Assessing the viability of microhydropower generation from the stormwater flow of the detention outlet in an urban area

Norashikin Ahmad Kamal, Heekyung Park and Sangmin Shin

ABSTRACT

Small-scale hydropower is the generation of electrical power of 10 MW or less from the transformation of kinetic energy in flowing water to mechanical energy in a rotating turbine to electrical energy in a generator. The technology is especially useful when installed with a stormwater infrastructure in countries teeming with abundant rainfall. It is upon this concept that this study is being pursued to assess the implementation of microhydropower within a stormwater infrastructure. In order to achieve sustainability of development, small-scale hydropower should be beneficial in the implementation of stormwater infrastructure, especially in countries that have abundant rainfall. The aim of this study is to provide an assessment method for microhydropower implementation within a stormwater infrastructure. PCSWMM software was used to simulate the flowing water at a detention outlet. Modification of the current detention pond was made to optimise the quantity and quality of water supplied to the turbine. Two important parameters in the modification design are quantity and quality of storm water, which optimise the energy generated. The total power that can be harnessed from the design is theoretically from 500 W to 0.5 MW. Therefore, it can be safely concluded that the implementation of microhydropower within a stormwater infrastructure is technologically feasible.

Key words | flowing water, microhydropower, PCSWMM software

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INTRODUCTION

Hydropower is a form of renewable energy that converts kinetic energy in flowing water to mechanical energy in a rotating turbine to electrical energy in a generator. It has been well explored by many researchers and its application is imperative for meeting the local energy demands. Major hydropower development can be found in reservoir systems, and its implementation requires significant environmental and economic considerations. Therefore, about 10 years ago, researchers around the globe started to investigate the feasibility of small-scale hydropower generation in the existing water infrastructure.

Microhydropower is categorized as small-scale hydropower that generates energy from flowing water amounting to less than 10 megawatts. The theory of hydropower is understood as the generation of energy that is produced from the transformation of kinetic energy in rotating or flowing water to mechanical energy. According to Shapes (2010) there are various methods by which small-scale hydropower could be implemented within the existing drinking water or wastewater infrastructure. However, there is limited equipment for use in the multipurpose hydropower generation schemes in the drinking water, raw wastewater and treated wastewater systems (Shapes 2010). There have also been various innovative techniques introduced. For instance, Guoliang & Kenichi (2012) studied the potential of energy harvesting in water distribution systems by using fewer energy types. Meanwhile, Anyi & Kirke (2010) introduced the idea of having a debris-resistant axial flow turbine in the river system for power generation in a small village area.

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There are a few important parameters to properly design a microhydropower system in stormwater infrastructure. The parameters are: (a) low head hydro, (b) amount of precipitation during storm events, and (c) storage of the treated water in the stormwater detention. Studies conducted by Bailey & Bass (2009a, b) and Ramos *et al.* (2012) provide a basic understanding of this concept. However, neither study sufficiently investigated all relevant parameters, but rather examined design concepts and types of turbine used in hydropower generation. There is a lacuna in studies on microhydropower generation from stormwater sources, especially those related to stormwater storage and climate conditions. This paper focuses on small-scale hydropower generation in relation to flowing water from storm events and examines the possibility of a low head implementation in the stormwater detention outlet.

The purpose of this paper is to recommend an assessment method to better understand the potential of having sustainable microhydropower generation within a stormwater infrastructure. Therefore, a detailed investigation is required for determining the stormwater flow from modification of an existing detention outlet. It is also important to optimise power that could be harnessed from the modification design. This assessment should simplify the feasibility study of microhydropower within stormwater infrastructure in urban areas which have similar climate conditions.

METHODOLOGY

Study area

An urban district in Kuala Lumpur, Malaysia, was used as the location of interest for our case study. The said location was selected due to the abundant rainfall. The average annual rainfall for this selected area was around 2,375 mm based on a 20-year (1989 to 2009) statistical analysis with total rainy days varying from 150 to 209 days per year. Figure 1 shows daily rainfall collected in 2012 for the study area. Total rainy days recorded were 175 and maximum daily rainfall was 72.5 mm.

Malaysia has a lot of detention or retention ponds that help to mitigate flooding in view of the abundant rainfall. In this study, a current design of the detention pond was selected for analysis purposes. This pond was chosen for its close

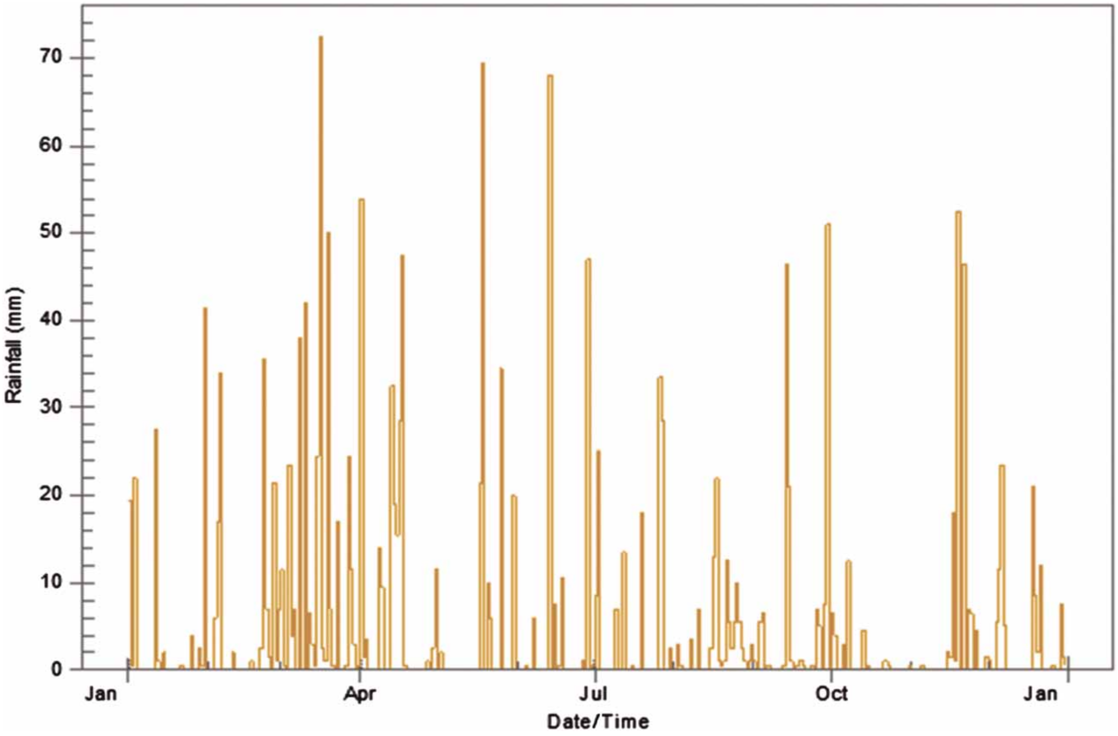

Figure 1 | Daily rainfall amount in 2012.

proximity to the urban downstream. The selection of area was based on the location of the detention pond from the urban downstream. In this selected pond, the detention outlet was located about 3 m from the urban downstream, with the stormwater flow through a 2.5 m length of conduit.

Based on the stormwater flow analysis, a modification of the current structure was deemed necessary to optimise the power generated. The proposed modification could not alter its aforementioned flood mitigation function.

Model development

PCSWMM software consists of a geographical information system engine which provides intelligent tools for streamlining model development, optimisation and analysis in a wide range of applications such as green infrastructure, integrated modelling, dynamic system analysis, detention storage, water quality and flood risk analysis.

In this study, the current design of the urban detention pond was initially modelled with PCSWMM software. Based on this initial model, the required modifications to the design were pursued to optimise energy production. A small urban hydropower model was then developed based on the said modifications. In the modified design, the input parameters that were used in the PCSWMM for running the simulation process were 1 year of rainfall data and low impact development (LID) controls for water quality; specifically, 15-minute intervals of rainfall data from 1 year and green infiltration for LID control.

Three main design parameters were considered, namely: capacity for stored water, retention time of suspended particle settlement and height of the pond outlet. All of these were important for optimising the energy generated from the storm water, and represented the quality and quantity of water flow just before entering the turbine and generator components. In order to optimise power generation, the minimum level of the pond discharged outlet was set at 3 m high. Figure 2 illustrates the detailed conceptual design of the small urban hydropower implementation. The detention pond is represented in the study area and energy generation is expected from the installation of turbine and generator components in that particular area. There are two main different components of the current and modification designs which were simulated by PCSWMM software. The first component is the type of detention outlet for the purpose of energy optimisation and the second component relates to the water quality controls.

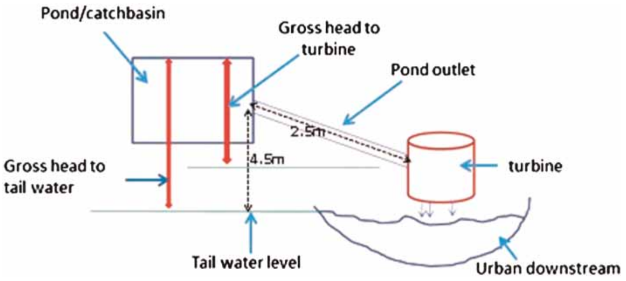

Figure 2 | Conceptual design for small-scale urban hydropower.

Sizing of the new detention pond outlet for small-scale urban hydropower

The detention pond was sized to accommodate water in the drainage system from an area of 130 ha. The area of the detention pond was sized for 36 m^2 with a depth of 4 m. The pond was designed based on 25 years average interval recurrence of rainfall.

Multiple outlets were considered in this modified design, which consists of a rectangular orifice for the purpose of energy generation and a weir outlet for avoiding flood inundation in the pond. The orifice was to regulate the water flow just before it enters the turbine, therefore optimising power generation. The rectangular orifice was positioned at an elevation of 1.5 m at the side of the detention pond. The size of the orifice was designed as a rectangular shape with width and height of 1 m respectively, for regulating the stormwater flow. Figure 3

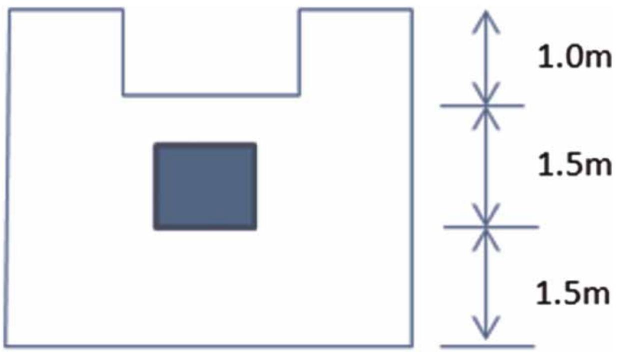

Figure 3 | Design concept of the new type of outlet.

shows the new detention outlet design, which was later used to simulate the corresponding power generation.

Estimation of power generation

The data for treated flow water (Q) at the detention pond outlet, just before entering the turbine, were extracted from the PCSWMM software. A flow duration curve was plotted to determine frequency of the flow at the detention pond outlet. The extracted parameters were then used in the following power energy equation. The equation that was used for estimating the power from the flowing water is represented as below

$$P = \aleph \rho g Q H$$

P = mechanical power produced at the turbine shaft (W), $\aleph$ = hydraulic efficiency of the turbine, ρ = density of water (1,000 kg/m^3), g = acceleration due to gravity (9.81 m/s^2), Q = volume flow rate passing through the turbine (m^3/s), H = effective head of pressure of water across the turbine (m).

The detailed conversion units of the water's density (ρ) and acceleration(g) units are expressed as below

$$1,000\,\mathrm{kg/m^3} \times 9.807\,\mathrm{m/s^2} = 9,807\,\mathrm{kg/m^2s^2}$$

$$1\mathrm{N/m^2} = 1\,\mathrm{kg/ms^2}$$

$$1\,\mathrm{N} = 1\,\mathrm{W/m}$$

$$\begin{aligned}\rho \times g &= 9.807 \times 1,000\,\mathrm{W/m^4}\\ &= 9,807\,\mathrm{W(s/m^4)}\end{aligned}$$

In the new modified design, 3 m height of the head level was set as the effective head of pressure of water to turn the turbine. The efficiency of the turbine used for this study was assumed to be 70% to account for the expected loss during energy conversion.

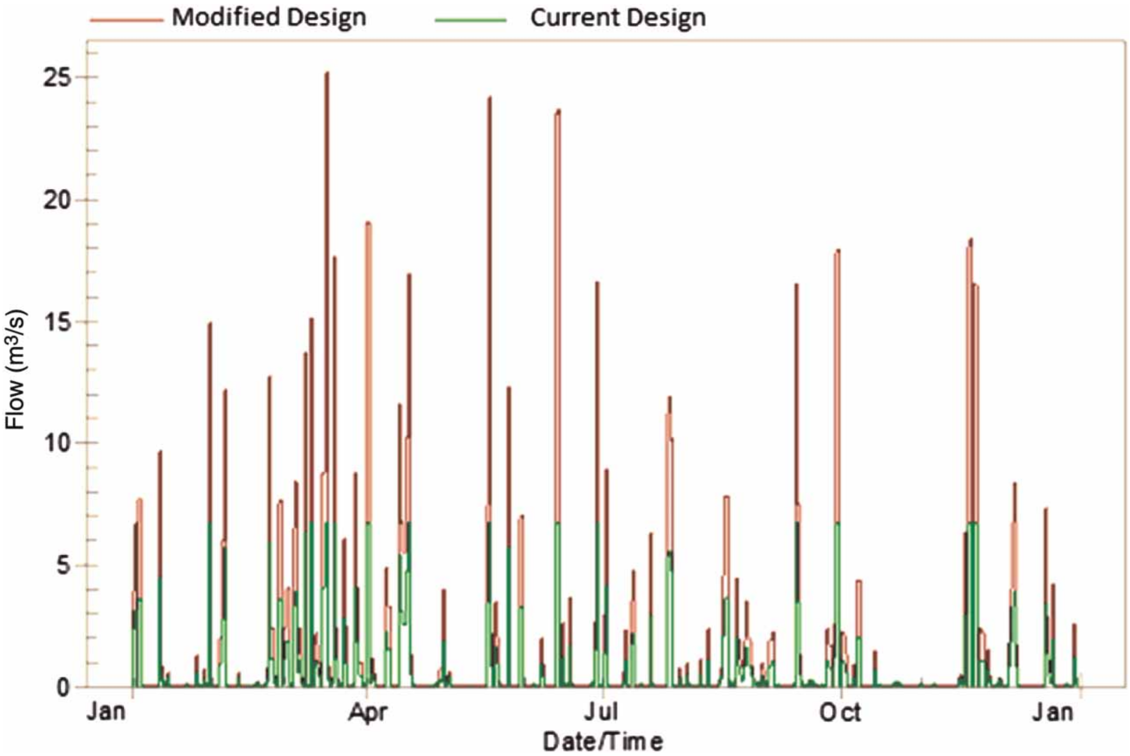

Figure 4 | Flow water in the detention pond outlet. The full colour version of this figure is available online at http://www.iwaponline.com/ws/toc.htm

RESULTS

Simulation results of flow water in the detention pond outlet

The results illustrate the treated stormwater flow in a detention outlet and the estimated power generated when the flowing water in the outlet enters the turbine and generator components. The outlet is a flow control device that is normally used to control outflow from detention storage.

Figure 4 illustrates the comparison between flow rates of the modified against the current detention pond outlets. It is apparent that the modified design (brown line) produced higher water flow discharge than the current design (green line) for a 1-year analysis. (The full colour

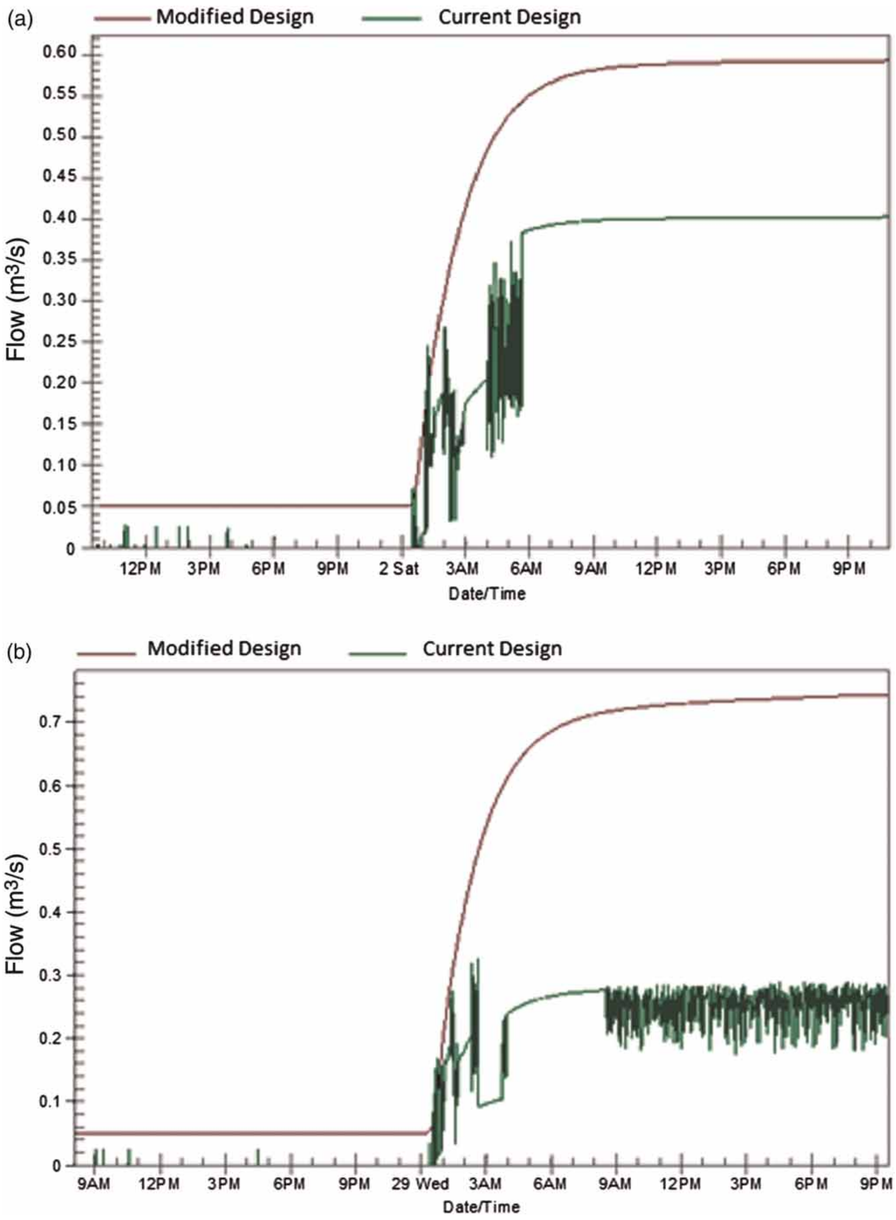

Figure 5 | (a) Detailed comparison of the flow water in a selected day from 365 days of analysis. (b) Detailed comparison of the flow water in a selected day from 365 days of analysis. The full colour version of this figure is available online at http://www.iwaponline.com/ws/toc.htm

version of Figure 4 is available online at http://www.iwaponline.com/ws/toc.htm.) This indicates optimisation of water flow discharge at the detention pond outlet is achievable by modifying the current structure of the detention pond and changing the type of the detention outlet. In other words, small-scale hydropower energy generation from treated storm water can be optimised according to the water flow in the modified design.

Continuous water flow is important to ensure turbine efficiency. Previous studies showed that the highest efficiency could be obtained if hydropower storage released continuously flowing water prior to entering the turbine and generator components (Montanari 2003; ESHA 2004 and Kumar *et al.* 2011). In this study, the rate of flowing water at the modified detention outlet was constant. Detailed comparison of the water flow pattern in both current and modified designs is presented in Figures 5(a) and 5(b) respectively for a selected time condition. In Figure 5(a), the flowing water fluctuated for few hours before stabilising, while in the Figure 5(b), the stable condition of flowing water was achieved only for 5 hours before the flow fluctuated again. The trend of water flow based on the modified design may solve the flow irregularity problem, which is required for energy generation from storm water. This flow irregularity from the current design (green line) limits the feasibility of energy generation from stormwater flow. Flow from the modified design (brown line) is more stable and this contributed to better flowing water for energy generation. (The full colour version of Figure 5 is available online at http://www.iwaponline.com/ws/toc.htm.)

Frequency of power generation based on the flow duration curve

The flow duration curve is the preferred method of evaluating and organising the frequency of flowing water in terms of percentage duration time. This method was used by Denis & Punys (2012); Heitz & Khosrowpanah (2010); Bruno (2010) and Bailey & Bass (2009a, b), for evaluating the percentage of energy generated. The value of exceeded flow, which had been specified in this analysis, was 0.02 m^3/s. This value is referred to as the minimum amount for energy generation in the detention outlet for this study. The flow duration curve is useful for identifying the frequency of availability of energy generation from the flowing water and it is widely applied, especially with respect to energy generation from river runoff. Comparison of flow duration curves for the modified and current designs is shown in Figure 6. The modified design had a higher flow of water and a larger percentage duration of flow occurrence than that of the current design. The modified design is likely to show greater efficiency in managing storm water in terms of its quality and quantity.

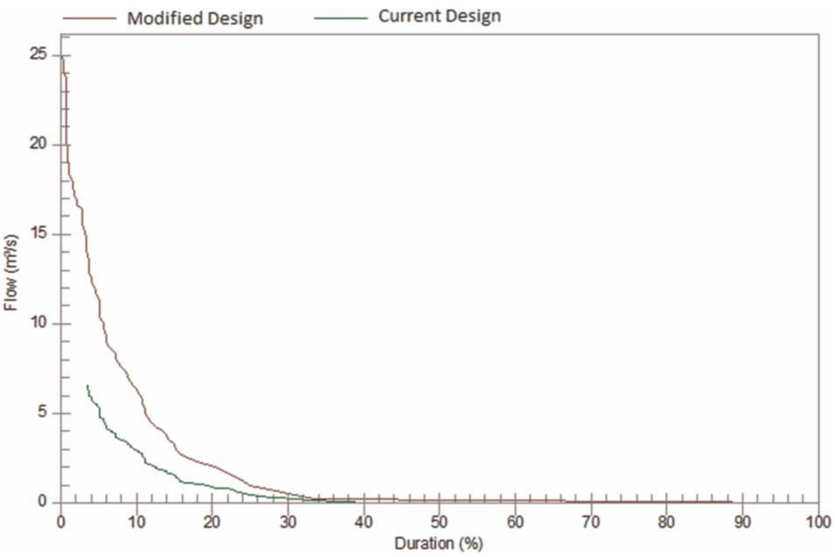

Figure 6 | Comparison graph of the flow duration curve in the detention outlet.

Table 1 shows the power generated, based on the flow duration time (in days) for a year, which exceeded the specified flow rate of 0.02 m^3/s. The minimum water that flowed in the simulation was 0.025 m^3/s. This water flow rate, and anything greater than this, might occur in 363 days and could generate at least 519.31 W when the flow entered the turbine and generator components. The maximum flow of water in the detention outlet after the modification of the design was 24.2 m^3/s and at least 0.5 MW could be produced from this flow in 1 day. As the power generated was shown to be in the range of 500 W to 0.5 MW, it could be categorised as mini-hydropower.

Table 1 | Power generation based on the flow duration time for a year in the modified design

Flow (m^3/s)	Duration (days)	Power (W)
0.025 and greater	363	519.31
1.009 and greater	91	20,772.27
2.017 and greater	74	41,544.51
3.026 and greater	55	62,316.78
4.034 and greater	49	83,089.03
5.043 and greater	41	103,861.30
6.052 and greater	38	124,633.56
7.060 and greater	32	145,405.81
8.069 and greater	26	166,178.08
9.078 and greater	22	186,950.35
10.086 and greater	21	207,722.68
11.095 and greater	18	228,494.90
12.103 and greater	16	249,267.13
13.112 and greater	14	270,039.35
14.121 and greater	13	290,811.58
15.129 and greater	11	311,583.81
16.138 and greater	11	332,356.24
17.147 and greater	7	353,128.47
18.155 and greater	5	373,900.69
19.164 and greater	3	394,672.92
20.172 and greater	3	415,445.14
21.181 and greater	3	436,217.37
22.190 and greater	3	456,989.60
23.198 and greater	3	477,762.03
24.207 and greater	1	498,534.26

DISCUSSION

The modified detention pond proposed in this study showed that it can optimise energy production by using the stormwater flow in the detention outlet. This also means that it is possible to have small-scale hydropower generation within stormwater infrastructure in an urban area. The modified design increased the amount of flowing water in the detention outlet and consequently optimised the energy production from it, in view of the fact that the modification design approach used in this study gave high consideration to the quality and quantity of the storm water.

The potential energy harnessable from the proposed design could reach from 500 W to 0.5 MW. The number was based on 1 year of rainfall data. This study also adds value in conceptualising energy production from the water flow within the stormwater infrastructure.

There are however two limitations in this study. The first is related to the height of the detention outlet. This research only focuses on the low head of the detention outlet, which is 3 m from the turbine and generator components, the current location of the detention outlet. Greater power would be generated by an outlet that is located higher from the turbine, due to the larger head of pressure. The second limitation refers to rainfall amount in an area, and may only be applicable for countries that have abundant rainfall.

Implementation of small-scale urban hydropower within stormwater infrastructure is therefore technically possible if the storm water is closely managed in terms of quality and quantity. Other than that, design considerations such as type of orifice and detention outlet must meet the requirements for optimising the energy generated from the stormwater flow. Hence, this study may introduce a new source of renewable energy in countries which experience abundant rainfall, such as Malaysia.

FUTURE WORK

In future studies, the authors plan to replicate this stormwater design in other city areas in order to assess the possibility of a distributed network of urban small-scale hydropower instead of one centralised system which requires more significant investment and has more environmental implications.

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