Malaysian Journal Of Civil Engineering

CALIBRATION AND VALIDATION OF SWMM MODEL IN A SUB CATCHMENT IN ELDORET TOWN, KENYA

Article history
Received
19 April 2020
Received in revised form
29 November 2020
Accepted
5 December 2020
Published online
31 March 2021

Rotich Abraham Metto[a], Kiptum Clement Kiprotich[a*], Kipkorir Emmanuel Chessum[b]

[a]School of Engineering, University of Eldoret, Kenya
[b]School of Engineering, Moi University, Kenya

*Corresponding author
ckiptum@uoeld.ac.ke

Abstract

Flooding in Eldoret town has been occurring during heavy downpours resulting in loss of property, live and interruption of transportation systems. This study aimed at determining the catchment characteristics in Eldoret town for the calibration and validation of SWMM5 model. This model was developed by US Environmental Protection Agency. The model has been evolving from Version 1 in 1971 to Version 5 of 2005 called SWMM5. It can simulate runoff quantity in any given catchment. Rainfall was measured using rain gauge while discharge was measured using current meter. Digital Elevation Model of the study area was also obtained. The results showed that the catchment drained an area of approximately 696.5 hectares with a total of 23 sub catchments. The average slope was found to be 2.57% and the mean average imperviousness was 25.72%. The drain base flow was found to be 0.002 m3/s. However, during prolonged rainfall, the discharge increased up to 32.4 m3/s. The maximum rainfall observed during the study period was 32.4 mm which resulted in the maximum average discharge of 0.131m3/s and resulted in overflow in the drain. Calibrated model had N-Imperv of 0.45, Dstore-Imperv of 2.5 and Dstore-Perv of 8. ISE values of 1.9 and 1.4 were observed for calibration and validation, respectively. NSE values of 0.97 and 0.99 were observed for calibration and validation, respectively. This meant that model excellently simulated rainfall-discharge relationship in the study area and can be used for final design by the Eldoret town engineers. Future study is required to calibrate the model based on more measurements of rainfall and their discharges in the catchment.

Keywords: Calibration, Discharge, Eldoret, Flooding, SWMM5 model

1.0 INTRODUCTION

Floods occur because of the rapid accumulation and release of runoff waters from upstream to downstream (Ouma and Tateishi, 2014). Urban stream flow is a subject of great concern worldwide (Booth et al., 2014). Some regions of the world have benefited from well managed urban stream flows while others have had problems associated with storm waters which lead to serious social economic and ecological impacts (Walsh et al., 2005). Floods occur in rural and urban areas in Kenya. Eldoret town, experiences floods during the rainy season. The main causes of the observed flooding phenomena in Eldoret are characteristically due to unplanned urban development, drainage clogging and precipitation intensities among other hydrological factors.

The situation is aggravated further by increase in population growth compounded by poorly planned land-use practices which have impacted negatively on the catchment's structural and natural ecological stability over the years. This is more pronounced in one of the main tributary to Sosiani River in Eldoret town. The stream was initially covered with reeds but now it is a drain. The area that used to be swampy has been developed leading to the increase of impervious surface with the attendant risk of flooding the drain. When flooding occurs, loss of property and lives can occur as witnessed in the study area (Bwisa, 2014).

As developments take place, the amount of impervious surface will increase and discharge into the drain will increase and if it is going to flood it will damage many houses and other properties next to the Trokadero Bus Stage. There is need to develop sustainable cities that guarantee safety of people and property from disasters like storms and resulting runoff. This calls for mitigation measures to control floods in the urban areas which can be done using modeling techniques like Storm Water Management Model (SWMM) which has been tested for small towns and is used worldwide (Kourtis et al., 2017, Niyonkuru et al., 2018). This model was developed by US Environmental Protection Agency. The model has been evolving from Version 1 in 1971 to Version 5 of 2005 called SWMM5. SWMM5 can be used for a single event or long-term simulation of runoff quantity primarily from urban areas. The model uses a 1-D approach for dynamic wave routing producing the most theoretically accurate results (Niazi et al., 2017).

Rainfall-runoff modeling informs flood control prevention in planning for sustainable and secure towns in regard to flood damages, through flood prediction (Blöschl et al., 2008), formulation of stormwater management strategy and drainage system design (Crobeddu et al., 2007). To model hydrological processes in SWMM5 model, sub-catchments are divided into impervious and pervious areas and expressed as a percentage of the total drain area. Losses in impervious areas are only due to depression storage, while in pervious areas losses occur due to infiltration (Cambez et al., 2008). Since SWMM is in use internationally, it is good practice to test in every corner of the globe to inform future versions improvement of the model by addressing model inefficiencies as argued by Pretorius et al., 2013.

Therefore, there was need to determine rainfall intensities and percentage of imperviousness that resulted in flooding of the Eldoret drain with a view of calibrating and validating SWMM5 model for rainfall-runoff simulation in Eldoret town stream which has not been done. Validated model will assist the town planning department to control development.

2.0 METHODOLOGY

2.1 Study Area

This study was conducted in Eldoret town (Figure 1) which lies within latitude 0.26°3' N - 0.35°34' N and longitude 35.12°21' E - 35.20°31' E.

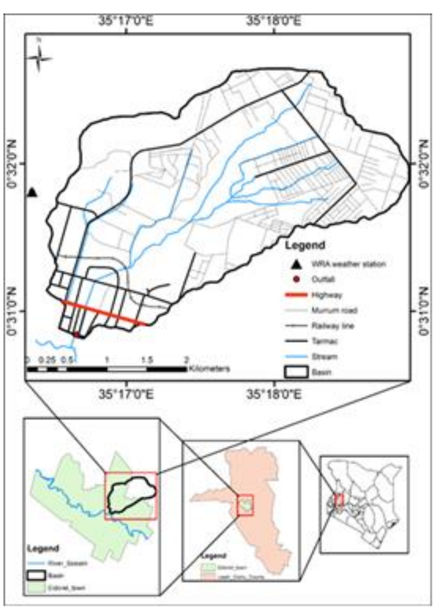

Figure 1: Map of the study area

The study area experiences two rainy seasons with average rainfall ranging from 900 mm to 1,200 mm per annum and average temperature range between 8.40C and 270C (Kemboi et al., 2018). Rocks in the study area are volcanic. Soils are primarily red to strong-brown friable clays with laterite horizon and gleysols that do not drain easily (Kiptum and Ndambuki, 2012).

2.2 Modeling Inputs

2.2.1 Area

A digital Elevation model (DEM) for 2014 was downloaded from earth explorer 2019 from United States Geological Survey's Earth Explorer site (http://earthexplorer.usgs.gov/) defined by attributes: Entity ID (SRTM1N00E035V3); Date of acquisition was 11.02.2000; Date of publication was 23.09.2014. This is an open source data download service. The digital elevation model had a resolution of 1-ARC SEC (30m x30m) in ASCII Grid format.

The study sub catchment was obtained through DEM delineation in ArcGIS 10.2.2 toolbox under hydrology. The gauging point at Bandaptai in Eldoret was selected as the outfall of the catchment. This process resulted in the definition of the basin (study sub catchment) that drains its water through the outfall of the sub catchment (gauging point). Area computation tool was then used in ArcGIS 10.2.2 environment to determine the area of the study sub catchment.

For detailed SWMM model structure, the study sub catchment had to be further sub divided into sub basins. Subdivisions were performed in ArcGIS by introducing additional pour points along the streams within a catchment based on the stormwater system layout and flow accumulation grid. Area of each sub basin was also determined.Width of each sub basin was estimated by dividing the area of a basin by its longest flow path.

2.2.2 Slope

Study sub catchment polygon which had been obtained during delineation to determine the area, was used to clip DEM for the sub catchment. The downloaded area of interest DEM was loaded as input feature, a process which resulted in obtaining a DEM for the study sub catchment. Slope was computed in percentage using surface tool under spatial analyst extension in Arc map 10.2.2 Software. Slope in percentage was then classified into three classes.

2.2.3 Percentage Imperviousness

Determination of percentage imperviousness for each sub catchment was done using the grid method. A shape file of the study area sub catchment indicating the sub basins was loaded onto Google Earth software; which was able to provide a 2019 April image of the area of interest. The sub basins were marked as S1 to S23. Each sub basin was zoomed in to fit the computer screen and printed upon which 1cm grids were drawn over and the grid method applied through close observation and calculation to obtain the percentage impervious area for each sub basin. Impervious areas include developed areas which could allow very low water infiltration to take place. Weighted percentage proportion of each sub basin as expressed in respect to its size and proportion to the entire area was determined. These percentages were then summed up to come up with the percentage imperviousness of the entire study sub catchment.

2.2.4 Rainfall and Outfall Discharge

Rainfall was measured using the standard rain gauge and rainfall records were recorded every 30 minutes. The rain gauge was located 1 km away from the discharge point and the observed rainfall was assumed to be the total amount of rain occurring in the catchment. Discharge through the outfall of the study area was measured by application of current meter method. Discharges were recorded before the rainfall, during the rainfall (30 minutes) and one hour after the rainfall event. The average discharge per rainfall event was determined for use in modeling. A total of six events were measured.

2.2.5 Flow System Layout Parameters

Hydraulics tool was used to enter junction parameters which were obtained through study area DEM analysis and ground measurement. These included the invert elevation of the junction and its maximum depth. A total of 19 junctions were considered for modeling. The same tool allowed for input of conduit parameters which were also obtained through DEM analysis and measurement. Conduit dimensions which included depth, bottom with and top width were determined through measurement by a tape measure. Side slopes were determined through calculation.

2.3 Calibration and Validation of SWMM5 Model

Three events were used in calibration. Parameters that were used for calibration of the model in Eldoret were; Manning's roughness coefficient for impervious area (N-IMPERV), Manning's roughness coefficient for impervious area (N-PERV), Depth of depression storage on impervious area (Dstore-Imperv), Depth of depression storage on impervious area (D-store-Perv). Three events were also used to validate the model after the calibration process.

2.3.1 Model Efficiency

Four measures of fitness used to test model efficiency were; Coefficient of Determination (R^2), Nash–Sutcliffe Efficiency (NSE), Integral Square Error (ISE) and Root Mean Square Error (RMSE). The coefficient of determination R^2 is defined as the squared value of the coefficient of correlation while RMSE represents the sample standard deviation of the differences between simulated and observed values. NSE value of 0.5 to 1.0 means excellent calibrating rating (Pretorious *et al*., 2013). ISE has an excellent measure of goodness-of-fit between observed and simulated hydrographs (Shamsi and Koran, 2017).

3.0 RESULTS AND DISCUSSION

3.1 Catchment Characteristics

The total area of sub catchment modelled was 696.5 hectares. This area was less than 1 % of 166,130 hectares modeled by Niyonkuru *et al*., 2018. This showed that the model is robust and can work for both small and large catchments. Sub-division of the catchment resulted in 23 sub basins that formed the drainage of the study area. The size of each sub basin, slope and width are shown in Table 1. Figure 2 indicates the sub basins, junctions and conduits within the study sub catchment.

The northern part of the study sub catchment consists of medium residential use while commercial buildings which are closely packed are found in the southern part of the sub catchment. The sub basin size averaged a value of 30.3 ha with the largest sub basin (S3) covering an area of 64.7 ha and the smallest (S23) being 3.9 ha.

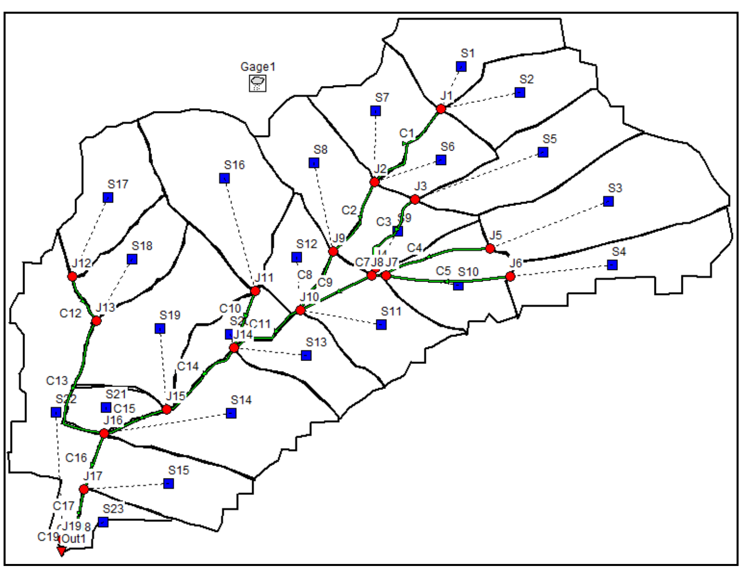

Figure 2 Sub basins, Channels, Junctions and gage station.

Table 1 Sub basins attributes

Sub Basin	Area (ha)	Width (m)	% Imperviousness	Average% Slope
S1	27.6	262	38	1.8
S2	28.2	265	23	1.8
S3	64.7	402	39	2.1
S4	34.7	290	24	3.1
S5	37.4	305	23	2.2
S6	14.0	184	1	2.3
S7	26.2	255	18	2.7
S8	31.0	276	28	3.3
S9	17.5	205	18	1.9
S10	29.1	270	27	2.3
S11	42.2	326	14	2.2
S12	12.1	174	13	1.9
S13	19.6	221	13	2.4
S14	51.2	360	19	3.3
S15	29.1	270	29	3.8
S16	56.4	375	43	3.2
S17	29.1	270	11	3.3
S18	19.7	221	9	2.9
S19	49.0	350	23	2.4
S20	11.3	168	14	1.8
S21	5.2	114	15	2.2
S22	57.3	360	38	2.8
S23	3.9	100	68	3.3

3.1.1 Slope

The maximum and minimum elevation above the sea level for the study area was found to be 2176m and 2074m, respectively with mean elevation of 2150m. Slope in percentage was categorized into three classes as shown in Figure 3.

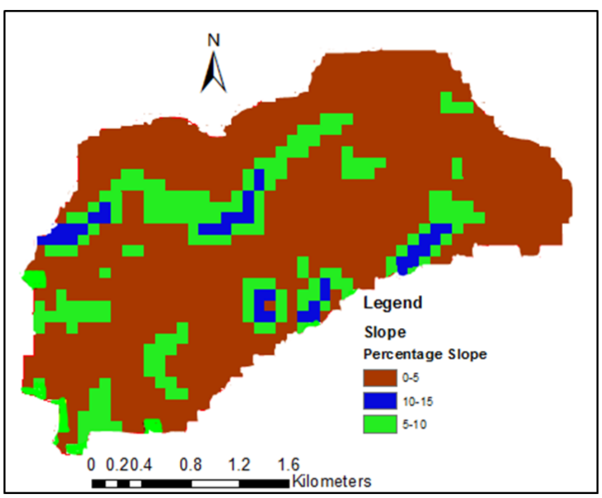

Figure 3: Slope Categories

The average slope used in SWMM5 model was 2.57%, while maximum and minimum slope for the sub catchment was 0.2% and 14.3%, respectively. There were three classes of slope namely; flat (0-5 %), gentle slope (5-10 %) and moderate slope (10-15 %). Flat area characterized the sub catchment with an area of 640.78 hectares equivalent to 92 % of the total area, while gentle slope was 5% and moderate slope was 3% (20.89 ha). The slopes are similar to 5.3% to 37.1% used in US by Thompson *et al*., 2013.

3.1.2 Percent Imperviousness

Estimated impervious surface area was 169.5 hectares (25.72%) of the total sub catchment area while 527 hectares (74.28%) constituted the pervious surfaces (Figure 4). Sub basin S23 had the highest percentage imperviousness at 68% while sub basin S6 had the lowest percentage imperviousness at 1%. Interestingly Sub basin 23 had the smallest area and had the highest imperviousness. S23 is in Eldoret town Central Business District.

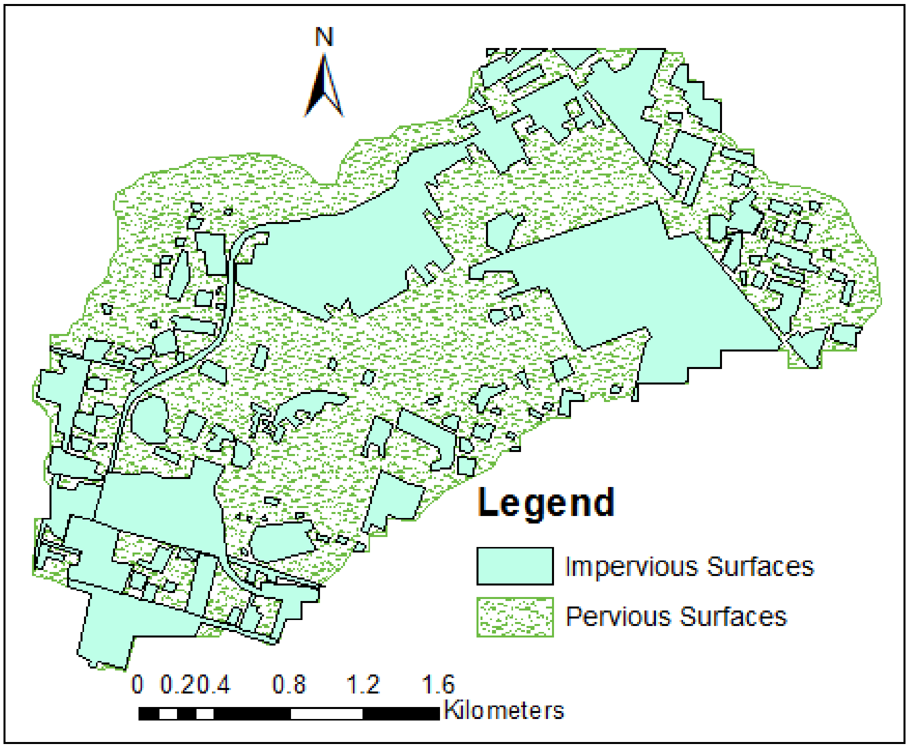

Figure 4: Impervious and Pervious areas

3.1.3 Rainfall and Discharge through the Outfall

The recorded rainfall and outfall discharges are presented in Table 2. The river base flow was found to be 0.002 m^3/s. However, during prolonged rainfall, the discharge increased up to 32.4 m^3/s. The highest recorded rainfall resulted in flooding while the rest didn't. The rainfall duration varied from thirty minutes to three hours. The time to peak was 30 minutes after rainfall.

.

Table 2: Recorded Rainfall and Discharge during the study

Year	Date	Rainfall recorded (mm)	Average Discharge at Catchment Exit (m^3/s)
2019	23 April, 2019	5.0	0.015
2019	27 April, 2019	7.0	0.025
2019	4th July, 2019	8.0	0.034
2019	11th July, 2019	12.1	0.060
2019	12th July, 2019	15.1	0.074
2019	9th August, 2019	32.4	0.131

3.1.4. Flow System Layout Parameters

The conduits were open channels with trapezoidal shape. The dimensions of the channels were as follows: maximum depth (1.5 m), bottom width (1.2 m), top width (1.5 m) and side slopes of 1:12. The longest stream that drains the sub catchment measured 4500 meters. The channels, junctions and lengths are tabulated in Table 3. C5 and C7 were longest and shortest conduits, respectively. Roughness coefficient of 0.05 were for gravel or stony areas while roughness coefficient 0.02 were for channels lined with rubble masonry.

.

Table 3: Junctions and Conduits data

Nodes			Links		
Junction	Invert Elevation (m)	Maximum Depth (m)	Conduit	Length (m)	Roughness Coefficient
J1	2160	1.5	C1	653	0.05
J2	2144	1.5	C2	541	0.05
J3	2144	1.5	C3	517	0.05
J4	2132	1.5	C4	713	0.05
J5	2148	1.5	C5	824	0.05
J6	2150	1.5	C6	89	0.05
J7	2133	1.5	C7	60	0.05
J8	2131	1.5	C8	447	0.05
J9	2131	1.5	C9	512	0.05
J10	2122	1.5	C10	394	0.05
J11	2127	1.5	C11	511	0.05
J12	2131	1.5	C12	326	0.05
J13	2118	1.5	C13	967	0.02
J14	2115	1.5	C14	607	0.05
J15	2103	1.5	C15	427	0.05
J16	2090	1.5	C16	381	0.05
J17	2081	1.5	C17	340	0.02
J18	2076	1.5	C18	47	0.02
J19	2075	1.5	C19	80	0.02
Out1	2074	1.5			

3.2 Calibration and Validation of SWMM5 Model for Eldoret

The adjusted values for calibration parameters are presented in Table 4. All the values were within the range indicated by the SWMM manual (Rossman, 2016). The value of N-imperv was similar to that observed by Niyonkuru et al., 2018. This suggests that this value is the same for large and small catchments.

Table 4: Modeling Parameters

Parameter	Description	Initial Value	Calibrated Value
N-Imperv	Manning's roughness coefficient for impervious area	0.01	0.015
N-Perv	Manning's roughness coefficient for impervious area	0.1	0.45
Dstore-Imperv	Depth of depression storage on impervious area	0.05	2.5
Dstore-Perv	Depth of depression storage on pervious area	0.05	8.0

Table 5 Observed and simulated values for calibration and validation

Calibration		
Date	Observer Avg. Runoff	Simulated Avg. Runoff
27/4/2019	0.025	0.024
23/4/2019	0.015	0.015
4/7/2019	0.034	0.033
Validation		
12/7/2019	0.074	0.076
9/8/2019	0.131	0.132
11/7/2019	0.060	0.057

From Table 5, the model under-estimated the measured average discharges during calibration for two events. During validation, the model overestimated the discharges for two events and under estimated for one event.

Table 6: Measures of fitness with evaluated values for Calibration and Validation

Measure of Fitness	Calibrated	Validated
Coefficient of Determination (R^2)	0.99	0.99
Nash–Sutcliffe Efficiency (NSE)	0.97	0.99
Integral Square Error (ISE)	1.91	1.41
Root Mean Square Error (RMSE)	0.0013	0.0022

Calculated NSE and ISE values in Table 6 meant that the model could be used for planning, preliminary design and final design (Shamsi and Koran, 2017). NSE had a calibrated and validated value of 0.97 and 0.99, respectively while ISE had a calibrated and validated value of 1.91 and 1.41, respectively. The NSE values were agreeing with other researchers who reported the range of NSE of between 0.23 and 0.91(Niazi et al., 2017). In this study, R^2 had the same calibrated and validated value of 0.99 which meant the model can be used with high percentage of accuracy to run simulations and hence make predictions. RMSE had a value of 0.0013 m^3/s calibrated and 0.0022 m^3/s validated. These values were close to 0 meaning that observed and simulated values matched and hence the model was able to fit the data (Harris et al., 2010).

4.0 CONCLUSION AND RECOMMENDATION

The catchment was calibrated by having the following; N-Perv (0.45), Dstore-Imperv(2.5), Dstore-Perv (8.0). The model excellently simulated the average discharges in the study area and hence the possibility of using the model for final designs of drains in Eldoret town. The catchment was subdivided into 23 sub catchments with varying areas and levels of imperviousness. Catchment imperviousness ranged from 1% to 68%. Average slope for the entire catchment was 2.57%. The longest stream that drains the sub catchment measured about 4500 meters. Rainfall event of 32.4 mm resulted in the maximum average discharge of 0.131m^3/s. The study recommends the widening of the drain to accommodate flows greater than 0.131 m^3/s. Another study can be done to calibrate the model by using different rainfall events and their resulting discharges.

Acknowledgment

The researchers would like to thank the Ministry of Education, Kenya, in collaboration with African Development Bank for financial support.

References

[1] Blöschl, G., Reszler, C., &Komma, J. 2008. A spatially distributed flash flood forecasting model. *Environmental Modelling& Software*, *23*(4): 464-478.

[2] Booth, D. B., Kraseski, K. A., & Rhett Jackson, C. 2014. Local-scale and watershed-scale determinants of summertime urban stream temperatures. *Hydrological Processes*, *28*(4): 2427-2438.

[3] Bwisa, G. 2014. Huge losses as floods cause havoc in Eldoret. *Kenya Daily Nation.*

[4] Cambez, M. J., Pinho, J., & David, L. M. 2008. Using SWMM 5 in the continuous modeling of stormwater hydraulics and quality. In *11th International Conference on Urban Drainage, Edinburgh, Scotland, UK*. 1-10.

[5] Crobeddu, E., Bennis, S., &Rhouzlane, S. 2007. Improved rational hydrograph method. *Journal of Hydrology*, *338*(1-2): 63-72.

[6] Harris, P., Fotheringham, A. S., Crespo, R., & Charlton, M. 2010. The use of geographically weighted regression for spatial prediction: an evaluation of models using simulated data sets. *Mathematical Geosciences*. *42*(6): 657-680.

[7] U.S. Geological Survey, 2014, USGS EROS Data Center (http://earthexplorer.usgs.gov/) accessed on June, 21, 2019

[8] Kemboi, T. H., &Jairus, K. N. 2018. Tour Guiding Performance Attributes and Tourist Satisfaction: Evidence from North Rift Tourist Region, Kenya. *Journal of Hotel Management and Tourism Research*, *3*: 8-23.

[9] Kiptum, C.K, and Ndambuki J.M. 2012. Well water contamination by pit latrines. A case study of Langas in Eldoret town. International *Journal of Water Resources and Environmental Engineering.* 4: 35-43.

[10] Kourtis, I. M., Kopsiaftis, G., Bellos, V., & Tsihrintzis, V. A. 2017. Calibration and validation of SWMM model in two urban catchments in Athens, Greece. In *International Conference on Environmental Science and Technology (CEST)*.

[11] Niazi, M., Nietch, C., Maghrebi, M. ASCE, A.M., Jackson, N., Bennett, R.B., Tryby, Massoudieh, M. A. 2017. Storm Water Management Model: A review and gap analysis. *Journal Sustainable Water Built Environment*, 017, 3(2): 04017002

[12] Niyonkuru, P., Sang, J.K., Nyadawa, M.O., and Munyaneza, O. 2018. Calibration and Validation of EPA SWMM for Stormwater runoff modeling in Nyabugogo Cathment, Rwanda. *Journal of Sustainable Research in Engineering*. 4(4): 152-159.

[13] Ouma, Y. O., &Tateishi, R. 2014. Urban flood vulnerability and risk mapping using integrated multi-parametric AHP and GIS: methodological overview and case study assessment. *Water*, *6*(6): 1515-1545.

[14] Pretorius, H., James, W. and Smith, J. 2013. A strategy for Managing Deficieciences of SWMM Modelling for Large Undeveloped Semi-Arid Watersheds. *Journal of Water Management Modelling* 10.14796/JWMM.R246-01.

[15] Rossman, L. A. 2016. *Storm water management model user's manual, version 5.0*, 276. Cincinnati: National Risk Management Research

Laboratory, Office of Research and Development, US Environmental Protection Agency.

[16] Shamsi, U. M. S., & Koran, J. 2017. Continuous calibration. *Journal of Water Management Modeling*.

[17] Thompson, J.R., Wu, J.Y., Kolka, R.K., Franz, K.J. and Stewart, T.W. 2013. Using the Storm Water Management Model to Predict Urban Headwater Stream Hydrological Response to Climate. *Hydrol. Earth System. Sci.,* 17: 4743-4758.

[18] Walsh, C. J., Roy, A. H., Feminella, J. W., Cottingham, P. D., Groffman, P. M., & Morgan, R. P. 2005. The urban stream syndrome: current knowledge and the search for a cure. *Journal of the North American Benthological Society*, *24*(3): 706-723.