JOURNAL OF FLOOD ENGINEERING
Vol. 10 No. 1 (January-June, 2019)

THE EFFECTS OF DEVELOPMENT ACTIVITIES ON THE OCCURRENCE OF FLOODS IN THE MBABANECITY: SWAZILAND

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Received: 13th March 2018 Revised: 24th April 2018 Accepted: 10th October 2018

ABSTRACT: Urbanization and expansion of structural developments within the urban area of Mbabane are challenges that require a rapid response in terms of flood-damage mitigation measures. There have been several cases of flash floods in Mbabane mostly resulting from heavy downpour and a poor drainage system, thus causing in loss of property and goods. In this study, the effects of development activities on the occurrence of floods in Mbabane City were investigated using two set of orthophotomaps one for 1972 (Scenario 1) and the other for 2003 (Scenario 2). Impervious areas were computed and quantified to determine the hydrological response of the catchment due to development activities. The study used two approaches, where the amount of runoff in two scenarios were estimated (i) using the runoff coefficient method and (ii) a runoff simulation model (SWMM). Before the simulation was run, some parameters of the model were computed using physical characteristics while others were estimated using secondary data. Results thus obtained indicate that increasing development activities were responsible for the occurrence of flash floods in Mbabane City and primarily due to percent increase of imperviousness which had increased in 2003 compared to 1972. It was also determined that the generated amount of volume (of runoff) from Scenario 2 far exceeded that from Scenario 1.Therefore, it is recommended that the drainage system in the Mbabane city be upgraded, properly re-routed and cleaned regularly while the Mbabane River should be channelized to accommodate excess runoff or alternatively a gauging station together with a flood-warning system be installed to reduce loss of life and property in the city.

Keywords: Catchment, Flash flood, Impervious areas, Rainfall-runoff modeling, Runoff coefficient, Surface runoff, Urbanization

1. INTRODUCTION

Over the years, Mbabane City, a riverside township in the north-eastern areas of Swaziland has been experiencing extensive development coupled with high urban growth hence increasing of impervious areas within its watershed. In addition to this, heavy rains in this area have been causing frequent floods with roads in many places submerged for several hours and the road traffic coming to a halt, taking the people at large off guard and bringing in considerable damage to public and private properties. The scientific debates on possible changes in runoff/ flood regimes induced by climate and land-use changes have been lively in the recent decades as these can influence the water cycle dramatically, and in turn the magnitude of flood peaks and volumes (Ranzi *et al.*, 2002).

The changes made to an area by construction of a concentration of buildings have a direct effect on its surface hydrology (Shaw, 1996). The covering of the land surface by a large proportion of impervious material means that a much larger proportion of any rainfall forms immediate runoff and any slope of the land also greatly enhances the runoff response of a paved area (Shaw, 1996). Mbabane, is at risk due to surface water flooding and as well as riverine flooding. Flowing through the city centre is the Mbabane River, whose capacity to convey water is being altered resulting in increased stage corresponding to a given discharge. In particular, structures that encroach into the floodplain, such as bridges, can increase upstream flooding by narrowing the width of the channel and increasing the channel's resistance to flow. As a result, the water is at a higher stage as it flows past the obstruction, creating a backwater that will inundate a larger area upstream (U.S. Geological Survey, 2005).

The World Meteorological Organization and Global Water Partnership (2008) assert that floods are a consequence of natural hydro-meteorological phenomenon, combined with their interaction with the catchment characteristics. Flood-damage mitigation embraces methods for combating the effects of excess water in streams (Linsley *et al*. 1992). It is important to note that little can be done to control floods either economically or physically. Therefore, according to Linsley *et al*. (1992), absolute control over floods is not feasible.

There have been several cases of flash floods in Mbabane mostly resulting from heavy downpour and poor drainage system whose operational capacities could not cope with excessive surface runoff (Bicon Consulting Engineers, 2008). The most recent flood event in Mbabane occurred on the17th February 2006. It was preceded by another flood event which occurred on the 17th March 2005 and another one which occurred on the 28th November 2003 (Bicon Consulting Engineers, 2008).

The progressive transformation of the watershed from rural to urban land uses have highlighted the need to understand the consequences of urban developmental activities on flooding of the Mbabane urban area. Since there is limited data on Mbabane River it is not easy to predict the occurrence of floods. Therefore, there is need to mitigate the flood-damage which needs proper identification of the effects of development activities on the occurrence of floods for an effective flood-damage mitigation/flood control measure.

1.1 Causes of Flooding

The World Meteorological Organization and Global Water Partnership (2008) assert that a flood as an extreme event/hazard is caused by natural forces or a combination of natural forces and human influences. Nelson (2010) contends that whenever humans modify the landscape in any way changes are to be expected in the way water drains from the land. Unless careful consideration is given to the possible drainage consequences, such landscape modifications can result in higher incidence of flooding. Development on floodplains should therefore be undertaken only with great care. Existing developments that have enhanced flooding problems are often costly to fix.

1.2 Effects of Urbanization on the Hydologic System

There are changes in land and water use when urbanization takes place. These changes have effects on the local water system. During initiation of urbanization, coupled with change in land use, there is often removal of trees and vegetation. Houses are built, some with sewers and some with septic tanks. The effect is more storm runoff and erosion because there is less vegetation to slow water as it runs down hills. More sediment is washed in to streams. Flooding can occur because water-drainage patterns are changed (U.S. Geological Survey, 2010).

1.3 Hydraulic Effects from Changes to Stream Channel and Flood Plains

Development along stream channels and floodplains can alter the capacity of a channel to convey water and can increase the height of the water surface (stage) corresponding to a given discharge. In particular, structures that encroach on the floodplain, such as bridges, can increase upstream flooding by narrowing the width of the channel and increasing the channel's resistance to flow. As a result, the water is at a higher stage as it flows past the obstruction, creating a backwater that will inundate a larger area upstream (U.S. Geological survey, 2005).

1.4 Effects of Urban Development of Flood Discharge and Frequency

Common consequences of urban development are increased peak discharge and frequency of floods. Typically, the annual maximum discharge of a stream will increase as urban development occurs, although the increase is sometimes masked by substantial year-to-year variation in storms (Konrad, 2005). Urbanization also affects the availability of sediment supplies and stream channel morphology. Knighton (1984) noted that available sediment sources can increase during urban construction and then decrease because of the increased stability of the urban landscape. Also, stream channel morphology adjusts to the increase in frequency of channel forming flows. Channel adjustments are often characterized by enlargement including: widening and down cutting of the streambed.

1.5 Managem, Ent Strategies

Mangarellaand Peter(2002) reviewed many different management programs in the USA that have been implemented nationwide. Typically, these programs focus on implementing Best Management Practices (BMP's) to maintain natural functions of the hydrologic and geomorphic processes, protect riparian corridors, and integrate storm water control measures into development to mitigate expected impacts. Some suggested actions include: maintaining the natural rainfall-runoff ratios, protecting hydrological sensitive areas, sediment sources, and sensitive habitat areas, minimize and hydraulically disconnect impervious areas, such as rooftops, rain gutters, parking lots and roads, minimize topography changes and soil compaction, cluster development in less sensitive areas, integrate flood control and water quality structure into the landscape, and stream channel day lighting (Alayande and Agunwamba, 2010). Therefore this study was designed to investigate the effects of development activities on the hydrology and thus the occurrence of floods in Mbabane City, by the comparison of two scenarios (before extensive and after extensive urbanization).

2. METHODOLOGY

2.1 Description of Study Area

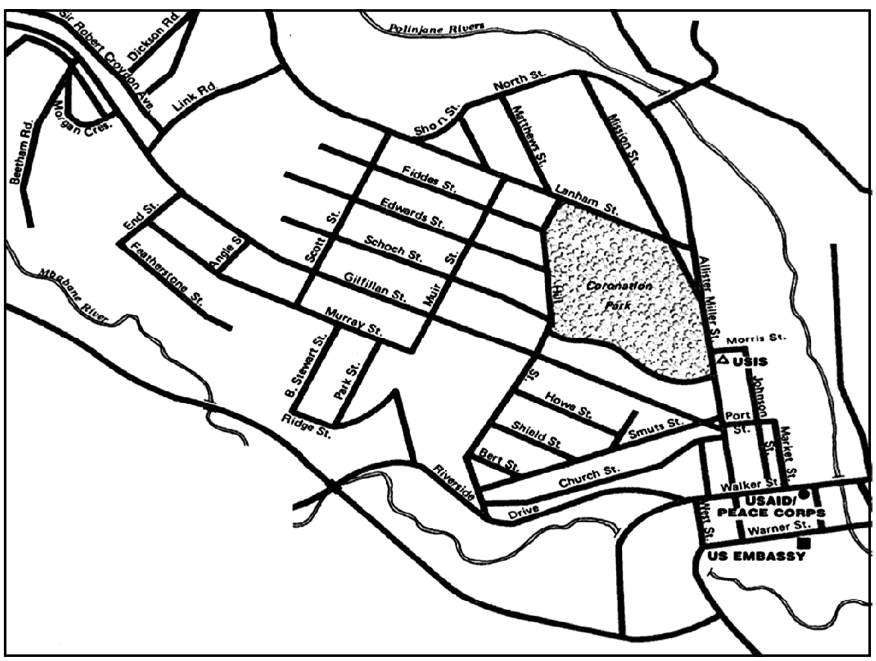
The Mbabane urban area is found in the Highveld, Hhohho region of Swaziland, in North-west Swaziland, between 31^0 8' 30" and 31^0 17' 45"E, and 26^0 5' 15" and 26^0 18' 45"S. The size of the urban area is 63.84 km^2 while the size of the study area is 64.82 km^2 (Central statistical office, 2007). The mean annual temperature for Mbabane is 18°C and the mean annual rainfall is 1450 mm (Swaziland Meteorological Service, 2010).

2.2 Hydrologic Conditions

The Mbabane urban area is drained by three streams, namely the Mbabane River, Pholinjane River and Umvubu River (Fig. 2). All these streams traverse the urban area. None of them is gauged. Upstream is the Mbuluzi drainage basin.

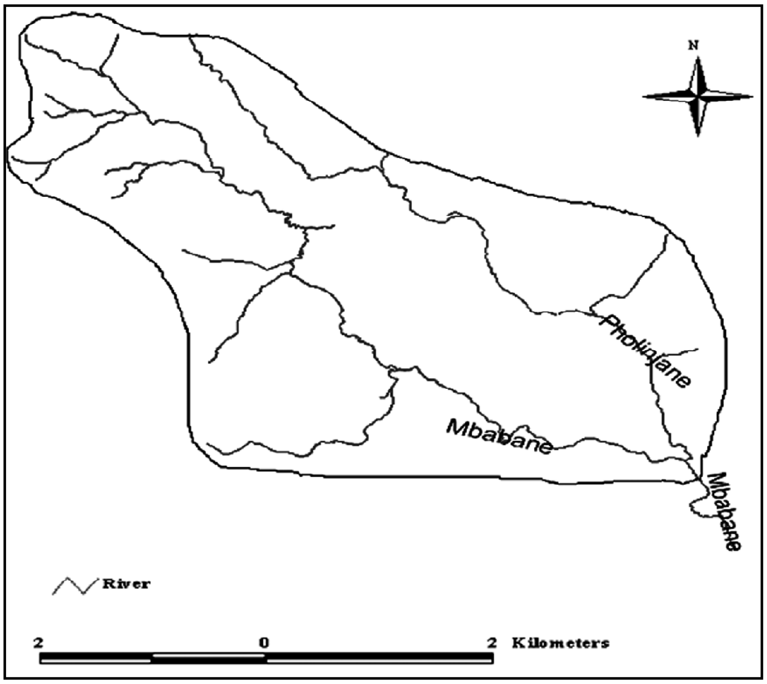
2.3 Developmetn Activities Existing in Mbabane Urban Area

Along the Mbabane River, hydraulic structures include the road bridge crossing the river near the Swazi Plaza. Just before the bridge is the Mall, characterized by structures and parking lots. Another bridge crosses the Mbabane River at the Plaza, where water moves below the Sales House building and another road crosses the river just below the Mbabane market and passes through the Mbabane Industrial Site where it then meets the Polinjane River (Fig. 1).



Source: **City Council of Mbabane (2008).**

Figure 1: Map Showing Mbabane City and a Section of Mbabane and Polinjane River



Source: **City Council of Mbabane (2008).**

Figure 2: Mbabane Drainage Map

2.4 Rainfall-Runoff Modeling

Hydrologic modeling is concerned with the flow of water and its constituents over the land surface and in the subsurface environment (Zulherman, *et al.*, 2003). It depends on the presentation of the land surface and subsurface because this is the environment through which water flows.

2.5 Structure of the Methodoliogy

The methodology developed in this study has two main stages with nine interrelated steps. The main stages include comparison of the amount of runoff volume generated in scenarios 1 and 2, and modeling of the rainfall-runoff processes for both scenarios.

2.5.1 Comparing the amount of runoff volume generated in scenarios 1 and 2

This stage has six steps which are explained as follows:

2.5.1.1 Compilation of existent meteo-hydrological data

2.5.1.2 Classification of land cover

2.5.1.3 Determination of impervious areas for scenarios 1 and 2

2.5.1.4 Determination of the Runoff coefficients

2.5.1.5 Computation of the catchment and sub-catchment area size

2.5.1.6 Estimation of runoff for scenarios 1 and 2

2.5.2 Modeling of rainfall-runoff process for scenarios 1 and 2

This stage has three steps which are explained bellow:

2.5.2.1 Derivation of the model parameters

2.5.2.2 Inserting parameters and input data in to the model

2.5.2.3 Running of the simulation

Topographical maps were the basis for conducting the study. The maps included the following set; an orthophoto, and the revised 1:50 000 topographic map. One set dated back to 1970s (before extensive urbanization) and the other for 2000s (after extensive urbanization). The land cover was determined using the orthophoto maps, to identify impervious areas. The Total Impervious Areas(TIA) for both periods were quantified and expressed as a percentage of the total area. The TIAs were then compared. This helped in detecting any land use changes between these two periods (increase/ decrease of size of impervious areas). The orthophoto maps were used since they have a high resolution compared to the topographic maps, often ranging from a scale of 1:10 000- 1:5000. The orthophoto maps with a scale of 1:10 000 were used in this study. Modeling of the rainfall-runoff process was conducted using the Storm Water Management Model (SWMM).

Comparison of the amount of runoff:

2.5.1.1 *Compiation of Hydro-Meterological Data*

Compilation of the hydro-meteorological data for the two periods was done. These include: terrain, soil, amount of rainfall. A Soil map of Swaziland was used to analyze the different soils which are found in the whole catchment.

2.5.1.2 *Determinition of Land Cover and Slope*

The land cover was classified into the following categories: namely grass, tar and gravel pavement, concrete pavement, rooftops and forest. Topographic maps were mainly used to analyze the terrain of the study area. These maps were also used to calculate the slope of each sub-catchment and the catchment as a whole.

The slopes were calculated using equations (1) and (2):

$$S_n = \frac{Y_{\max} - Y_{\min}}{X} \quad (1)$$

Where: S_n is the slope of a sub-catchment; $Y_{\max}$ and $Y_{\min}$ is the highest and lowest altitude of the sub-catchment and X is the horizontal distance between highest and lowest points.

$$S = \frac{Y_{\max} - Y_{\min}}{X} \tag{2}$$

Where: S is the slope of the catchment; $Y_{\max}$and $Y_{\min}$ is the highest and lowest points in the catchment and X is the distance between these two points

2.5.1.3 *Determinitaion of Impervious Areas*

The Total Impervious Area (*TIA*) was determined by using a Plannimeter for both scenarios and expressed as a percentage of the total area. This was done with an aid of orthophoto maps, by identifying all the impervious areas which only fell within the continental divide. These included any area which falls within the definition of building coverage and is paved with concrete, asphalt, pervious paving. It also includes roofed areas, parking areas and all areas prohibiting the infiltration of water. The scale of the orthophoto was used to convert the area of the impervious surfaces into the actual size on the ground. A simple equation was used to compute the percent imperviousness of the catchmentwhich is expressed as follows:

$$PIA = (TIA/A_d)\ 100\% \tag{3}$$

Where: *PIA* is the percentage of imperviousness (%); *TIA* is the total impervious areas and A_d is the total catchment area.

Therefore, all these calculated areas were then summed up to obtain the size of the total impervious areas. These were then expressed as a percentage.

2.5.1.4 *Determinitaion of the Runoff Coeffcients*

Equation 3 was modified to compute the runoff coefficient, k forall the sub catchments, which is expressed as follows:

$$k = TIA/A_s, \tag{4}$$

Where: k is runoff coefficient and A_s is the total catchment area

Appendix F,contains the values of k for various surfaces as reported by Linsley *et al.*, (1992) which were used as a guideline in computing the coefficients. It is important to note that the runoff coefficient is a function of land use of a specified area.

From Appendix F, urban residential houses have a low value of k, while impervious areas characterized with asphalt/concrete have a high value of k. A high value of k implies that the surface is more impervious, hence low infiltration and high volume of runoff is expected to be generated.

2.5.1.5 *Determinitaion of the Catachment and Sub-Catachmentareas*

The catchment was first divided in to two sub catchments. This is a requirement of the SWMM model. The sizes of each sub catchment and the total catchment (study area) were determined using a Plannimeter.

2.5.1.6 *Estimation of the Amount of the of Runoff*

Since the runoff coefficients for the study area were determined first, they were then used for the estimation of the amount of runoff.

The following are some of the approaches for computation of runoff from a catchment that were considered in this study. They include the Runoff coefficient approach and the Basin recharge method.

The two approaches:

(a) The Runoff coefficient approach;

$$R = kP \text{ (Linsley } et\ al.\text{, 1992)} \tag{5}$$

Where;

R : Runoff (mm)

k : Runoff coefficient (percentage of impervious area)

P : Rainfall amount (mm)

Therefore, since the runoff in equation (5) above was computed as a depth, it was necessary to modify it to allow for the computation of runoff in volume, hence equation (6) of the form:

$$R = kPA \tag{6}$$

was also used,

Where A is the area of the catchment

(b) Basin recharge method

$$(R = P - L - G) \quad \text{(Linsley } et\ al.\text{, 1992)} \tag{10}$$

Where R is runoff, P is precipitation, L is basin recharge and G is groundwater accretion (Linsley, *et al*., 1992).

In this study the estimation of the amount (depth and volume) of runoff was done using the Runoff coefficient approach, since according to Linsley *et al*., (1992) it is suitable for urban drainage problems where the amount of impervious area is large.

3. MODELING

The modeling of rainfall-runoff using the data for the two scenarios was conducted to determine whether or not development activities have an effect on the occurrence of floods in Mbabane City. This was done using the Storm Water Management Model (SWMM). The model parameters were to be derived first, before the simulation of runoff. The model parameters include the following; percentage imperviousness, time of concentration, slope, Manning's roughness coefficient for the streams and the land surface, runoff curve numbers, suction head and hydraulic conductivity.

3.1 Time of Concentration

This is the time taken to travel from the farthest point of the catchment to the outfall. The time of concentration is a function of the distance from the farthest point of the catchment to the outfall, the catchment slope, roughness and geometry. After time T_c from the commencement of rain, the whole catchment is taken to be contributing to the flow. Therefore, the peak flow Q_p occurs after the period T_c (Shaw, 1996), thus if T_c is long, Q_p will be delayed. Since the response of the impervious surfaces is rapid, it results to short time of concentration of the flow in the drainage basin (Shaw, 1996).

The time of concentration (T_c) was computed using the equation.

$$T_c = 0.00025 \left(\frac{L}{\sqrt{S}} \right)^{0.80} HRS \text{ (Shaw, 1996)} \quad (7)$$

Where

T_c : time of concentration (HRS)

L : length of catchment along longest river channel

S : overall catchment slope

3.2 Manning's *n* Roughness Coefficient

The Manning's roughness coefficients were estimated from Appendices B and C (Typical values). These included the Manning's roughness coefficients for open channels and overland flow. For scenario 2, the coefficient was derived through inspection of the channel, while for scenario 1, the value of *n* was assumed to be the same as in scenario 2, because it was impossible to derive.

3.3 Suction Head and Hydraulic Conductivity

The Suction head and the Hydraulic conductivity were estimated from Appendices D and E respectively. It can be noted from Appendix D that the suction head increases with a corresponding decrease of the size of the grains. However, the opposite is evident with hydraulic conductivity. The suction head and hydraulic conductivity are required in the Green-Ampt equation to model infiltration.

The soil suction is important since it is used to determine how much water can be held in different soils at specific energy levels. If a specific soil can retain more water, it follows that it has a potential to produce more runoff, due to less infiltration. Therefore, soils with larger pores can retain less water at a given suction than soils with smaller pores. This is because the smaller pores exert greater suction on soil water than can be exerted by larger pores.

Hydraulic conductivity is influenced by the properties of the fluid being transmitted (such as viscosity) as well as porous medium (The Australian Government, 2011). Since hydraulic conductivity defines the ease of water movement through the pore spaces of the soil, it follows that any grains whose particle size distribution is not consistent (does not permit the free flow of water) will impact the infiltration of water in the soil. Therefore, soils with high hydraulic conductivity will tend to produce less runoff than those with low hydraulic conductivity.

3.4 Curve Numbers (Cns)

Curve numbers were estimated using Appendix A. The curve numbers were estimated on the basis of the following; soil type, soil hydrologic group, land cover and the land use. The estimation was done using the Weighting method. The land cover, land use and the soil type were identified for each sub catchment. However, the hydrologic soil groups were determined for the two sub catchments. These (soil groups) enabled the derivation of the curve numbers. Therefore, the CNs for the corresponding soil groups and land uses, were weighted to derive the CNs for each sub catchment. The curve numbers were used in the estimation/ prediction of runoff and infiltration (in SWMM) from rainfall excess in the Mbabane river catchment.

Table 1 is a presentation of the hydrological soil groups with their saturated conductivity which are a function of the hydrological response of the soil. It can be noted, from Table 1 that soils with a low runoff potential have high infiltration rates (for example, Group A). Conversely, soils with low runoff potential are characterized with a low infiltration rate (for example, D).

Storm Water Management Model (SWMM) application and simulation.

Modeling of the rainfall-runoff was done using the SWMM model. This model was used to conduct the hydrological analysis for the two scenarios (1972 and 2003).

This helped to describe realistically the processes of the rainfall, overland flow and infiltration within the entire catchment. The aim of the model was to determine the hydrological response of the Mbabane watershed at the specified two scenarios.

Table 1
RCS Hydrologic Soil Group Definitions

Group	*Meaning*	*Saturated conductivity (in/hr)*
A	Low runoff potential. Soils having high infiltration rates even when thoroughly wetted and consisting chiefly of deep, well to excessively drained sands or gravels	≥ 0.45
B	Soils having moderate infiltration rates when thoroughly wetted and consisting chiefly of moderately deep to deep, moderately well to well-drained soils with moderately fine to moderately coarse textures. E.g., shallow loess, sandy loam.	0.30 – 0.15
C	Soils having slow infiltration rates when thoroughly wetted and consisting chiefly of soils with a layer that impedes downward movement of water, or soils with moderately fine to fine textures. E.g., clay loams, shallow sandy loam.	0.15 – 0.05
D	High runoff potential. Soils habing very slow infiltration rates when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a clay-pan or clay layer at or near the surface and shallow soils over nearly impervious material.	0.05 – 0.00

Source: U.S. Soil Conservation Service (1986)

Figure 3 shows the sketch of the study area which was drawn in SWMM before the simulation was conducted. It was expected that runoff contributions from subcatchment.

1 is higher than that of sub catchment 2. This is because sub catchment 1 is larger and had higher impervious areas as compared to sub catchment 2.

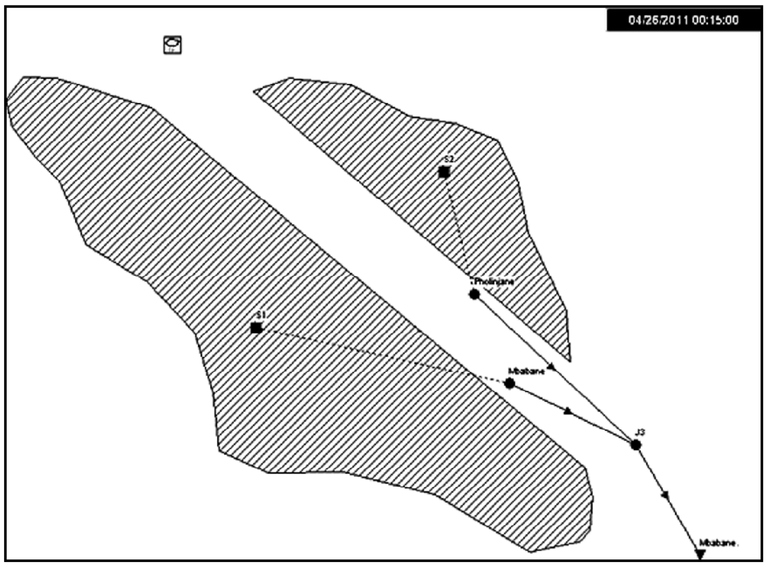


Figure 3: Schematic Representation of the Study Area According to Storm Water ManagementModel (SWMM)

Sensitivity analysis of the model parameters was performed prior to the simulation. It provides an insight on the relation between the assigned model parameters and the simulated hydrological response. Parameter sampling was performed. The output of the analysis helped in ranking the parameters of the model in terms of their sensitivity towards the model output. The analysis enabled better representation of the system which produces more accurate and reliable outputs. The results of the analysis showed that in most conditions the parameters: runoff coefficient and catchment size, have more significant effects on the results than other parameters.

4. RESULTS

Rainfall storm events data and physical characteristics of the catchment. The data on the amount of rainfall for the two scenarios were collected from the National Meteorological Services and these are shown in Table 2. The 176 mm (before extensive urbanization) for scenario 1 was selected since it far exceeds that of scenario 2 (after extensive urbanization). This helped to show the effect of the impervious surfaces on runoff, thus enabling the study to draw concrete and sound conclusions. The 21st January 1971 falls under Scenario 1, while the 28th November 2003 falls under scenario 2.

Table 2
The Selected Daily Rainfall Data for (Scenario 1 and 2)

Scenario	*Date*	*Rainfall amount (nm)*
1	21st January 1971	176
2	28th November 2003	78.2*

Source: Swaziland Meteorological Services (2010).

It can be seen from Table 2 that high rainfall amount was received in scenario 1 as opposed to scenario 2. It should be noted that the little rainfall amount (78.2 mm) received on the 28th November 2003 resulted in a flood in Mbabane City.

4.1 Soils

The different soil types were determined by using a Soil map of Swaziland. These different soils were identified in the two sub catchments. Table 3 presents the soil types of the Mbabane River catchment area.

4.2 Key

DH-shallow black hill peat, Organic Soil; U-Rock outcrops and stony ground Raw Mineral Soil; JH-Grey loam; Q-Grey on orange gravelly loam; G-Grey sandy loam; O-Shallow grey sand to sandy loam on hard rock; N-Deep yellow on red loam; ZH-Shallow red loam; I-Marsh soil, mottled sand to clay; SH-Dark brown clay; A-Deep yellow loam; TH-Pale red sandy loam on rotten rock; M-Deep red loam

Table 3
Soil Types of Each SubCatchment

Sub catchment	*Dexcription of the Soils*	*Soil type*
Sub catchment 1	DH, U, N, ZH, JH, I, SH, A, TH, O	Clay sandy loam
Sub catchment 2	N, I, TH, U, G, DH, O, Q, JH, A, SH, M	Clay sandy loam

It can be concluded from Table 3 that the catchment has almost homogeneous soils. Generally, the soil type found in all the two subcatchment can be defined as clay sandy loam. However, it can be noted that subcatchment 1 slightly differs from subcatchment 2. This is because Sub catchment 1 has shallow red loam while 2 do not have. Also, Sub catchment 2 has grey on orange gravelly loam and grey sandy loam which are not found in sub catchment 1.

4.3 Suction Head and Hydraulic Conductivity

Table 4 presents the Soil Suction Head and the Hydraulic conductivity for the two sub catchments. The suction head and hydraulic conductivity were found to be the same for the two subcatchments. This could be due to the similar soil types of the two subcatchments.

Table 4
Soil Suction Head and Hydraulic Conductivity for theCorresponding Sub Catchments

Sub catchment	*Suction head (mm)*	*Hydraulic conductivity (mm/hr)*
1	218.5	1.5 (sand clay loam)
2	218.5	1.5 (sand clay loam)

The suction head and the hydraulic conductivity were derived from the soil types in Table 3 and the customary values given by Smith, (2010), in Appendix D and E. These were derived since they were required in the rainfall-runoff simulation.

4.4 Curve Numbers

As stated earlier,a Curve Number is a function of the hydrologic soil group and land cover (imperviousness) of the area. It was essential to estimate the CN for each sub catchment since the land cover varies significantly. Table 4 presents the estimated CNs for each sub catchment.

It can be noted that the two sub catchments have similar hydrologic soil groups but different CNs. This can be attributed to the fact that a CN is a function of many factors. These factors include soil (type and hydrologic group), land use and the hydrologic condition. Therefore, two areas can have similar hydrologic soil groups but different land use and thus different curve numbers.

Table 5
The SubCatchments and the Corresponding Soil Groups and Estimated Curve Numbers

Sub catchment	*Soil type and group*	*CN*
1	Clay sandy loam (B)	81
2	Clay sandy loam (B)	77

4.5 Slope

The slopes were calculated using equations (8) and (9) and are shown in Table 6.

$$S_n = \frac{Y_{\max} - Y_{\min}}{X} \tag{8}$$

Where: S_n-Slope of the Sub catchment;

$Y_{\max}$: highest altitude in ridge$_n$;

$Y_{\min}$: lowest altitude in ridge$_n$;

X : horizontal distance between the 2 altitudes in ridge$_n$

$$S = \frac{Y_{\max} - Y_{\min}}{X} \quad (9)$$

Where: S-Slope of the catchment;

$Y_{\max}$: highest altitude in the catchment

$Y_{\min}$: lowest altitude in the catchment

and X is the horizontal distance between the highest and lowest altitude in the catchment.

Table 6
Mbabane River SubCatchments and Corresponding Slope

Sub catchment	*Slope*
Sub catchment 1	0.0383
Sub catchment 2	0.0503
Catchment slope	0.0443

The generated runoff in any catchment is a function of slope among other factors. Slope has an effect on the hydrology; it moves water more rapidly to the major stream systems and greatly reduces the lag time and increases the peak discharge of the streams collecting the runoff from the catchment, hence a possibility of the occurrence of the flash floods downstream.

4.6 Classification of Land Cover

The types of land cover in each sub catchment of the study area are shown in Table 7. These land covers were determined to be able to identify the impervious areas within the catchment. The land cover does not vary much in the sub catchments as shown in Table 7. However, the size of each type of land cover in each sub catchment, vary significantly.

Table 7
Classifications of Land Cover in the Mbabane River Catchment

Area	*Type of land cover*
Sub catchment 1	Forests, Tar, Concrete pavement, Rooftops, Grass
Sub catchment 2	Tar, Concrete pafement, Rooftops, Grass, Forests

4.7 Impervious Areas

Using the equation $PIA = (TIA/A_d)\%$, for calculation of the percent imperviousness yielded the values which are presented in Table 8. There has been an increase in the size of impervious areas in the watershed from scenario 1 to scenario 2 (Table 8). This increase in the impervious areas can be attributed to the development activities in the urban area of Mbabane. It can be concluded that in scenario 1, the urban area was not yet developed as in scenario 2 hence more impervious areas in the latter scenario.

Table 8
Percent Imperviousness in the Different Scenarios

Scenario	*% Imperviousness*
1	6.1
2	41.6

4.8 Estimation of Runoff

Equation 5 ($R = kP$) of the Runoff coefficient approach was used to compute the runoff generated in the two periods, as a depth while equation 6 ($R = kPA$), a modification of equation 5 was used to estimate runoff as a volume.Table 9 shows the size of each sub catchment and the whole catchment, which were determined using a Plannimeter as well as runoff.

Table 9
Size of the Sub Catchments and Corresponding Runoff Coefficient

Catchment	*Size (km²)*	*K*
Sub catchment 1	42.02	0.06
Sub catchment 1	22.8	0.41
Total	64.82	

It can be seen from Table 9that in scenario 2, the runoff coefficient was calculated to be higher than that of scenario 1. It can be concluded that between these two periods (scenario 1 and 2) the area in the Mbabane city has developed extensively in terms of impervious areas. The floodplain has since been encroached, and extensive development has taken place even atop the Mbabane River, since huge shopping complexes have been erected.

The computed amount of the generated runoff, using equation 5 ($R = kP$) and 6 ($R = kPA$) from the two rainfall storms, for the two scenarios is presented on Table10.

Table 10
Runoff Amounts for Selected Storm Events of (Scenario 1 and 2)

			Runoff amount
Scenario	*Date*	*Depth (mm)*	*Volume (m^3)*
1	21st January 1971	28.2	1 825 331.2
2	28th November 2003*	43.8	2 838 597.44

Table 10 reveals that a high volume of runoff was generated during the flood event (28th November, 2003), while less amount of volume was generated in scenario 1. This high volume of runoff in scenario 2 can be attributed to the high impervious areas which are a result of an increase in development activities within the catchment. On the other hand, the rainstorm generated from Scenario 1 did not produce much runoff since the catchment was less impervious than that of Scenario 2. This is regardless of the low magnitude of the rainfall in Scenario 2.

4.9 Time of Concentratio

The time of concentration was computed to be 7.345 hours. This is another SWMM parameter which needed to be computed before running the simulation.The time of concentration (T_c) was computed using equation 11 ($T_c = 0.00025\,(\frac{L}{\sqrt{S}})^{0.80}$).

4.10 Manning's N Roughness Coefficient

Table 11 presents the Manning's *n* roughness coefficient for overland flow and open channel which were estimated from the typical manning values (Appendix B and C). It shows the value of *n* for the two scenarios. The roughness coefficients for scenario 2 are actual values, since they were ascertained in the field, while those for scenario 1 were generalized from the values for scenario 2.

Since the roughness was not uniform across the channel width, it was essential to select different values of the coefficient. Then, the value of *n* was averaged to account for the varying channel roughness of the Mbabane River.

Table 11
Manning Values for the Mbabane River Catchment (Scenario 1 and 2)

	Mbabane River	
Scenario	*n; overland flow*	*n; open channel*
1	0.2	0.045
2	0.2	0.045

4.11 Modeling of Rainfall-Runoff Process

The Storm Water Management Model (SWMM) required that the sketch of the study area be drawn before the simulation. The sketch is shown in Figure 3.

Runoff was simulated using the hydro-meteorological data and parameters derived from the two scenarios. The detailed simulation results for the 21st January, 1971 rainfall storm and the 28th November, 2003 flood which were run in the SWMM model.

It can be noted from the results that the simulation from SWMM that a high volume of runoff was generated in scenario 2, which lead to the flooding of the area under study. It indicates that the Junction (J2) had the highest total flood volume (1730.89 liters). This high volume of runoff in scenario 2 can be attributed to the high impervious areas which are a result of an increase in development activities within the catchment. This prohibited infiltration, hence more overland flow.

5. SUMMARY ANDCONCLUSIONS

The hydro-meteorological data were gathered from the Swaziland Meteorological Services and the model parameters were computed while some were estimated. The SWMM model was selected since it was regarded as the most relevant model to address the aim of the study and it can be used in un-gauged catchments. These results show that there was an increase of the impervious areas between the two periods.

The runoff generated results in scenario 1 and 2 showed that in scenario 1, runoff was computed to be lower than in scenario 2, yet the rainfall in scenario 1 was higher than in scenario 2. This may be the result of the increase of impervious surfaces in the catchment due to development activities in the urban area of Mbabane. The simulation results from the SWMM model showed that the rainfall storm from scenario 1 did not result in any flood despite its high amount as opposed to the lower rainfall amount of in scenario 2 which resulted to flooding of the City.

The study proved that changes in land use in the urban area of Mbabane river catchment result in less vegetation, more bare land and more impervious areas. This is coupled with decreased pervious areas which often help in storing water (in the soil) that could have resulted in runoff. More sediment is washed off to streams thus reducing water carrying capacity, hence increasing peak stage of the stream. It can be concluded in this research study that more storm runoff is a result of more imperviousness, hence high possibility of flooding. However, it cannot be ascertained that urbanization has an effect in the occurrences of floods in general. These conclusions can only be drawn for the Mbabane river catchment.

Recommendations

The following recommendations emanated from this research study:

(i) To reduce the flood occurrences, the drainage system should be upgraded/ overhauled to correct operational capacities so to cope with excessive surface water runoff from the catchment.

(ii) To increase the carrying capacity of the stream, it is recommended that channelization that results to the widening of channel width at the flood zone be undertaken.

(iii) It is recommended that the stream and the entire drainage system be cleaned at least two/ three times a year or as per need.

(iv) To ensure minimum runoff, proper re-routing (of the system by storm sewers) that will convey the flood waters to safe areas downstream other than to the nearby stream (Mbabane river) traversing the City, is recommended. This can reduce the peak stage of the stream. It has been gathered that the system discharges the storm waters into the Mbabane River hence increasing its chances of flooding.

(v) Erection of flood-control structures (dams) is recommended.

(vi) The gauging of the river and the review of the land-use systems beyond the City and over the whole catchment is recommended. An early-warning system could also be put in place.

Acknowledgements

The authors are grateful to the people of Mbabane city and those who have helped to make this study a success.

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APPENDIX A

Typical Values of Curve Numbers for Different Cover Types for Urban Areas

Group *Cover description*		*CN* *Hydrologic soil*			
A Cover type and hydrologic condition	Average per cent impervious area	A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.) 3/:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only) 4/		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82

Source: U.S. Soil Conservation Services (1986).

APPENDIX B

Manning's Roughness *n* for Open Channels

Channel type	*Manning n*
Lined Channels	
– Asphalt	0.013 – 0,017
– Brick	0.012 – 0.018
– Concrete	0.011 – 0.020
– Rubble or riprap	0.020 – 0.035
– Vegetal	0.030 – 0.40
Excaveted or dredged	
– Earth, straight and uniform	0.020 – 0.030
– Earth, winding, fairly uniform	0.025 – 0.040
– Rock	0.030 – 0.045
– Unmaintained	0.050 – 0.140
Natural channels (minor streams, top width at flood stage < 100 ft)	
– Fairly regular section	0.030 – 0.070
– Irregular section with pools	0.040 – 0.100

Source: American Society of Civil Engineers (1982).

APPENDIX C

Manning's Roughness *n* for Overland Flow

Surface	*n*
Smooth asphalt	0.011
Smooth concrete	0.012
Ordinary concrete lining	0.013
Good wood	0.014
Brick with cement mortar	0.014
Vitrified clay	0.015
Cast iron	0.015
Corrugated metal pipes	0.024
Cement rubble surface	0.024
Fallow soils (no residue)	0.05
Cultivated soils	
Residue cover < 20%	0.06
Residue cover > 20%	0.17
Range (natural)	0.13
Grass	
Short, prarie	0.15
Dense	0.24
Bermuda grass	0.41
Woods	
Light underbrush	0.4
Dense underbrush	0.8

Source: McCuen, Johnson, and Ragan (1996).

APPENDIX D

Typical Suction Head Values

	Suction Head S	
Soil type	*Inch*	*Mm*
Sand	1.949	49.5
Loamy sand	2.413	61.3
Sandy loam	4.335	110.1
Loam	3.5	88.9
Silt loam	6.567	166.8
Sand clay loam	8.602	218.5
Clay loam	8.22	208.8
Silt clay loam	10.748	273
Sandy clay	9.41	239
Silt clay loam	11.504	292.2
Clay	12.543	316.3

Source: Smith (2010).

APPENDIX E

Typical Soil Conductivity Values

	Hydraulic conductivity	
Soil type	*Inch/hr*	*mm/hr*
Sand	4.638	117.8
Loamy sand	1.177	29.9
Sandy loam	0.429	10.9
Loam	0.134	3.4
Silt loam	0.256	6.5
Sand clay loam	0.06	1.5
Clay loam	0.039	1
Silt clay loam	0.039	1
Sandy clay	0.024	0.6
Silt clay loam	0.02	0.5
Clay	0.012	0.3

Source: Smith (2010).

APPENDIX F

Customary Values of the Runoff Coefficient *k* for Various Surfaces

Surface	*Value of k*
Urban residential Sigle houses	0.2
Garden apartment	0.3
Commercial and Industrial	0.9
Parks	0.05 – 0.30
Asphalt or concrete pavement	0.85 – 1.0

Source: Linsley, *et al.*, (1992).