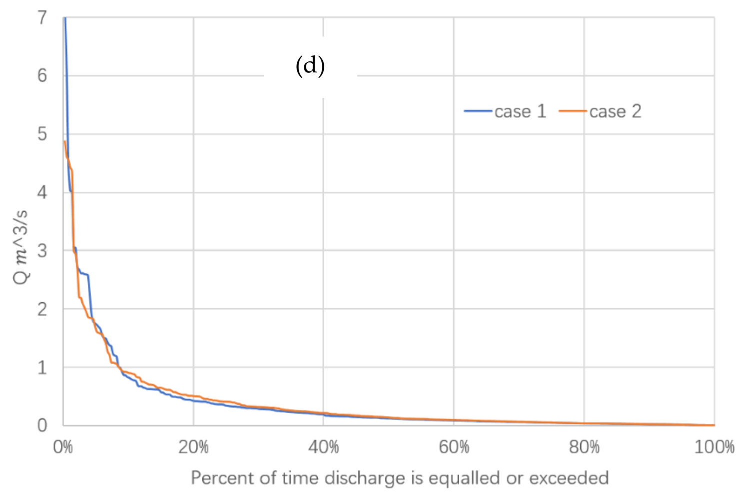


Figure 8. FDCs of case 2 (with detention tanks) for the baseline and the future period.


(a)
(b)
(c)
case 1
case 2
Q m^3/s
0
1
2
3
4
5
6
7
0%
20%
40%
60%
80%
100%
Percent of time discharge is equalled or exceeded



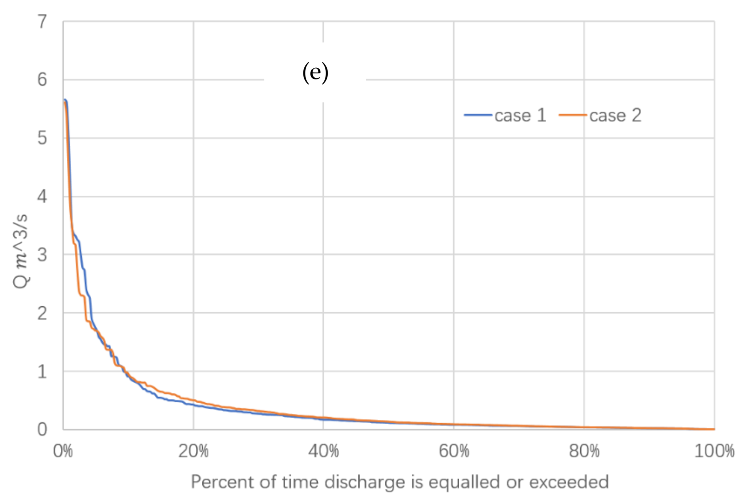


Figure 9. Comparison of flow duration curves (FDCs) of the two cases (with and without detention tanks), with sub-figs. (a), (b), (c), (d) and (e) for the historical period, the RCP2.6 scenario, the RCP4.5 scenario, the RCP6.0 scenario, and the RCP8.0 scenario respectively.

Based on the water-energy nexus relation in Eq. (2) and the results of FDCs in Figure 7 through Figure 9, the annual power of the baseline and the future period for both case 1 and case 2 can be evaluated and shown in Table 5. Compared to the baseline (historical period), the annual power of the future period has a significant change under the RCP2.6 and the RCP4.5 scenarios for these two cases (the values in the blankets in Table 5). In case 1 (without detention tanks), the annual power of the future period under the RCP2.6 scenario increases by 9.90% but decrease by -7.26% under the RCP4.5 scenario, while the annual power of the future period increases by 10.97% under the RCP2.6 scenario but decrease by -5.15% under the RCP4.5 scenario in case 2 (with detention tanks). It is also observed that the change of annual power between the baseline and the future period is relatively small for both the two cases (less than ±1.5%).

Table 5. Annual power (*KW*) for the two cases of the baseline and the future period (the numbers in brackets are relative changes related to the historical baseline).

	Historical	**RCP2.6**	**RCP4.5**	**RCP6.0**	**RCP8.0**
Case 1	14.238	15.648 (9.90%)	13.200 (-7.29%)	14.238 (-0.05%)	14.209 (-0.20%)
Case 2	14.121	15.670 (10.97%)	13.394 (-5.15%)	14.218 (0.69%)	14.408 (2.03%)
Relative change (case 2 to case 1)	-0.82%	0.14%	1.47%	-0.09%	1.40%

To further analyze, the energy generation capacity for the studied drainage system for the flow duration time (in days) of an average year is elaborated in Tables 6(a)~(e) (for case 1) and Tables 7(a)~(e) (for case 2). By comparison of these results, it is shown that the number of days for that the power exceeds 100 KW is distributed more evenly in case 1 (without detention tanks) than in case 2 (with detention tanks). Specifically, in case 1 (without detention tanks), the number is 14 days for the future period under the RCP2.6 scenario, increased by 40% than that in the baseline. For other RCP scenarios of the future period, the change of the number of the exceedance days is less obvious than that for the RCP2.6 scenario, i.e., about -10%, -10%, and 20% for the RCP4.5 scenario, the RCP6.0 scenario, and the RCP8.0 scenario respectively. In case 2 (with detention tanks), the change of the number of the future period under the RCP2.6 scenario, the RCP4.5 scenario, the RCP6.0 scenario, and the RCP8.0 scenario relevant to the historical period is around 10%, -10%, 10%, and 10% respectively, which fluctuates less than in case 1.

Table 6(a). Power generation for the flow duration of an average year of the baseline for case 1 (without detention tanks).

Q **(m^3/s) (≥)**	**Duration (Days)**	**Power (KW)**
2.680	10	101.222
1.376	26	51.952
0.796	38	30.375
0.531	63	20.042
0.270	116	10.186
0.135	167	5.096
0.027	316	1.003

Table 6(b). Power generation for the flow duration of an average year of the future period under RCP2.6 scenario for case 1 (without detention tanks).

Q **(m^3/s) (≥)**	**Duration (Days)**	**Power (KW)**
2.734	14	103.261
1.344	30	50.748
0.811	44	30.630
0.539	65	20.367
0.286	119	10.794
0.136	177	5.139
0.027	319	1.005

Table 6(c). Power generation for the flow duration of an average year of the future period under RCP4.5 scenario for case 1 (without detention tanks).

Q **(m^3/s) (≥)**	**Duration (Days)**	**Power (KW)**
2.838	9	107.189
1.346	25	50.830
0.803	37	30.324
0.548	52	20.683
0.266	109	10.034
0.133	171	5.028
0.027	316	1.007

Table 6(d). Power generation for the flow duration of an average year of the future period under RCP6.0 scenario for case 1 (without detention tanks).

Q **(m^3/s) (≥)**	**Duration (Days)**	**Power (KW)**
2.670	9	100.855
1.354	27	51.151
0.795	38	30.043
0.541	57	20.440
0.267	117	10.099
0.134	171	5.049
0.027	315	1.028

Table 6(e). Power generation for the flow duration of an average year of the future period under RCP8.0 scenario for case 1 (without detention tanks).

Q **(m^3/s) (≥)**	**Duration (Days)**	**Power (KW)**
2.727	12	103.012
1.422	26	53.724
0.807	41	30.473
0.533	56	20.125
0.266	111	10.057
0.133	171	5.011
0.027	315	1.008

Table 7(a). Power generation for the flow duration of an average year of the baseline for case 2 (with detention tanks).

Q **(m^3/s) (≥)**	**Duration (Days)**	**Power (KW)**
2.798	7	105.681
1.326	23	50.065
0.796	44	30.075
0.537	69	20.275
0.274	124	10.346
0.133	180	5.039
0.027	318	1.033

Table 7(b). Power generation for the flow duration of an average year of the future period under RCP2.6 scenario for case 2 (with detention tanks).

Q (m^3/s) (≥)	Duration (Days)	Power (KW)
2.918	8	110.190
1.346	27	50.827
0.809	52	30.249
0.530	79	20.009
0.271	129	10.224
0.134	187	5.058
0.266	320	1.005

Table 7(c). Power generation for the flow duration of an average year of the future period under RCP4.5 scenario for case 2 (with detention tanks).

Q (m^3/s) (≥)	Duration (Days)	Power (KW)
2.914	7	110.044
1.327	23	50.124
0.800	39	30.223
0.532	64	20.076
0.272	118	10.287
0.133	182	5.009
0.27	320	1.008

Table 7(d). Power generation for the flow duration of an average year of the future period under RCP6.0 scenario for case 2 (with detention tanks).

Q (m^3/s) (≥)	Duration (Days)	Power (KW)
2.683	8	101.325
1.409	24	53.209
0.815	43	30.798
0.533	66	20.129
0.269	124	10.144
0.133	184	5.006
0.027	319	1.005

Table 7(e). Power generation for the flow duration of an average year of the future period under RCP8.0 scenario for case 2 (with detention tanks).

Q (m^3/s) (≥)	Duration (Days)	Power (KW)
2.721	8	102.752
1.365	27	51.547
0.800	46	30.199
0.535	67	20.190
0.275	120	10.385
0.134	182	5.064
0.027	318	1.020

For clarity and convenience of comparison, these relative changes of the results for different future climate change scenarios relative to the baseline (historical climate change) are calculated and plotted in Figure 10 (case 1) and Figure 11 (case 2), respectively. Furthermore, the comparative results also demonstrate that there are more days for the power generation capacity exceeding 10 KW or less (e.g., 1 KW) in case 2 than that in case 1 for both the historical and future periods under all the four scenarios. Meanwhile, compared with former result with exceeding 100 KW, for both cases (with and without detention tanks), the change of the number of exceedance days of the future period under all the four scenarios relevant to that of the historical period is less than $\pm$6% for the capacity exceeding 10 KW and less than 1% for the capacity exceeding 1 KW (see Figure 10 and Figure 11). This result indicates a relatively consistent and uniform energy generation trend with period for obtaining relatively low capacity (e.g., 10 KW or less in this study). In fact, this consistent power generation capacity trend will be more useful and beneficial for practical energy utilization, e.g., power facility design and application, in urban hydrosystems such as stormwater drainage system of interest in this study.

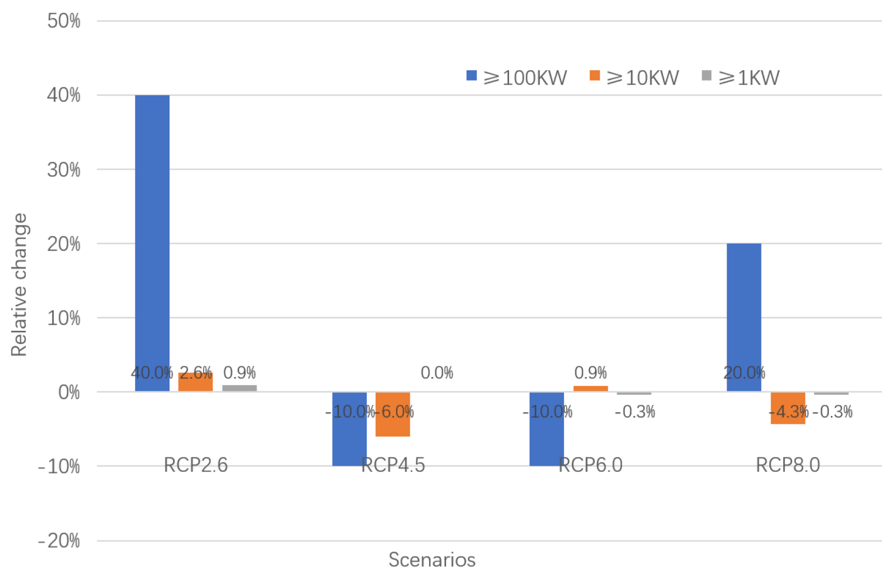


Figure 10. Relative changes of exceedance days for climate change scenarios for case 1 (without detention tanks).

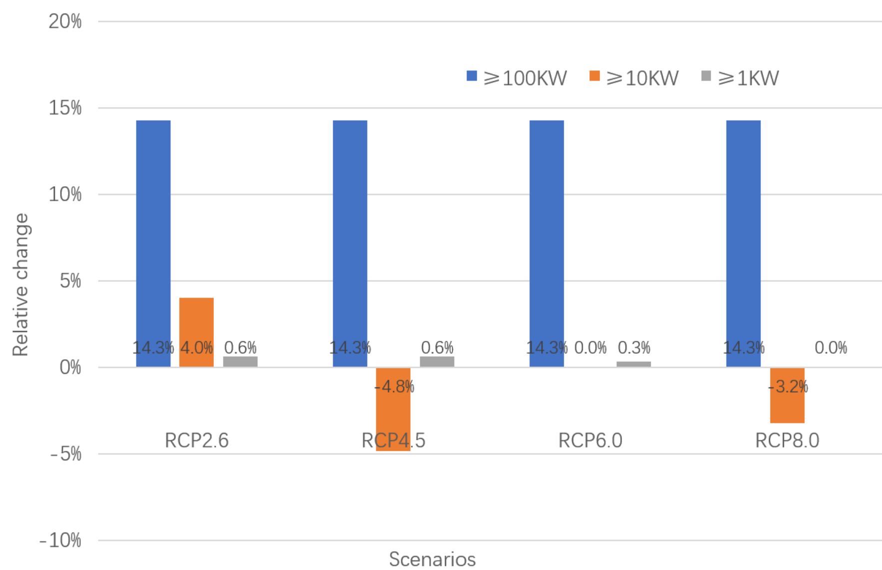


Figure 11. Relative changes of exceedance days for climate change scenarios for case 2 (with detention tanks).

For the drainage system of interest in this study, the number of days when the hydropower exceeds 1 KW for all the four scenarios is more than 315 days per year, accounting for about

86% of a year, in both case 1 and case 2, which provides a very affirmative result for the hydro-energy generation and utilization in USDS. Considering the relatively small scale and drainage condition of the studied system, it is expected that the potential capacity of hydro-energy generation in a whole and well-established urban drainage system like Hong Kong will be enormous. From this perspective, it is essential to develop the hydro-energy in the urban drainage system of Hong Kong, so as to better utilize the renewable energy.

5. Results Discussion

Despite that the potential and feasibility of hydro-energy in USDS has caused great of interests to public and professionals (researchers and engineers), the systematical evaluation and implementation of such renewable energy resource has yet to be performed in previous studies, especially for the cities with relatively high population density and extremely large energy consumption such as Hong Kong. To this end, this study develops a usable and implementable framework for the design and assessment of hydro-energy generation and capacity from the stormwater drainage process in USDS. Furthermore, the practical case study of the USDS in Hong Kong has evidenced the potential and feasibility of the hydro-energy utilization under the influence of climate change. Meanwhile, the application results also indicate that appropriate implementation of hydro-energy generation facilities such as SHP and detention tanks is also beneficial to the flooding control and management in the focused urban region (see the results in Table 3 and the relevant analysis in former section in this paper).

From a general perspective, the design and utilization of hydro-energy facilities in USDS will be helpful to develop clean and renewable energy, with a great potential to reduce the emission of GHGs worldwide under the influence of climate change trend. From a particular perspective, both the urban flooding risk and the energy/water resources wastage/shortage have become critical issues in Hong Kong (or other similar cities in the world). As a result, the implementation of such hydro-energy in the USDS of Hong Kong will be useful to solve simultaneously these problems in this city (i.e., water storage, energy generation and flooding control). Actually, in Hong Kong, the detention tanks and other stormwater storage facilities have been widely developed in recent years, with aim to mitigate flooding disasters in the urban area (Chan et al., 2010; DSDHK, 2017). According to the results and analysis of this study, these developed infrastructures in the USDS of Hong Kong will be easily extended and used to the implementation of hydro-energy generation and utilization in the future. Consequently, the results and findings of this study may provide scientific basis and useful tool for the design, assessment and implementation of renewable hydro-energy in USDS in Hong Kong and other cities worldwide.

6. Conclusions

This paper investigates the possibility of flooding control and hydro-energy generation in the urban stormwater drainage system (USDS). In this study, a systematical analysis framework has been developed to design and assess the feasibility and capacity of the hydro-energy capacity in USDS through the integration of different models (GCMs and HBV) and computation platform (SWMM). The practical USDS of Tung Chung town in Hong Kong has been used for the validation of developed method and framework, and the results are then analyzed for the hydro-energy capacity assessment in this region.

The application results have demonstrated clearly the potentials of hydro-energy generation in USDS and at the same time, evidenced the beneficial function of energy generation facilities

(SHP and detention tanks) to both the flooding control and water resources management. Particularly, the capacity of hydro-energy generation in the studied USDS has been examined for different climate change scenarios and under different stormwater drainage conditions (with/without detention tanks). Finally, the practical implications of the obtained results and findings of this study to the USDS in Hong Kong (also other cities in the world) have been discussed with regard to the development and utilization of renewable hydro-energy from USDS.

It is also noted that the model and parameters used in this study have not been fully calibrated and validated by the local data due to the lack of detailed runoff measurements for the studied USDS, which needs further investigations in the future work. Meanwhile, more applications of the developed framework to other USDSs are necessary to further improve and generalize the proposed method of this study.

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