Journal of Engineering Science and Technology
Vol. 17, No. 6 (2022) 4398 - 4409

HYDROLOGICAL MODELLING AND EVALUATION OF DETENTION PONDS TRANSFORMED FROM ROUNDABOUT TO MITIGATE URBAN FLOODING

KING KUOK KUOK[1,*], PO CHAN CHIU[2]

[1]Faculty of Engineering, Computing and Science, Swinburne University of Technology Sarawak Campus, Jalan Simpang Tiga, 93350 Kuching, Malaysia
[2]Faculty of Computer Science and Information Technology, Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia
*Corresponding Author: kkuok@swinburne.edu.my

Abstract

Kota Samarahan, Sarawak, Malaysia has emerged from a fishing village into an education hub and urban society within 30 years. The changes in land use increased the peak and volume of surface runoff. However, the non-upgrading of the existing stormwater drainage system and the impact of climate change caused Kota Samarahan to be plagued with multiple flood events in recent years. One of the efficient flood mitigation methods is to construct a detention pond that requires enormous land, which is difficult to fulfil in a developed township. It is proposed in this study to convert the large roundabout in front of University Malaysia Sarawak, Kota Samarahan into a detention pond. Different scenarios were investigated, including rainfall intensity 2, 10 and 100 years average recurrence intervals (ARIs), different orifice sizes ranging from 1.5 m × 1.5 m to 4.5 m × 4.5 m using Storm Water Management Model (SWMM). Results proved that transforming the roundabout into detention pond is an effective way to manage excess stormwater and reducing the peak runoff significantly. The ideal detention pond geometry is circular, 134 m bottom diameter, 150 m top diameter, and 2 m depth with a side slope of 4:1 ($H:V$). Results also revealed that orifice size 4.0 m × 4.0 m is sufficient for mitigating the 100 years ARI flooding problem. Therefore, building a stormwater detention pond within a roundabout is advantageous because it helps with stormwater runoff management and saves space for pond construction.

Keywords: Detention pond, Orifice, Peak runoff

1. Introduction

Since 1990s, Kota Samarahan has emerged from a fishing village into an increasingly urban society. The changes in land use associated with urban development have increased the peak and volume of surface runoff with the increment of impervious surfaces, thus resulting less surface runoff infiltrating into the ground. Vegetation removal, land surface covering with asphalt and concrete, and drainage networks construction led to the rapid rising of urban streams water levels resulting in higher peak discharge than non-developed areas. Negligence of relevant authorities to improve flood-prone areas and non-upgrading existing stormwater drainage systems to suit the impact of climate change is making the situation worse. As a result, floods frequency is increasing nowadays.

The primary effects of flooding include loss of life, damage to buildings, bridges, and other infrastructures, such as sewerage systems, roadways, transport infrastructure and canals. Floods also frequently damage power transmission and power-generation facilities, such as pumps [1, 2]. Lack of clean water combined with human sewage in the floodwaters raises the risk of waterborne diseases, including typhoid, giardia and cholera [3]. Besides, the flooded areas will also face severe economic hardship due to the decline of visitors in the tourism industry, food shortages, repair and rebuild damaged buildings and infrastructure [4]

Flood routing can be simulated with linear and non-linear Muskingham Method [5]. To overcome the flooding issue, various mitigation methods, such as detention basins, piers, bunds and reservoirs, are built to prevent waterways from overflowing [6, 7]. Flood controls, such as dams can be built and maintained over time to reduce the occurrence and severity of floods [8].

Another possible strategy is to reduce impervious surfaces in the streets, parking lots, and buildings by constructing vegetated swale, porous pavements, bioretention systems, and wetlands [9, 10]. Flood-prone areas can be converted into parks and playgrounds during the dry season but will serve as detention pond to accommodate the excess rainwater occasionally during the raining season [11]. New legislation can be enforced to require developers to build infrastructure for retaining on-site stormwater compulsory and only allow new developments in flood-free zones.

One of the effective ways to mitigate the flooding problem in the developed area is to construct a detention pond to slow down the peak and volume runoff [12-16]. Detention pond is part of green infrastructure and Low Impact Development (LID) utilities, specially constructed to store excess runoff during heavy rainfall temporarily. It emphasizes the conservation of natural areas wherever possible and the use of on-site natural features to improve water quality [17, 18], such as controlling and removing the sediments [19] and nitrogen [20] in water. Apart from that, detention ponds also help minimize the hydrological impact of development while creating additional water supply for irrigation and other purposes [21]. Meanwhile, detention pond increases the aesthetics of surrounding areas, raising community value and protecting animal habitat [11].

However, detention ponds may require an enormous area of expensive land located in urban areas, which is more profitable for developers to build more buildings on the same plot of land [22]. It was observed that the roundabout in Kota Samarahan is large with a diameter of 180 m. Therefore, it is proposed in this study to transform the immense roundabout into a detention pond to store the excess water during heavy rainfall, release it slowly after the rain stops, and yet still serve as a roundabout for traffic flow with no complications. The effectiveness of this detention pond was modelled and evaluated using the Environmental Protection Agency's Storm Water Management Model (SWMM), a dynamic rainfall-runoff simulation model for either a single event or continuous simulation of runoff quantity and quality from primarily urban areas.

2. Study Area

The selected study area is the roundabout located in front of the University Malaysia Sarawak (UNIMAS) campus main entrance, intersecting among Muara Tuang Road, Kuching-Samarahan Expressway, Kuching-Samarahan Highway and Kuching Outer Ring road. All the drains flowing through the study area are discharging from the sub-catchment of Samarindah Garden and INTAN Institute, as indicated in Fig. 1.

The orange circle in Fig. 1 is an existing roundabout that is proposed to be converted into a detention pond. Samarindah Garden is a residential area consisting of single-storey, double-storey terrace houses, and flats, covering an area of 139.55 Hectares. In recent years, the study area is always plagued with flooding problems, where the whole roundabout and upper catchment will be inundated with water after heavy rainfall.

Fig. 1. Area of study.

Occasionally, areas located downstream, including Uni-Garden, are also inundated with flood when too much excess rainwater flows from upstream (refer to Fig. 2). Therefore, the best possible solution is to construct a detention pond within the roundabout while maintaining the function of the roundabout for controlling traffic.

(a) Flood at Uni-Garden.

(b) Flood at Uni-Garden.

(c) Flood at Samarindah Garden.

(d) Flood at Uni-Garden.

Fig. 2. Flood event in Uni-Garden and Samarindah housing estates on 22 February 2020.

3. Methodology

The model is developed to direct all the surface runoff from Samarindah Garden and INTAN areas toward the roundabout in front of UNIMAS main entrance. After establishing all necessary parameters, Tc for the studied catchments was estimated as the sum of the overland flow time (T_o) and the drain flow time (T_d) [23]. T_o is estimated to be 7 minutes with a 3.5% slope of the overland surface. The concrete drain has a reach length of 3120 m. The t_d is 13 minutes with an estimated average velocity of 0.25 m/s. As a result, the Tc is estimated to be 20 minutes in this study. The developed model will be investigated with rainfall intensity of 2, 10 and 100 years Average Recurrence Intervals (ARIs) at 20 minutes duration, and various orifice sizes located at the bottom of the tank.

The input data for the SWMM model includes drainage properties, sub-catchments area, intensity duration frequency (IDF) curves, stage-storage relationships, etc. Drainage properties were obtained through site visits, where the depth, width, length, and drain flow direction are measured and recorded.

Catchment and sub-catchment areas were measured through google earth maps. IDF curves for Kota Samarahan was obtained from 2019 Hydrological Yearbook published by the Department of Drainage and Irrigation (DID) Sarawak.

The model will be calibrated and validated to ensure the simulated hydrograph is matching as closely as possible with the observed hydrograph's runoff, including volume, peak discharge, time of peak, and rising and falling limbs. The model calibration and validation were performed under post-development scenario at the drainage located at Uni-Garden to determine the appropriate drainage manning coefficient, percent of impervious area, depression storage of impervious area, and other parameters. The model's performance is assessed using the Nash-Sutcliffe coefficient (*E*) and the Root Mean Squared Error (*RMSE*), as shown in Eqs. (1) and (2), respectively.

$$E = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (1)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - S_i)^2} \quad (2)$$

where O_i=observed runoff at time *i*; S_i=model simulated output at time *i*; $\bar{O}$= mean of the observations; and *n*= number of observations.

Calibration and validation results revealed that the *E* and *RMSE* at Uni-Garden were 0.9328 and 0.0062, respectively, for model calibration, and 0.8554 and 0.0238, respectively, for model validation. For model calibration, the predicted hydrograph shape and peak discharge match well with the observed one. However, the simulated hydrograph's peak is slightly lower than the observed peak for the validation dataset. These findings imply that the values used in model calibration are reasonable and fall within the expected range.

After the model calibration and validation, a detention pond was built within the existing roundabout to store the excess rainwater by controlling the peak of post-development release rates is comparable to its pre-development levels. The details of research methodology for SWMM development are illustrated in Fig. 3. Figure 4 presents the model developed in SWMM.

Fig. 3. Research methodology using SWMM.

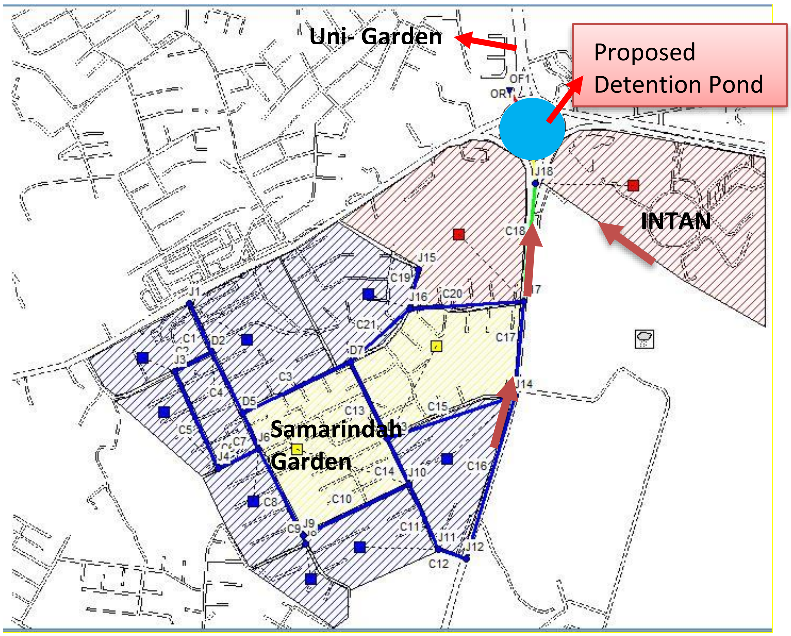

Fig. 4. SWMM numerical model with detention pond.

The roundabout has a diameter of 180 m. As a result, the maximum pond surface diameter at the top is limited to 150 m to construct guard rails around the pond and fit the roundabout shape well. With the depth of 2 m and side slope of 4:1 (*H:V*) surrounding the pond, the pond geometry at the bottom will be reduced to 134 m (refer to Fig. 5). A side slope of 4:1 (*H:V*) is chosen to increase slope stability and avoid slope failure caused by fluctuating water levels within the pond. The volume capacity at different depths is calculated using Eq. (3).

$$V = \frac{1}{3}\pi({r_1}^2 + r_1 r_2 + {r_2}^2)h \tag{3}$$

where, r_1= longer radius; r_2= shorter radius and h = depth.

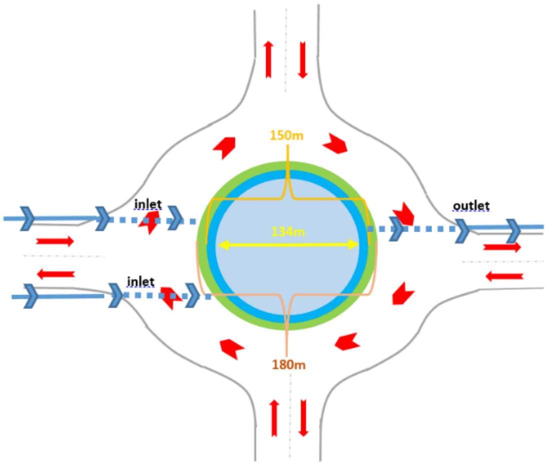

Fig. 5. Plan view of detention pond.

Figure 6 presents the geometry of the detention pond and the orifice. Orifice is the variable that controls the release of water from the detention pond. Different sizes of rectangle orifices were investigated. Since it is a dry detention pond, the outlet offset for the orifice is located at 0 m, which is at the bottom of the detention pond. The purpose is to flash out the excess water inside the detention pond after the rain stop.

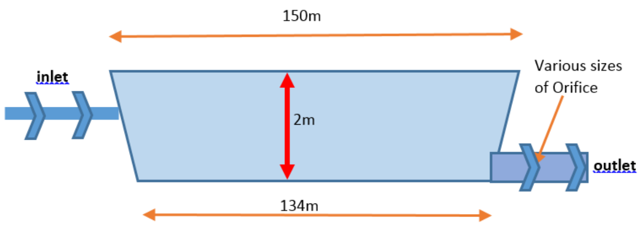

Fig. 6. Geometry of detention pond.

4.Results and Discussion

The resulting hydrographs are shown in Figs. 7, 8 and 9 for 2, 10 and 100 years ARIs storm events, respectively. The outflow hydrographs produced by the detention pond with different orifice sizes were compared against those resulting from the pre-development discharge targets without detention pond. The pre-development hydrographs were generated using the impervious surfaces of 25%, while post-development hydrographs were generated with impervious surfaces of 90%. The outflow hydrographs were generated at the interval of every 15 minutes time step.

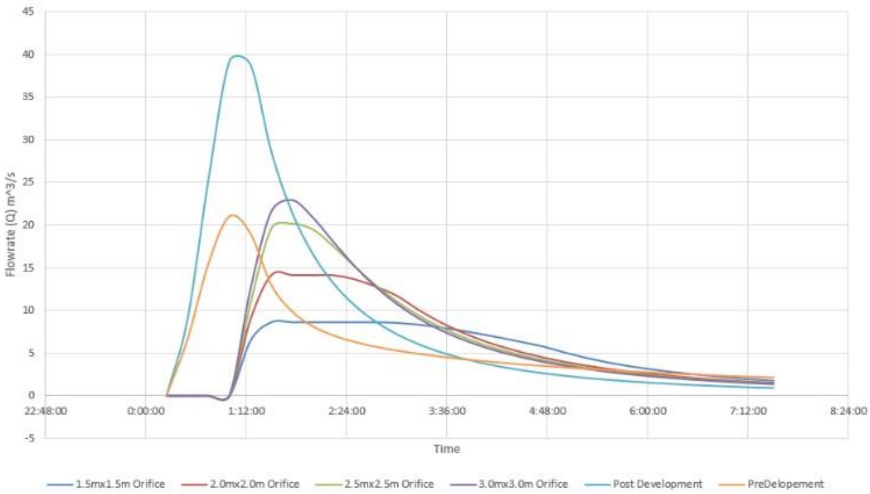

Fig. 7. Outflows simulation for 2 years ARI storm event.

Figure 7 revealed that peak runoff discharge for 2 years ARI storm events under pre-development scenario was 20.99 m^3/s. During post-development, the peak runoff discharge was increased to 39.18 m^3/s. Hence, the target peak discharge for post-development with the help of detention pond is set to be 20.99 m^3/s. With the orifices size of 1.5 m × 1.5 m, the outflow peak discharge is only 8.57 m^3/s. As the orifice sizes increased to 2.0 m × 2.0 m, 2.5 m × 2.5 m, and 3.0 m × 3.0 m, it was found that the outflow peak discharge will be increased to 14.11 m^3/s, 20.13 m^3/s and 22.97 m^3/s, respectively. The hydrograph peak for orifice size of 1.5 m × 1.5 m and 2.0 m × 2.0 m have stayed constant. This is because inadequate orifice sizes had restricted the outflow of water from the detention pond, and occasionally may overflow it. Since the target peak discharge before development is only 20.99 m^3/s, results revealed that the orifice size of 2.5 m × 2.5 m is sufficient to achieve the desired outflow.

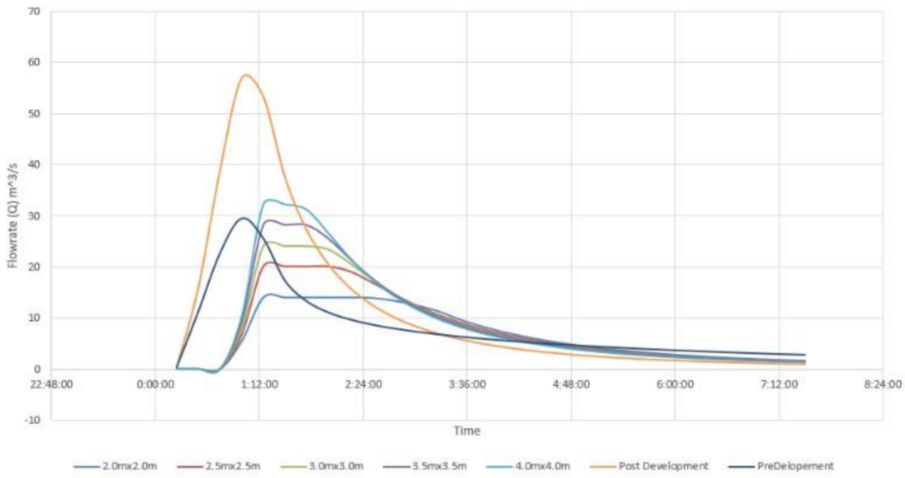

Fig. 8. Outflows Simulation for 10 years ARI storm event.

The peak runoff discharge for 10 years of ARI storm events under the pre-development scenario was 29.50 m^3/s, as shown in Fig. 8. The peak runoff discharge for post-development was discovered to be 56.9 m^3/s. The peak outflow discharge was reduced to 14.11 m^3/s, 20.13 m^3/s, 24.15 m^3/s, 28.18 m^3/s, and 32.2 m^3/s for orifice sizes of 2.0 m × 2.0 m, 2.5 m × 2.5 m, 3.0 m × 3.0 m, 3.5 m × 3.5 m, and 4.0 m × 4.0 m, respectively, with the construction of a detention pond. The results show that the peak of hydrograph for orifice sizes of 2.0 m × 2.0 m, 2.5 m × 2.5 m and 3.0 m × 3.0 m were stagnant at peak. This revealed that these orifice sizes are undersized to cater the outflow from the detention pond. At extreme rainfall event, the pond water may be overflown and cause the flood. Therefore, the optimal orifice size of 3.5 m × 3.5 m is selected to achieve the desired peak outflow of 29.50 m^3/s for 10 years ARI.

The pre-development peak runoff discharge for 100-year ARI storm events was found to be 35.41 m^3/s (refer to Fig. 9), which is also the target peak outflow. The peak runoff discharge was increased to 69.30 m^3/s after development. During the investigation, orifices of 3.5 m × 3.5 m, 4.0 m × 4.0 m, and 4.5 m × 4.5 m were found to reduce peak outflow discharge to 28.18 m^3/s, 32.20 m^3/s, and 36.23 m^3/s, respectively, after development with the construction of detention pond. Hydrograph generated reveals that peak of hydrograph for orifice sizes of 3.5 m × 3.5 m was stagnant at peak for a more extended period, indicating that this orifice size is slightly undersized. Therefore, the optimal orifice size was discovered to be 4.0 m × 4.0 m for catering 100 years ARI storm events.

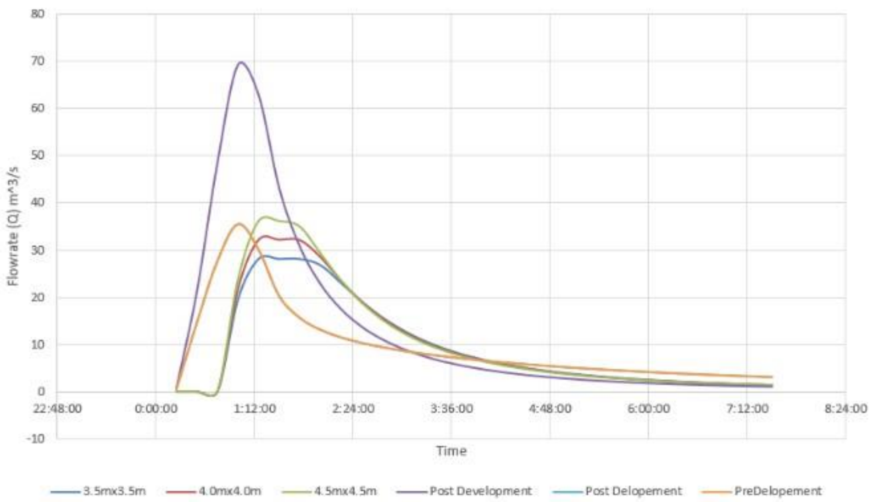

Fig. 9. Outflows Simulation for 100 years ARI storm event.

The rate of change of the water level in the storage pond against time is used to calculate the discharge through the orifice. Calibration of water level against volume drained is used to determine the rate of volume change over time, thus the discharge coefficient. The hydrographs show that a low water level with a small hydrostatic pressure variation across the orifice at the small head has little effect on the discharge. On the other hand, a higher water level with high hydrostatic pressure variation across the orifice at higher head has a significant impact on the discharge.

The study reveals that the discharge coefficient increases as the size of orifice increases. The small orifice size restricts the outflow of water at reasonable discharge, causing it to accumulate too much in the detention pond and occasionally overflow it. Larger orifice sizes will provide an extra outlet in place, allowing more water to be discharged from the detention pond.

Basically, it was found that the detention pond can control post-development peak discharges to their pre-development levels. The storage unit cannot reduce the total volume of post-development runoff resulting from the large increase of impervious area, but it can temporarily store the rainwater and release it to the drainage system after the rain stops.

Meanwhile, the percentage of peak reduction with the constriction of detention pond at different sizes of orifice can be calculated using Eq. (4) [23]. Figure 10 presents the peak discharge after construction of detention pond and orifice, compared with the peak pre-and post-development scenarios.

$$\text{Percentage of redution (\%)} = \frac{\text{Peak Discharge} - \text{Reduced Peak Dischage}}{\text{Peak Discharge}} \times 100 \qquad (4)$$

It was observed that the orifice sizes control the detention pond outflow discharge. For 2 years ARI, it was found that the orifice size of 2.5 m × 2.5 m is able to reduce the peak reduction to 48.62%. Meanwhile, orifice sizes of 3.5 m × 3.5 m and 4.0 m × 4.0 m are able to reduce the peak to 50.47% for 10 years ARI and 53.54% for 100 years ARI. Among 2, 10 and 100 years ARI, it is proposed to construct the orifice size of 4.0 m × 4.0 m for mitigating the flooding problem in this particular case study.

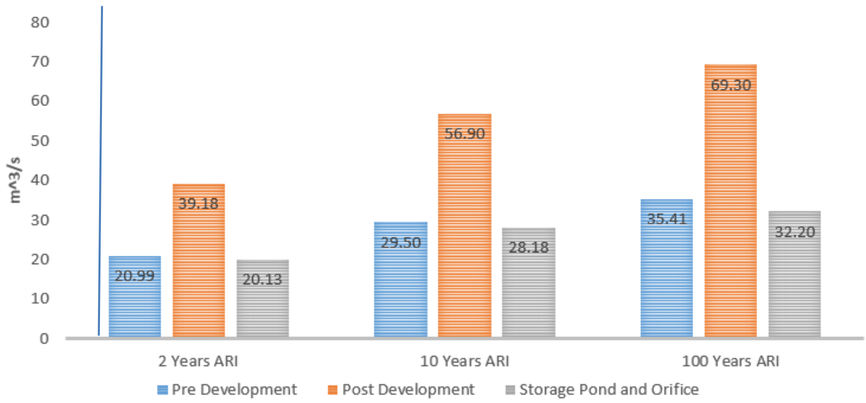

Fig. 10. Comparison of Peak Runoff under Pre and Post developments and with detention pond and orifice.

The sizes of the orifice play an important role in runoff generation from the detention pond. Smaller orifice sizes allow less total outflow, and the water will be stored longer in the detention pond. In contrast, a larger orifice allows larger volumes of discharge that will reduce the pond detention time.

5. Conclusion

The results revealed that SWMM can evaluate the performance of detention ponds for storing the water temporarily and slowly release it to the discharge point when the rain stops. The detention pond constructed within the roundabout in front of UNIMAS main entrance can reduce the total runoff downstream, thus avoiding floods. Therefore, it is viable to construct a detention pond within the roundabout as it is feasible in terms of cost and space. This is an ideal concept as Sarawak has many enormous roundabouts. Besides, simulation results also proved that transforming the roundabout into detention pond is an effective way to manage stormwater runoff. In this study, the ideal detention pond geometry is a circular shape, 134 m bottom diameter, 150 m top diameter, 2 m depth with a side slope of 4:1 (*H:V*). The orifice size of 4.0 m × 4.0 m is able to cater the rainstorms for 100 years ARI flood.

References

1. Kuok, K.K.; Liew, Z.Z.; and Chiu, P.C. (2013). Flood map development by coupling satellite maps and three-dimensional drafting software: Case study of the Sarawak River Basin. *Water S.A.*, 39(1), 175-182.
2. Rossman, L.A.; and Huber, W.C. (2016). *Storm water management model reference manual*. *Volume I – Hydrology*. U.S. Environmental Protection Agency, Water Supply and Water Resources Division, EPA/600/R-15/162A.
3. Kuok, K.K.; and Chiu, P.C. (2018). Indigenous drinking-water consumption pattern of residents in Kuching city: results of a pilot study. *Journal of Water, Sanitation & Hygiene for Development*, 8(4), 817-824.
4. Duan, H.-F.; Li, F.; and Tao, T. (2016). Multi-objective optimal design of detention tanks in the urban stormwater drainage system: Uncertainty and sensitivity analysis. *Water Resources Management*, 30(7), 2213-2226.

5. Hayder, H.A. (2010). Flood routing by linear Muskingum method in Tigris River using computer programs. *Journal of Kerbala University*, 8(1), 249-269.
6. US EPA. (1999). *Storm water technology fact sheet – Wet detention ponds*. United States Environmental Protection Agency, Officer of Water Washington DC, EPA832-F-99-048.
7. US EPA. (1999). *Preliminary data summary of urban storm water best management practices*. United States Environmental Protection Agency, Officer of Water Washington DC, EPA821-R-99-012.
8. Kuok, K.K.; Mah, Y.S.; Imteaz, M.A.; and Kueh, S.M. (2016). Comparison of future intensity duration frequency curve by considering the impact of climate change: case study for Kuching city. *International Journal of River Basin Management*, 14(1), 47-55.
9. Kuok, K.K.; Harun, S.; and Chiu, P.C. (2011). Comparison of particle swarm optimization and shuffle complex evolution for auto-calibration of hourly tank model's parameters. *International Journal of Advances in Soft Computing and its Applications*, 3(3), 1-17.
10. Damodaram, C.; Giacomoni, M.H.; Khedun, C.P.; Holmes, H.; Ryan, A.; Saour, W.; and Zechman, E.M. (2010). Sustainable stormwater management. *Journal of the American Water Resources Association*, 46(5), 907-918.
11. Shinde, P.S. (2002). *Multi-use of stormwater detention ponds in parks and open spaces*. Mater of Landscape Architecture Thesis, University of Georgia in Partial, Athens, Georgia, Greece.
12. Liew, Y.S.; Selamat, Z.; Ghani, A.A.; and Zakaria, N.A.N. (2012). Performance of a dry detention pond: case study of Kota Damansara, Selangor, Malaysia. *Urban Water Journal*, 9(2), 129-136.
13. Drake, J.; Young, D.; and McIntosh, N. (2016). Performance of an underground stormwater detention chamber and comparison with stormwater management ponds. *Water*, 8(5), 211.
14. Louis, Y.H.T.; Kuok, K.K.; Imteaz, M.; Lai, W.Y.; and Derrick, K.X.L. (2019). Development of whale optimization neural network for daily water level forecasting. *International Journal of Advanced Trends in Computer Science and Engineering*, 8(3), 354-362.
15. Sahoo, S.N.; and Pekkat, S. (2018). Detention ponds for managing flood risk due to increased imperviousness: Case study in an urbanizing catchment of India. *Natural Hazards Review*, 19(1), 05017008.
16. Pereira Souza, F.; Leite Costa, M.E.; and Koide, S. (2019). Hydrological modelling and evaluation of detention ponds to improve urban drainage system and water quality. *Water*, 11(8), 1547.
17. Eckart, K.; McPhee, Z.; and Bolisetti, T. (2017). Performance and implementation of low impact development – A review. *Science of the Total Environment*, 607-608, 413-432.
18. Li, H. (2020). Investigation of highway stormwater management pond capacity for flood detention and water quality treatment retention via remote sensing data and conventional topographic survey. *Transportation Research Record: Journal of the Transportation Research Board*, 2674(7), 514-527.

19. Suripin, S.; Darsono, S.; Kurniani, D.; Hutagalung, W.F.; and Dintia, D.V. (2020). Development of sustainable detention ponds for flood and sediment control in urban areas. *Journal of Physics: Conference Series*, 1625(1), 012046.
20. Rosenzweig, B.R.; Smith, J.A.; Baeck, M.L.; and Jaffé, P.R. (2011). Monitoring nitrogen loading and retention in an urban stormwater detention pond. *Journal of Environmental Quality*, 40(2), 598-609.
21. Beecham, S.; Kandasamy, J.; Khiadani, M.; and Trinh, D. (2005). Modelling on-site detention on a catchment-wide basis. *Urban Water Journal*, 2(1), 23-32.
22. Phillips, D.I. (1995). A generic method of design of on-site stormwater detention storages. *Water Science and Technology*, 32(1), 93-99.
23. MSMA (2001) *Urban storm water management*. Department of Irrigation and Drainage Malaysia, Ministry of Environment and Water, Malaysia.
24. Saleh, L.A.M.; Majeed, S.A.A.D.; and Algretawee, H.H. (2021). Analysis of the Euphrates River's movement within Al-Hindiya, Karbala, relative to steady flow conditions using the HEC-RAS model. *IOP Conference Series: Materials Science and Engineering*, 1067(1), 012081, 1-13.