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Calibration and validation of EPA SWMM for stormwater runoff modelling in Nyabugogo catchment, Rwanda

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Abstract Rapid urbanization is known to have several negative impacts towards hydrological cycle. Urban growth contributes to the increase of impervious area which increases stormwater runoff peak flows and volumes. Nyabugogo catchment has been repeatedly subjected to a growing number of flooding events which resulted in negative effects on water supply system, damage of properties, disruption to business and traffic, discomfort to community, loss of human lives, loss of biodiversity, destruction of environment and deterioration of health conditions owing to water bone diseases. Characterization of stormwater runoff is essential in implementing stormwater management and flood mitigation strategies. Hydrological and hydraulic models are used to perform the study and analysis of stormwater quantity and floods in a catchment. In this study, the United States Environmental Protection Agency's Storm Water Management Model (EPA SWMM 5.1) was calibrated and validated for stormwater runoff quantity modelling in Nyabugogo catchment. The Geographic Information Systems (ArcGIS) tool was used for catchment delineation; dividing the catchment into sub-catchments and parameterizing the required elements for the model. The collected data from three meteorological stations for period of 1996 to 2017 and three hydrological stations for a period of 1996 to 2017 were used to calibrate and validate EPA SWMM. The performance of EPA SWMM for Nyabugogo catchment was assessed using the coefficient of determination r^2, Nash-Sutcliffe efficiency NSE, and index of agreement d. The calibration resulted in r^2 of 0.72, NSE of 0.6 and d of 0.77 and validation resulted in r^2 of 0.84, NSE of 0.72 and d of 0.8. The calibration and validation results indicated a good fit between simulated and measured data. Overall, the model is acceptable for runoff quantity modelling in Nyabugogo catchment.

Keywords Calibration, Nyabugogo catchment, Runoff quantity, Storm Water Management Model, Validation.

1. Introduction

Urbanization contributes to the development level of a country [1]. However, rapid urbanization leads to fast land-use change and the increase of impervious surface

[2]. The increased runoff volumes and peak flows associated with faster response time result in urban flood risks [3]. A study conducted on Hyderabad city in India, concluded that urbanization leads to increase of flood peaks from 1.8 to 8 times and flood volumes by up to 6 times [4]. The common practice for many cities to manage stormwater runoff is relying on conventional stormwater drainage systems of pipe and channel network designed to remove urban runoff as fast as possible [5]. However, this traditional drainage system is no longer adequate to deal with larger and more intense stormwater events as they promote large runoff volumes and urban pollution [6].

Nyabugogo has experienced a growing number of floods and their impacts increased due to its low altitude and its nature of convergence zone of drainage systems of Kigali city [7]. The conventional stormwater drainage systems have failed to deal with intense rainfall events and a drastically changed land-use in many cities including Kigali [8]. Nyabugogo River itself and drainage systems within catchment have lost the former carrying capacity to accommodate all excess water within its active domain due to drainage congestion, over siltation, riverbank erosion and poor maintenance planning [9].

There is a need to focus on new stormwater management techniques such as, infiltration of rainfall on site, and detention of runoff during large storm events, rather than removing stormwater runoff as fast as possible [6]. Urban hydrological models are used to understand and evaluate urban water quantity and quality responses to potential land-use changes and climate change. Models are calibrated and validated in order to produce accurate scenarios of runoff generation and pollutant loading with urban storm water [2]. EPA SWMM model is the most widely used by researchers to model rainfall-runoff processes in urban areas [10], [11]. The aim of this research was to carry out the calibration and validation of EPA SWMM for stormwater runoff quantity modelling in Nyabugogo catchment, Rwanda.

2. Materials and Methods

3.1 Modelling input data

The required spacial and time series input data were compiled from different public institutions in Rwanda. Spacial data included Digital Elevation Model (DEM), land-use maps, drainage network maps and soil information which were obtained from Rwanda Land Management and Use Authority (RLMUA). Time series data required were daily rainfall, evaporation, wind speed and streamflow for a period of 1996 to 2017. The time series input meteorological data were obtained from Rwanda Meteorology Agency for three meteorological stations (Kigali airport station, Gitega and Byumba). Streamflow data were obtained from Rwanda Water and Forestry Authority (RWFA) for three stations (Nemba, Muhazi and Yanze).

3.2 Study area description

The Nyabugogo catchment covers the central, eastern and northern part of Rwanda (Fig.1). Nyabugogo catchment has a total area of 1661.3 km^2 [9].The climate of the catchment is mostly of temperate and equatorial type with average temperature ranging between 16°C and 23°C, depending on the altitude of the area. The annual rainfall in the catchment varies from about 800 mm to 1,600 mm. The monthly rainfall pattern is quite uniform with highest frequently recorded in April and November [7]. The catchment was subdivided into 8 sub-catchments and the characteristics required by the model were obtained using ArcGIS tool. Each sub-catchment was assigned to a correct outlet node in the drainage network and was named according to the main streams in the sub-catchment.

3.3 Approach and Modelling

The methodology used to achieve the objective of this research consisted of two main parts, each of which was related to the use of the two tools: ArcGIS and EPA SWMM Model. The first part was fully developed using ArcGIS 10.3, especially through its toolbar Arc Hydro. ArcGIS-based editing tools were also applied to obtain parameters required by the model such as the areas, width and imperviousness of the sub-catchments. The runoff quantity processes were then simulated using EPA SWMM 5.1.

3.4 Model description

EPA SWMM is a dynamic rainfall-runoff simulation model used for single event or continuous simulation of runoff quantity and quality from primarily urban areas. The runoff component of EPA SWMM operates on a collection of sub-catchment areas that receive precipitation and generate runoff and pollutant loads. The routing portion of EPA SWMM transports this runoff through a system of pipes, channels, storage devices, pumps, and regulators. EPA SWMM tracks the quantity and quality of runoff generated within each sub-catchment, and the flow rate, flow depth, and quality of water in each pipe and channel during a simulation period comprised of multiple time steps [12].

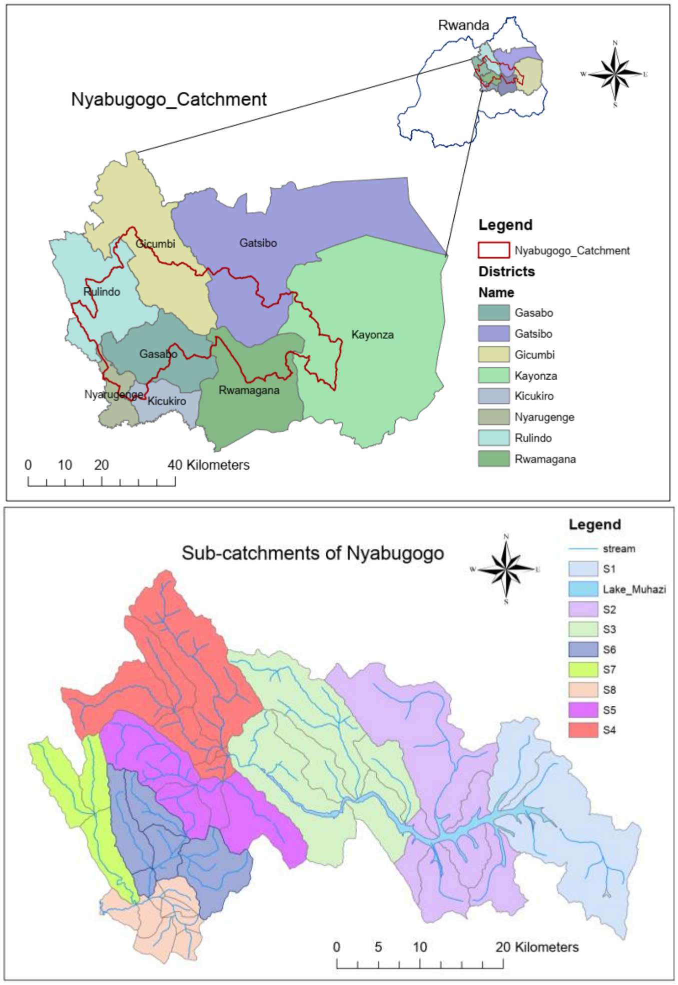

Fig. 1. Location and sub-catchments of Nyabugogo catchment

EPA SWMM conceptualizes a sub-catchment as a rectangular surface that has a uniform slope S and a width W that drains to a single outlet channel. Overland flow is generated by modeling the sub-catchment as a nonlinear reservoir as shown in (Fig.2). The sub-catchment experiences inflow from precipitation and losses from evaporation and infiltration. The net excess ponds atop the sub-catchment surface to a depth d. Ponded water above the depression storage depth d_s can become runoff outflow q. Depression storage accounts for initial rainfall abstractions such as surface ponding, interception by flat roofs and vegetation, and surface wetting [12].

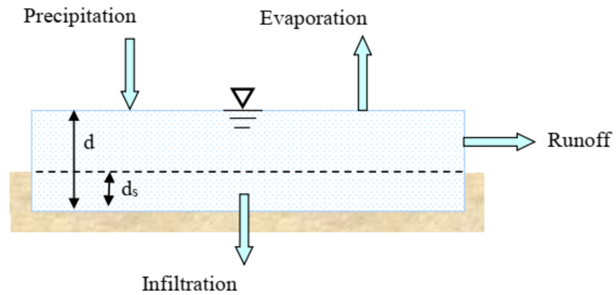

Fig. 2. Nonlinear reservoir model of a sub-catchment

From conservation of mass, the net change in depth d per unit of time *t* is simply the difference between inflow and outflow rates over the sub-catchment, as in (1):

$$\frac{\partial d}{\partial t} = i - e - f - q \qquad (1)$$

Where:
i = rate of rainfall (mm/s)
e = surface evaporation rate (mm/s)
f = infiltration rate (mm/s)
q = runoff rate (mm/s).

Assuming that flow across the sub-catchment's surface behaves as if it were uniform flow within a rectangular channel of width W, height d–d_s, and slope S, the Manning equation can be used to express the runoff's volumetric flow rate Q as in (2):

$$Q = \frac{1.49}{n} * S^{1/2} * R_x^{2/3} * A_x \qquad (2)$$

Here n is a surface roughness coefficient, S the apparent or average slope of the sub-catchment, A_x the area across the sub-catchment width through which the runoff flows, and R_x is the hydraulic radius associated with this area. Referring to (Fig.2), Ax is a rectangular area with width W and height d-ds. Because W will always be much larger than d it follows that $A_x = W(d - d_s)$ and $R_x = d - d_s$. Substituting these expressions into (2) gives (3):

$$Q = \frac{1.49}{n} * W * S^{1/2} * (d - d_s)^{5/3} \qquad (3)$$

To obtain a runoff flow rate per unit of surface area, q, (3) is divided by the surface area of the sub-catchment A and gives (4):

$$q = \frac{1.49 * W * S^{1/2}}{A * n} * (d - d_s)^{5/3} \quad (4)$$

Substituting this equation into the original mass balance relation (1) results in (5):

$$\frac{\partial d}{\partial t} = i - e - f - \alpha (d - d_s)^{5/3} \quad (5)$$

Where α is defined as (6):

$$\alpha = \frac{1.49 * W * S^{1/2}}{A * n} \quad (6)$$

Equation (5) is an ordinary nonlinear differential equation. For known values of i, e, f, ds and α can be solved numerically over each time step for ponded depth d. Once d is known, values of the runoff rate q can be found from (4). Note that (5) only applies when d is greater than d_s. When d <= d_s, runoff q is zero and the mass balance on d becomes simply (7):

$$\frac{\partial d}{\partial t} = i - e - f \quad (7)$$

The basic input parameters required to simulate the runoff quantity are rainfall and the catchment physical characteristics.

In this analysis, the dynamic wave routing method was used to calculate runoff. The infiltration loss on pervious area was estimated by curve number because of the availability of soil data.

3.5 Model parameterization

EPA SWMM requires three major parameters categories for runoff quantity modelling including the physical catchment characteristics, rainfall and infiltration data. The physical catchment data required for runoff modeling include catchment area, percentage of impervious area, catchment width, average slope, surface depression storage and surface roughness [13]. Most of this information was derived from topographic map and drainage network dataset.

Curve numbers were assigned for each drainage area within the catchment. Curve numbers are indicators of the runoff potential of a watershed during a rainfall event. The main significant variables for defining a curve number are the hydrologic soil group and cover type. In order to determine the pervious soil curve number, the hydrologic soil group for each drainage area was determined from the existing soil maps [14].

Field survey was also carried out to confirm the surface drainage patterns in order to accurately describe the sub-catchment physical characteristics. The area-weighted percent imperviousness was determined by summing the amount of impervious area of each sub-catchment and dividing this sum by the total catchment area. The imperviousness parameter describes the percentage of impervious surfaces in relation to the total area of a sub-catchment. The values of imperviousness were estimated based on land-use and soil data. The sub-catchment slope was assumed equal with the flow path slope and was estimated as the elevation difference divided by the flow path length on map [13]. The physical characteristics of Nyabugogo catchment are described in Table I.

Table I: Physical Characteristics of Nyabugogo

ID	Area (ha)	Width (m)	Average slope (%)	Imperviousness (%)
S1	22692.15	301.28	0.25	3.84
S2	31135.47	352.90	0.32	2.7
S3	33230.26	364.58	0.73	1.99
S4	26665.43	326.59	1.04	2.1
S5	17061.17	261.24	1.25	3.5
S6	14689.78	242.40	1.22	72
S7	9670.49	196.68	1.04	2.3
S8	7702.22	175.52	1.35	78.4

Other input parameters for catchment properties were adopted from the range provided in SWMM User's manual (Table II).

Table II: Modelling parameters

Parameter	Description	Value range	Value
Width-K	flow width coefficient	0.2–5	2
N-Imperv	Manning's roughness coefficient for impervious area	0.011–0.015	0.015
N-Perv	Manning's roughness coefficient for pervious area	0.05–0.8	0.08
Destore-Imperv	Depth of depression storage on impervious area	0–3	3
Destore-Perv	Depth of depression storage on pervious area	3–10	6
Conduit Roughness	Manning's roughness coefficient for conduit	0.011–0.024	0.011
Drying Time	Time for a fully saturated soil to completely dry	1–7	5

Sensitivity analysis was used to identify key parameters and the parameter precision required for calibration. The sensitivity analysis was carried out by varying the value of a particular input parameter while holding the other parameters constant during the simulation. The sensitivities of runoff depth to the input parameters are represented by the sensitivity coefficient (S_r), as in (8).

$$S_r = \left(\frac{x}{y}\right)\left(\frac{y_2-y_1}{x_2-x_1}\right) \quad (8)$$

Where x is the input parameter and y is the predicted output. x_1, x_2 correspond to ±10 % ranges of the initial default value and y_1, y_2 are the corresponding output values [15]. The greater the S_r, the more sensitive a model output parameter is to that particular input parameter.

Model calibration was performed by carefully adjusting values of model input parameters with well-defined ranges until the simulated results closely match the observed values. The runoff depths measured at three hydrological stations were used as evaluation data where they were compared with simulated runoff depths. The simulated and measured values of runoff quantity used were for a period of 10 years (1996 to 2005). The most sensitive parameters were used while conducting the adjustment for the calibration and validation of the model.

The verification of model efficiency and performance was done using the efficiency criteria: coefficient of determination r^2, Nash-Sutcliffe efficiency E, and index of agreement d.

3.6 The coefficient of determination r^2

The coefficient of determination r^2 is defined as the squared value of the coefficient of correlation [16]. It is calculated as in (9):

$$r^2 = \left[\frac{\sum_{i=1}^{n}(O_i-\bar{O})(P_i-\bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i-\bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i-\bar{P})^2}}\right]^2 \quad (9)$$

With O: Observed values and P: Predicted (Modelled) values.

The range of r^2 lies between 0 and 1 which describes how much of the observed dispersion is explained by the prediction. A value of zero means no correlation at all whereas a value of 1 means that the dispersion of the prediction is equal to that of the observation [17].

3.7 Nash-Sutcliffe Efficiency NSE

The efficiency NSE proposed by Nash and Sutcliffe (1970) is defined as one minus the sum of the absolute squared differences between the predicted and observed values normalized by the variance of the observed values during the period under investigation [16]. It is calculated as in (10):

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i-P_i)^2}{\sum_{i=1}^{n}(O_i-\bar{O})^2} \quad (10)$$

with O: Observed values and P: Predicted (Modelled) values;

The range of NSE lies between 1 and −∞. An efficiency of 1 (NSE = 1) corresponds to a perfect match of modelled to the observed data [18]. An efficiency of lower than zero indicates that the mean value of the observed time series would have been a better predictor than the model [19].

3.8 Index of agreement d

The index of agreement represents the ratio of the mean square error and the potential error and is calculated as in (11):

$$d = 1 - \frac{\sum_{i=1}^{n}(O_i-P_i)^2}{\sum_{i=1}^{n}(|P_i-\bar{O}|+O_i-\bar{O})^2} \quad (11)$$

The range of d is similar to that of r^2 and lies between 0 and 1. A value of zero means no correlation at all whereas a value of 1 means that the dispersion of the prediction is equal to that of the observation [16].

3. Results and discussions

3.1 Sensitivity Analysis

For Nyabugogo Catchment, the sensitive input parameters used are flow width coefficient (Width-K), Manning's roughness coefficient for impervious area (N-Imperv), Manning's roughness coefficient for pervious area (N-Perv), Depth of depression storage on impervious area (Destore-Imperv), Depth of depression storage on pervious area (Destore-Perv), Manning's roughness coefficient for conduit (Conduit Roughness) and Time for a fully saturated soil to completely dry (Drying Time).

Width-K has an influence on runoff flow depth of S_r = 0.7, Conduit Roughness has an influence with S_r of 0.57 for flow depth. Destore-Imperv and Destore-Perv have a low influence on flow depth. N-Imperv and Destore-Imperv have negative coefficients, which indicate that the output values will increase with a decrease in these input parameters. The sensitive parameters were used to identify the values to be used for model calibration and validation.

A research conducted on modelling runoff quantity and quality in tropical urban catchments using Storm Water Management Model found percentage impervious and flow width coefficient more influential and sensitive to runoff depth and peak flow. The percentage impervious had S_r of 0.96 on runoff depth and 0.72 on peak flow.

Manning's roughness coefficient for impervious area (N-Imperv) and Depth of depression storage on impervious area (Destore-Imperv) had negative S_r values which indicate that the values of runoff depth and peak flow decrease with their increase in values [20].

A study conducted on modeling the quality and quantity of runoff in a highly urbanized catchment using storm water management model concluded that the depth of depression storage on impervious area and conduit roughness had the most influence on the hydrology and hydraulic component. Destore-Imperv was the most sensitive parameter in the determination of the total flow, and had a sensitivity coefficient value of 0.142. Conduit roughness was highly sensitive to total flow and was the most sensitive parameter to peak flow [10].

A sensitivity analysis performed for a large basin in Tallinn, Estonia found that the model is sensitive to the percentage of the impervious area for predicting both flow rate and peak flow. Impervious depression storage regulates the initial peak flow. Impervious surface roughness and width of catchment have weak connections to the model predictions [21]. Previous studies using EPA SWMM have found that runoff flow depth is more sensitive to Width-K and N-Imperv and Destore-Imperv have negative coefficients which are similar to the results found for this study.

3.2 Model calibration

The model was evaluated for the modelling capabilities through three indicators using Equations (9), (10) and (11). The model for runoff simulation is acceptable at the three indicators: r^2 of 0.72 which is close to 1; NSE of 0.6 which is between 0 and 1; and d of 0.77 which close to 1. The simulated runoff depth show good relationships with the measured values at three outlets in the catchment. The results show that the r^2, NSE, and d are within the acceptable range for runoff quantity for all events, indicating the modelled and measured runoff to be in a good relationship.

The model performance is judged satisfactory for flow simulation at catchment scale for the values of r^2 greater than 0.6, NSE greater than 0.5 and d greater than 0.7 [22]. The model is considered well calibrated for estimating the runoff depth. The goodness of fit was also plotted by the modelled, observed values of runoff depth and rainfall as shown in Fig. 3.

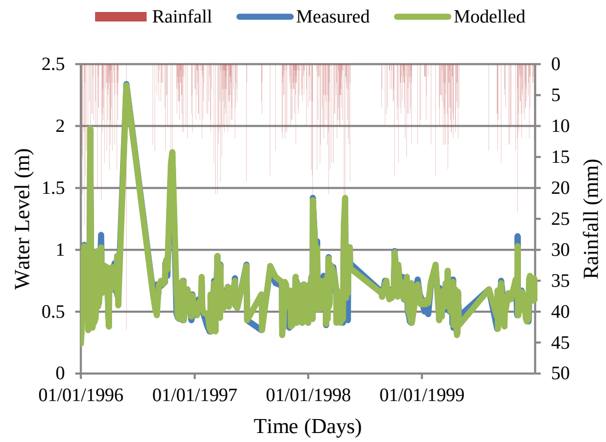

Fig. 3. Runoff depth of measured and modelled values during calibration

A research conducted on modeling the quality and quantity of runoff in a highly urbanized catchment using storm water management model resulted in calibration values of E greater than 0.87 and r^2 values of 0.86, 0.90, and 0.87 for three events. The research concluded that the runoff volume and peak flow had a good fit between the measured and simulated data [10].

Continuous simulations were used for calibration and validation for a research conducted on the calibration and verification of SWMM for low impact development in the Long Island Sound in Waterford, Connecticut. Agreement between predicted and observed data was assessed using r^2 and E coefficients. The calibration resulted in r^2 greater than 0.7 and NSE of 0.78 and 0.64 for runoff volume and peak flow, respectively [23].

A study conducted on a long-term hydrological modelling of an extensive green roof by means of SWMM. The Model calibration and validation was evaluated based on the comparison of the observed and simulated runoff flow rates. In order to assess the model performance, the Observation Standard Deviation Ratio (RSR) and NSE were used. The calibration resulted in values of NSE ranging from 0.58 to 0.93 and RSR of 0.27 to 0.65 of flow rates [24]. In the present study, the values of testing parameters from calibration were reasonable and in acceptable ranges.

3.3 Model validation

The input parameters that were derived in the calibration process were used to validate the model. The purpose of model validation is to confirm whether the input parameters are able to simulate new events. The model for runoff simulation is acceptable at the three indicators: r^2

of 0.84 which is close to 1; NSE of 0.72 which is between 0 and 1; and d of 0.8 which close to 1.The results show that the r^2, NSE, and d are within the acceptable range for runoff quantity for all events, indicating the modelled and measured runoff to be in a good relationship.

The model performance is judged satisfactory for flow simulation at catchment scale if the values of r^2 greater than 0.6, NSE greater than 0.5 and d greater than 0.7 [22]. The model is considered well validated for estimating the runoff quantity. Generally, the model was found to be appropriate for runoff quantity modelling in Nyabugogo catchment. The values of modelled and observed runoff depth and rainfall were plotted as shown in Fig. 4.

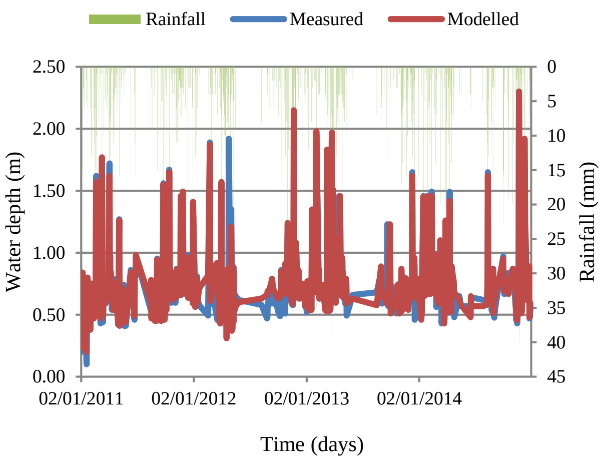

Fig. 4. Runoff depth of measured and modelled values during validation

A study on Calibration and validation of SWMM model in two urban catchments in Athens, Greece resulted in a validation showing the good fit between the measured and simulated values of runoff quantity with NSE of 0.93, d of 0.98 and r^2 of 0.96 [25].

EPA SWMM was used to conduct a research on the rehabilitation of concrete canals in urban catchments using low impact development techniques. For the calibration and validation process, both the r^2 and E measures were used to comprehensively evaluate the model performance. The NSE values for the validation events ranged from 0.79 to 0.99 and the r^2 values ranged from 0.89 to 0.99 for peak runoff [26].

A research conducted on a high resolution application of a storm water management model (SWMM) using genetic parameter optimization. The Model validation was evaluated using NSE, the linear correlation coefficient LCC and the sum of squared errors SSE. The highest values of NSE equal to 0.95 and LCC of 0.97 for validation events were achieved [27]. In the present study, the values of testing parameters from validation were reasonable and in acceptable ranges.

4. Conclusions

The objective was to calibrate and validate EPA SWMM for Nyabugogo catchment in order to be used for stormwater runoff modelling. Calibrated and validated models are much need to evaluate the performance of drainage systems and to be used for floods mitigation strategies.

Catchment delineation and subdivision was successfully performed and eight sub-catchments were resulted. EPA SWMM model was set up based on the topographical and drainage network data, and parameters derived based on the properties of the sub-catchments. The parameter sensitivity analysis shows the parameter robustness. The runoff depth is sensitive to changes in Width-K, Conduit Roughness, N-Imperv and Destore-Imperv, and the other parameters have relatively minor effect.

The model was calibrated and validated with values of r^2 greater than 0.6, NSE greater than 0.5 and d greater than 0.7, therefore, the model is acceptable for simulation of runoff quantity in Nyabugogo catchment.

Application of EPA SWMM in Nyabugogo catchment will be helpful in assessing the performance of drainage systems, finding solutions to floods problem and designing monitoring strategies of storm water management in the catchment.

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References

[1] P. C. Annez and R. M. Buckley, *Urbanization and Growth*. 2008.

[2] M. Guan, N. Sillanpää, and H. Koivusalo, "Modelling and assessment of hydrological changes in a developing urban catchment," *Hydrol. Process.*, vol. 29, no. 13, pp. 2880–2894, 2015.

[3] Q. Zhou, "A Review of Sustainable Urban Drainage Systems Considering the Climate Change and Urbanization Impacts," *Water*, vol. 6, no. 4, pp. 976–992, 2014.

[4] V. A. Rangari, "Development of Different Modeling Strategies for Urban Flooding: A Case Study of Hyderabad City," vol. 5, no. Cec, 2016.

[5] P. Mguni, L. Herslund, and M. B. Jensen, "Sustainable urban drainage systems: examining the potential for green

infrastructure-based stormwater management for Sub-Saharan cities," *Nat. Hazards*, vol. 82, no. 2, pp. 241–257, 2016.

[6] H. Schreier, "Innovative Stormwater Management: Translating Science Into Actions," p. 5, 2014.

[7] E. Rukundo and A. Dogan, "Assessment of Climate and Land Use Change Projections and their Impacts on Flooding," *Polish J. Environ. Stud.*, vol. 25, no. 6, pp. 2541–2551, 2016.

[8] O. Munyaneza, Y. K. Nzeyimana, and U. G. Wali, "Hydraulic structures design for flood control in the Nyabugogo wetland , Rwanda," vol. 8560783, no. January 2013, pp. 1–12, 2013.

[9] WFGR, "IWRM Programme Rwanda," no. January, 2017.

[10] C. Li, M. Liu, Y. Hu, J. Gong, and Y. Xu, "Modeling the quality and quantity of runoff in a highly urbanized catchment using storm water management model," *Polish J. Environ. Stud.*, vol. 25, no. 4, pp. 1573–1581, 2016.

[11] Z. Xu and G. Zhao, "Impact of urbanization on rainfall-runoff processes: case study in the Liangshui River Basin in Beijing, China," *Proc. Int. Assoc. Hydrol. Sci.*, vol. 373, pp. 7–12, 2016.

[12] L. A. Rossman and W. C. Huber, "Storm Water Management Model Reference Manual Volume I – Hydrology," *U.S. Environ. Prot. Agency*, vol. 3, no. July, 2016.

[13] Lewis A. Rossman, "United States Enviromental Protection Agency Storm Water Management Model Reference Manual," vol. I, p. 233, 2016.

[14] L. A. Rossman, "Storm Water Management Model User's Manual," no. EPA/600/R-14/413b, pp. 1–353, 2015.

[15] L. James and S. Burges, "Selection, calibration, and testing of hydrologic models, Hydrologic Modeling of Small Watersheds CT Haan, HP Johnson, DL Brakensiek, 437–472," *Joseph, Mich*, no. January 1982, 1982.

[16] P. Krause and D. P. Boyle, "Advances in Geosciences Comparison of different efficiency criteria for hydrological model assessment," *Adv. Geosci.*, vol. 5, no. 89, pp. 89–97, 2005.

[17] J. Y. Wu, J. R. Thompson, R. K. Kolka, K. J. Franz, and T. W. Stewart, "Using the Storm Water Management Model to predict urban headwater stream hydrological response to climate and land cover change," *Hydrol. Earth Syst. Sci. Discuss.*, vol. 10, no. 6, pp. 7091–7126, 2013.

[18] D. N. Moriasi, J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, and T. L. Veith, "M e g s q a w s," vol. 50, no. 3, pp. 885–900, 2007.

[19] C. Hewes, R. F. Smith, and C. Nicolson, "Modeling Effectiveness of Low Impact Development on Runoff Volume in the Tan Brook Watershed Presented by," vol. i, 2013.

[20] M. F. Chow, Z. Yusop, and M. E. Toriman, "Modelling runoff quantity and quality in tropical urban catchments using Storm Water Management Model," *Int. J. Environ. Sci. Technol.*, vol. 9, no. 4, pp. 737–748, 2012.

[21] B. Maharjan, K. Pachel, and E. Loigu, "Modelling stormwater runoff, quality, and pollutant loads in a large urban catchment," *Proc. Est. Acad. Sci.*, vol. 64, no. 3, pp. 1–9, 2015.

[22] D. N. Moriasi, M. W. Gitau, N. Pai, and P. Daggupati, "Hydrologic and Water Quality Models: Performance Measures and Evaluation Criteria," *Trans. ASABE*, vol. 58, no. 6, pp. 1763–1785, 2015.

[23] D. J. Rosa, J. C. Clausen, and M. E. Dietz, "Calibration and Verification of SWMM for Low Impact Development," *J. Am. Water Resour. Assoc.*, vol. 51, no. 3, pp. 746–757, 2015.

[24] S. S. Cipolla, M. Maglionico, and I. Stojkov, "A long-term hydrological modelling of an extensive green roof by means of SWMM," *Ecol. Eng.*, vol. 95, pp. 876–887, 2016.

[25] I. M. Kourtis, G. Kopsiaftis, V. Bellos, and V. A. Tsihrintzis, "Calibration and validation of SWMM model in two urban catchments in Athens , Greece," vol. 2, no. September, 2017.

[26] B. Palanisamy and T. F. M. Chui, "Rehabilitation of concrete canals in urban catchments using low impact development techniques," *J. Hydrol.*, vol. 523, pp. 309–319, 2015.

[27] G. Krebs, T. Kokkonen, M. Valtanen, H. Koivusalo, and H. Setälä, "A high resolution application of a stormwater management model (SWMM) using genetic parameter optimization," *Urban Water J.*, vol. 10, no. 6, pp. 394–410, 2013.