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Influence of Low Impact Development on Peak Floods Using System Dynamics

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ABSTRACT

This study presents the simulations of peak floods in Upper Opeki using Curve Number (CN) method incorporated into System Dynamics (SD). In order to simulate flood events, a basin model, land use and soil maps of the study area were developed and integrated to create a CN grid. The physical characteristics of the drainage basin were estimated and used as input for the system dynamics simulations. The study revealed that a CN reduction of about 9.6 would lead to a 25 % reduction of peak flood based on SD simulations. Therefore, techniques that promote infiltration and storage of water in the soil column, such as infiltration trenches, permeable pavement and conservation of forest should be adopted in the study area. The study presents SD as a simple and efficient tool for modeling flood in small un-gauged basins with limited data.

Keywords: Climate Variability, Curve Number, System Dynamics, Low Impact Development

1. INTRODUCTION

Low Impact Development (LID) has been proposed as an effective method for decreasing peak floods induced by urbanization (Sin *et al.* 2014). LID facilities are spread on a small scale throughout target area to induce retention and infiltration when runoff is generated unlike conventional facilities for flood runoff reduction applied after runoff generation (Sin *et al.,* 2014). Recent advancement on LID has been documented by Yoo *et al.* (2012) who proposed a methodology for quantifying the flood runoff reduction effect of storage facilities by curve number (CN). While *Sin et al*. (2014) validated the applicability of a simple and straight forward procedure for reducing the effect of flooding by reducing CN value. Therefore, the present study endeavors to simulate LID as a flood reduction technique in flood prone areas of the tropics where the study is being located.

There is strong need to explore simulation tools that can represent complex systems in a realistic way. A promising tool is System Dynamics (SD) and it does not require complex mathematical description of a system when compared to traditional systems analysis techniques. System dynamics is a computer based simulation approach for understanding how the structure of a system perpetuates the behavior exhibited by the system overtime (Simonovic, 2009). It was developed in the 1960s for better understanding of economic and industrial systems, and has been applied in the analysis of social, economic, physical and biological systems (Sterman, 2000). In water resources management, system dynamics has been used to integrate physical, social and economic factors that influence water resources to address long term planning (Winz *et al.*, 2009). In scenarios involving design flood estimations, impact of flood damage and modeling of system resilience to climate-induced hazards, more attention has been given to SD, this is because it takes care of interactions among various elements (Bagheri, 2006).

This study seeks to evaluate the responses of peak floods to LID installation in Upper Opeki River Basin based on system dynamics approach. In order to achieve this goal, hydrological modeling of the area was performed to establish model parameters, which serves as input for the system dynamics simulation for different scenarios.

2. METHODOLOGY

The study area is the upper part of the Opeki River Basin (Figure 1) and occupies an area of about 497.9 km^2. It lies entirely within one climatic environment and a consistent geological environment of the Basement Complex of Southwestern Nigeria (Idowu and Martins, 2007). Upper Opeki catchment is located in Oyo State, Nigeria and has Opeki as its major river. It lies between longitudes 3 º 15' and 3 º 30 'E and between latitudes 7º 20' and 7º 54'N (Agbede et al., 2019). The Opeki catchment falls within the humid tropical climate with distinct wet and dry seasons. The wet season, starts in April and ends in October. The annual average rainfall for a period of 35 years (1979-2013) is 1433.34 mm based on satellite derived data obtained from the Global Weather Data for Soil and Water Assessment Tool (SWAT) website. The basin lies within the savanna environment of southwestern Nigeria (Idowu and Martins, 2007). Its vegetation consists of tall grasses in addition to trees with long tap roots, which ensure access to water during the dry season when the water table drops and the grasses wither and die (Idowu and Martins, 2003). However, along the water courses, darker and denser vegetation occur throughout the year. The population is mainly rural and the dominant land use is arable agriculture in the wet season. The crops are mainly maize, cassava and yams. A detail description of the whole Opeki basin could be found in Idowu and Martins (2007).

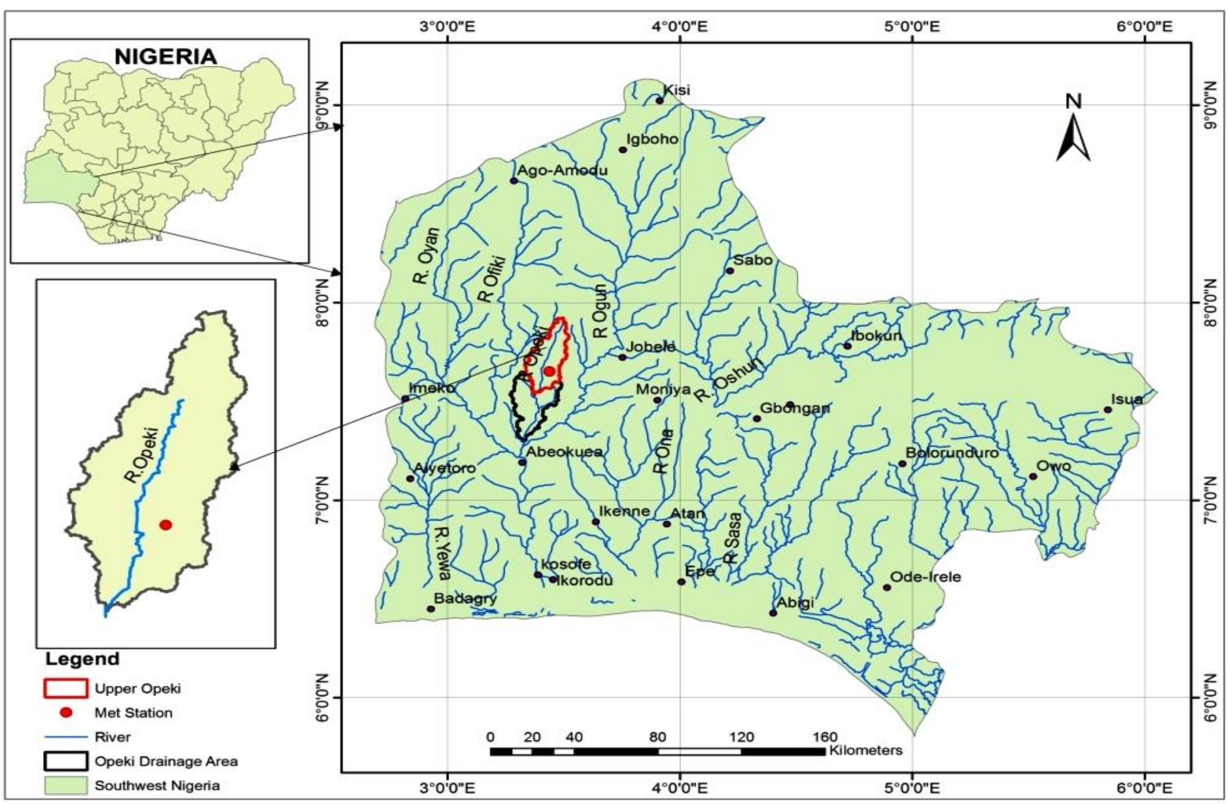

Figure 1: Drainage Map of the Study Area (Agbede *et al.*, 2019)

2.1 Materials

A 36-year (1979-2014) daily rainfall data based on Climate Forecast System Reanalysis (CFSR) was obtained from https://globalweather.tamu.edu, Digital Elevation Model (DEM) and Landsat image was obtained from https://earthexplorer.usgs.gov, while the soil of the study area was delineated from Harmonized World Soil Database Viewer. Delineated land use and soil classification for the study area were used to create SCS CN grid. These data were integrated to establish the hydrologic model of the study area.

2.2 Estimation of Basin Physical Features

The Opeki River basin hydrologic model was created by applying the HEC-geoHMS software functionality within the ArcMap GIS environment. The first major step in creating the basin model was to delineate the stream network and the watershed boundaries of the area of interest. This process is commonly referred to as terrain preprocessing and is entirely based on the input of DEM. After the completion of the terrain preprocessing of the river basin a project point was defined close to Adeniji town. The project point defines the outlet of the Upper Opeki watershed and was placed on a drainage line. Based on the outcomes of the terrain preprocessing and the definition of the project point, HEC-geoHMS delineates the project area and creates all necessary layer files for this area. All the created data was stored in a new geodatabase.

For each of the resulting stream segments and the related subbasins, a series of physically-based characteristics were computed based on the depressionless DEM by using the HEC-geoHMS functions. These characteristics include the lengths and slopes of each river segment as well as the average basin slope and the longest flow path of each subbasin. The resulting data is automatically stored in the attribute table of the river and subbasin layer. The result of the river basin characterization served as input for the System Dynamic modeling using Vensim PLE software.

2.3 System Dynamics Modeling Approach

2.3.1 Dynamic Hypothesis

The analyst's mental model of the dominant loop structure and how it creates the important time patterns is described in detail in writing. This written description is called the Dynamic Hypothesis (Fey, 2004). In this study, floods in the study area were assumed to depend on daily rainfall, drainage area, average drainage slope, total stream length and changes in land use for urban development which determines the runoff coefficient and surface run off.

2.3.2 Flow Structure

The flow structure of the system dynamics model is based on the Soil Conservation Service (SCS) Curve Number (CN) method of flood simulation, which is a simple and widely used method. The SCS Curve Number method was primitively formulated by the Soil Conservation Service for the management of water resource in the United States for agricultural development (Chow, 1964). Equation 1 was used to calculate the direct runoff from Upper Opeki Basin:

$$Q = \frac{(P - 0.2S)^2}{P+0.8S} \qquad (1)$$

Where: Q is estimated direct runoff (mm), P is maximum storm rainfall within a day (mm), and S is the potential maximum retention. S can be calculated from CN value by this equation; that is:

$$S = \frac{25400}{CN} - 254 \quad (2)$$

and CN value was extracted from the table 5.2.2 in Chow (1964). After calculating the direct runoff or excess runoff from any basin (Q), to estimate the peak flood (m3/s), the following equation should be used (Chow 1964):

$$qt = 0.208 * \frac{A*Q}{T_p} \quad (3)$$

where: A is area of drainage basin (km^2), Q is excess rainfall (mm), q_p is peak runoff rate unit hydrograph (m^3/s), and T_p is time to peak. In that equation, the only unknown parameter is time to peak (Tp). This was estimated in terms of time of concentration (T_c). Relation between T_p and T_c is shown in the equation below:

$$Tp = 0.7Tc \quad (4)$$

Where: T_c is the time of concentration; for a given watershed, the time of concentration is the time required for rainfall landing on the farthest point of the watershed to reach the watershed outlet. Time of concentration used in the study was based on the empirical formula given by Kirpich (1940), represented by: $Tc = 0.0195\ L^{0.77}\ S^{-0.385}$ Where L is the stream length and S is the slope.

A system dynamics (SD) model was selected for simulating flood in the study area because of its ability to handle complex systems. The software package Vensim PLE, Version 6.4b, developed by Ventana Systems, Inc. (Tracing and Checking, 2002), was employed to formulate the SD model of Upper Opeki River Basin (SDURB). The structure of SDURB is presented in Figure 2. The figure shows that peak instantaneous rainfall flows into the system while peak flood flows out in the basin, while the auxiliary components of the model are direct runoff, potential maximum retention, coefficient of runoff, time to peak and basin area are all connected with model connectors (blue arrows).

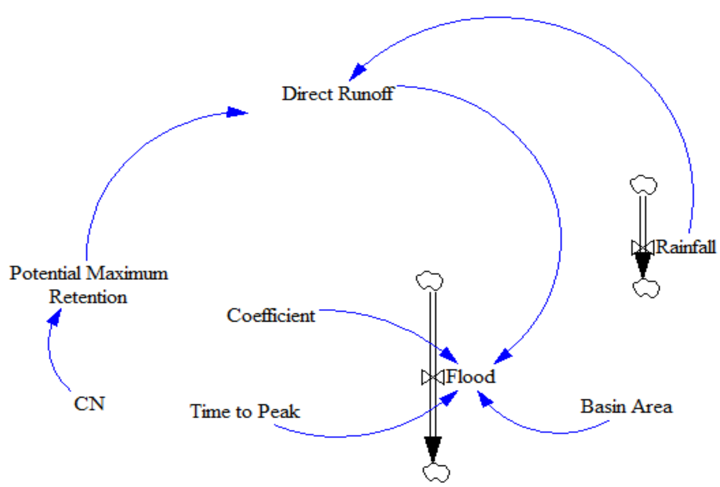

Figure 2: Flow Diagram of Peak Flood in the Study Area

The assumptions made for the model, are that daily instantaneous rainfall is lumped over the basin area, a composite CN is a good representative of the entire basin, a change in CN translates to change in the flow dynamics of the entire basin.

3. RESULTS AND DISCUSSION

3.1 Descriptive Statistics of Rainfall

An exploratory representation of the rainfall occurrence in the study area between 1st of January 1979 and 31st of July 2014 is presented in Figures 3 to 5. Figure 3 shows that daily rainfall was well distributed below 100 mm, while highest instantaneous rainfall occurred in September of the year 2005 with a value of 199.55 mm. The average monthly distribution of rainfall in the study area is presented in Figure 4. The figure shows that rainfall represents a double modal distribution with peaks of 270.21 mm in September and 252.65 in July. While monthly average rainfall was found to be low during the dry season between November and March, which goes to show that floods are expected to be high between July and September when average rainfall is greater than 200 mm. Figure 5 shows the trend of annual for the study period. The figure shows that there is an insignificant decreasing trend in annual rainfall, which indicates the possibility of reduction in annual rainfall the study area.

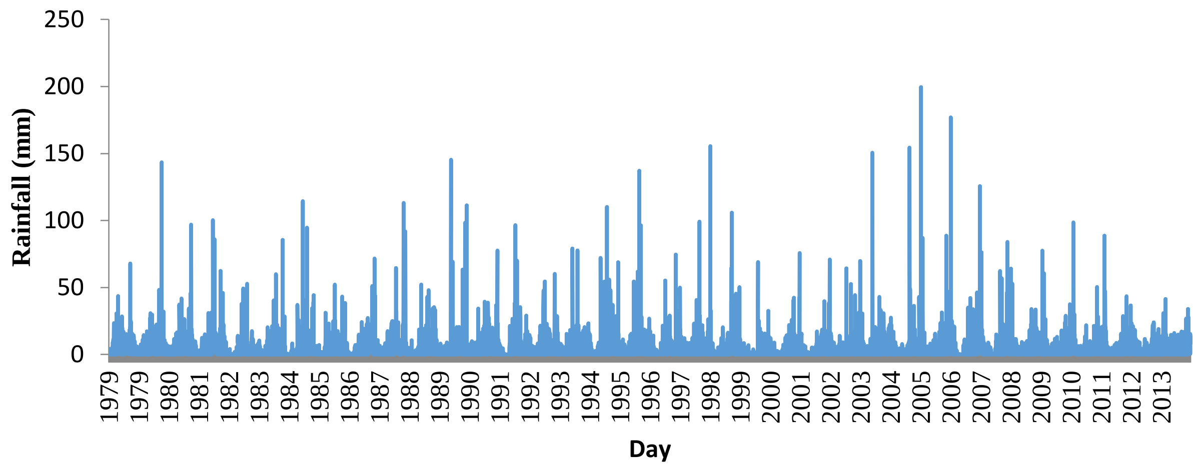

Figure 3: Time Series of Daily Rainfall between 1979 and 2014

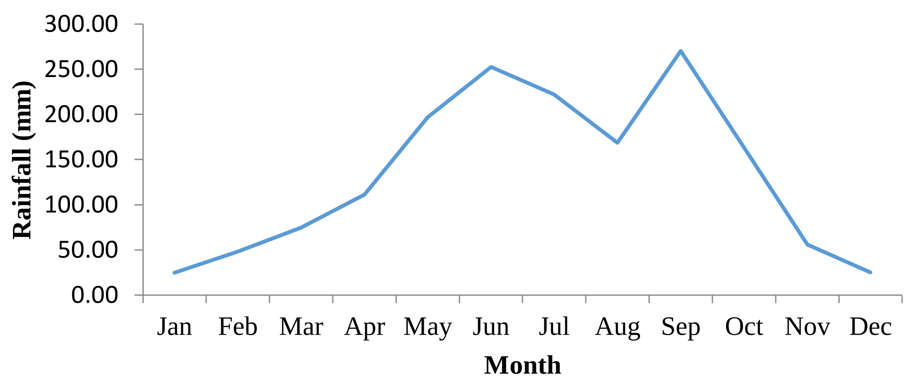

Figure 4: Average Monthly Distribution of Rainfall

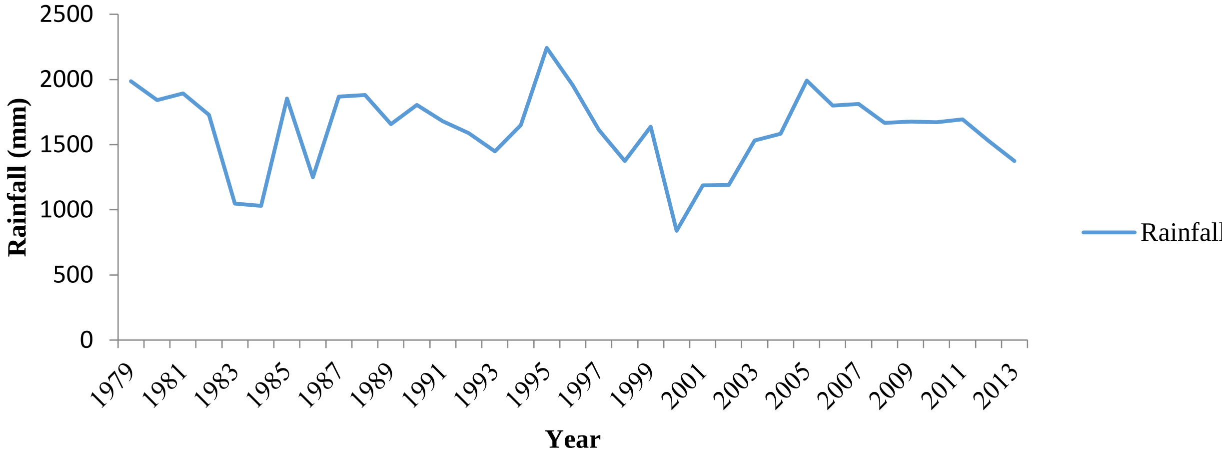

Figure 5: Trend of Variation in Annual Rainfall

Table 1 presents the highest recorded instantaneous rainfall for the study period with respect to months and year of occurrence. The table shows that the highest rainfall that was recorded for the months of January throughout the study period was 16.04 mm, a peak record of 150.56 mm was observed for the month of February, while peak instantaneous rainfall of 72.21 mm, 145.37 mm, 154.50 mm, 137.08 mm, 105.70 mm, 125.58 mm, 199.55 mm, 155.45 mm, 16.35 mm, and 14.66 mm was recorded for the month of March, April, May, June, July, August, September, October, November and December respectively. This implies that more than 100 mm daily rainfall occurred mostly in the wet season between April and October; however, a record of 150.56 mm in the month of February shows that rainfall may become more unpredictable in the study area.

Table 1: Highest Instantaneous Daily Peak Rainfall Observed between 1979 and 2014

Year	Month	Daily Rainfall (mm)
2014	January	16.04
2004	February	150.56
1995	March	72.21
1990	April	145.37
2005	May	154.50
1996	June	137.08
1999	July	105.70
2007	August	125.58
2005	September	199.55
1998	October	155.45
2005	November	16.35
2013	December	14.66

3.2 Delineation of Upper Opeki River Basin

Table 2 show series of physically-based characteristics of the study area which were computed from processing the DEM using the HEC-geoHMS functions. The elevation, land use and soil map of the study area are shown in figure 5, 6 and 7 respectively. The land use map shows that larger spatial extent of the area constitutes agricultural lands. The land use and soil map were integrated to create the CN map (figure 8), while a composite CN value of 80.23 was computed in HEC-geoHMS for simulation purpose. This information summarized in table 2 was used as input values for the system dynamics simulation.

Table 2: Summary of Upper Opeki River Basin Characteristics

Sub-Basin Characteristics	Value
Area (Km^2)	497.9
Length of Stream (m)	40,512
Slope (Dimensionless)	0.00042
Time of Concentration (Tc) (Mins)	1374
Time to Peak (Tp) (Mins)	961.8
Composite CN	80.23

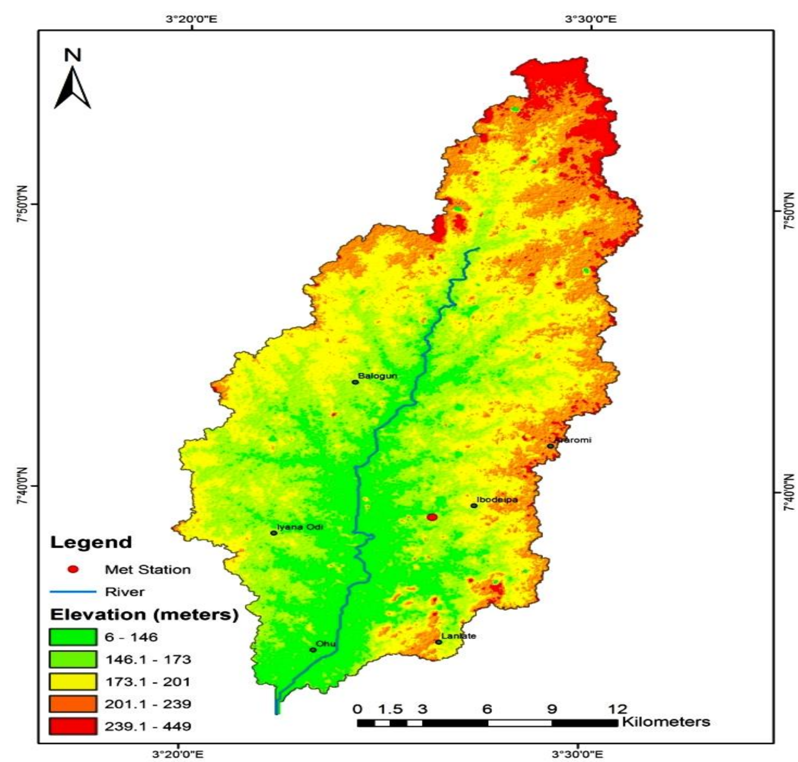

Figure 5: Elevation of Opeki River Basin Derived from DEM

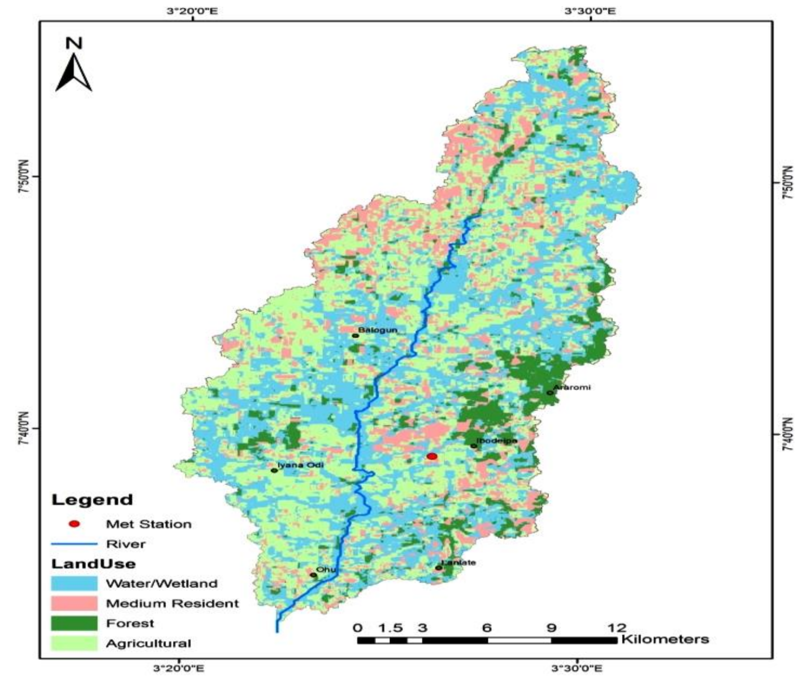

Figure 6: Land Use Map of the Study Area

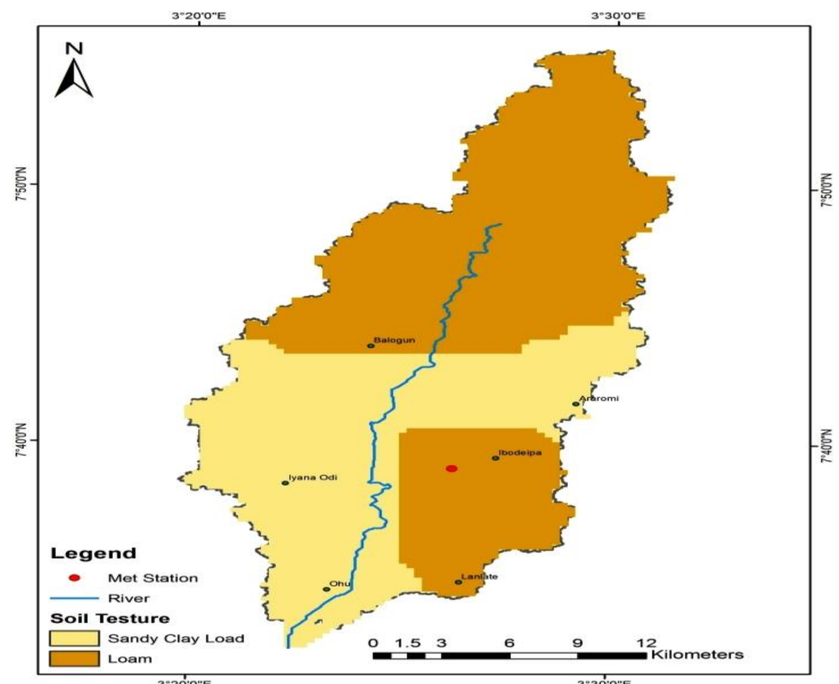

Figure 7: Soil Map of the Study Area

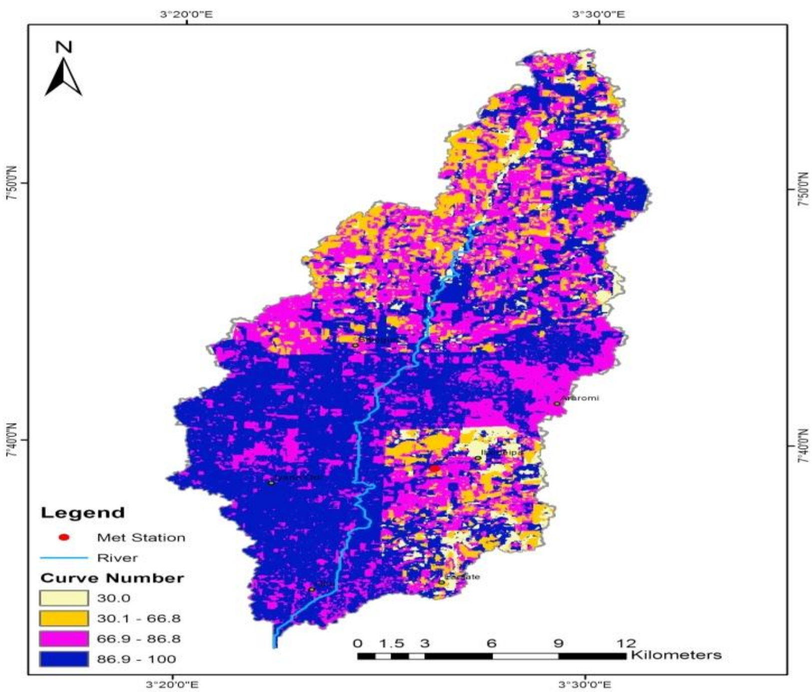

Figure 8: Computed Curve Number of Study Area

4.3 Estimation of Floods based on SCS CN

The estimated daily peak floods for the study period are presented in figure 9. The figure shows that rainfall is a major contributor of floods in the study area. However, there is evidence that the time to peak of less than a day (961.8 minutes) contributes to quick rise of water at the outlet of the basin due to rainfall.

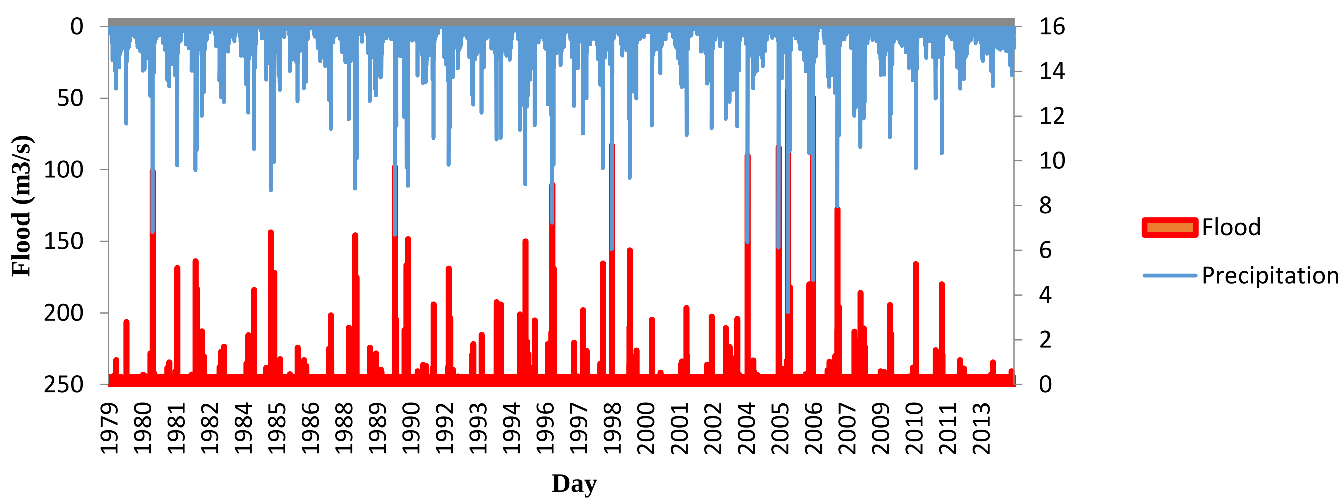

Figure 9: Computed Flood based on CN method (1979-2013)

3.4 Simulation of Peak Floods using System Dynamics (SD)

In order to examine the system dynamics of peak flood in the study area with respect to installing LIDs, three scenarios were considered (table 3), which are represented by a conceptual flow diagram based on the SCS CN method (Figure 10). The series of peak storms recorded for each month served as input for the system dynamics model, while corresponding peak flood served as output. The responses of peak flood as CN was changed were observed by sliding the bar of CN in the Synthesis of Simulations mode in Vensim.

In the first scenario, a base run simulation for rural condition (medium residential), based on high percentage of forest, slope of less than 0.05 and soil condition of clay and slit loam (Chow, 1964) with a CN value of 80.23 (table 3) was run. The second scenario assumes a CN reduction of 9.6 is adopted for the basin due to the installation of an underground storage based on Sin et al. (2014) recommendation. While the third scenario was investigated for a further reduction of CN value (table 3).

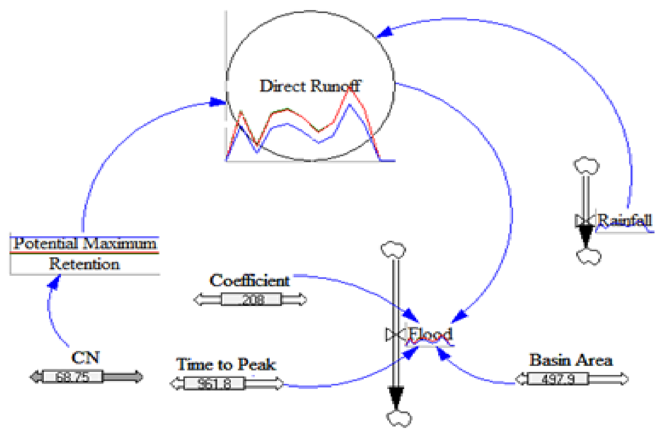

Figure 10: Flood Flow Diagram during Synthesis of Simulations in Vensim

Table 3: Summary of Scenarios used in the Study

Scenario	CN	Maximum Peak Flood (m3/s)	Percentage Reduction in Peak Flood
Base Run	80.23	15.12	
Installation of LID with 9.6 CN reduction	79.63	14.90	1.4%
Installation of LID with 11.48 CN reduction	68.75	11.49	24.0%

Figure 11 shows a comparison between the simulation of the base run and the simulations of flood assuming the introduction of storage facilities. The figure shows that, if CN reduction of 9.6 had been adopted for the study area, reduction in peak flood will amount to 1.4%, while a further reduction of CN by 11.48 will lead to a 24% reduction of peak flood in the study area. This implies that in order to reduce peak flood in the study area, LID such as infiltration and storage facilities should be installed taking consideration of CN not more than 68.75.

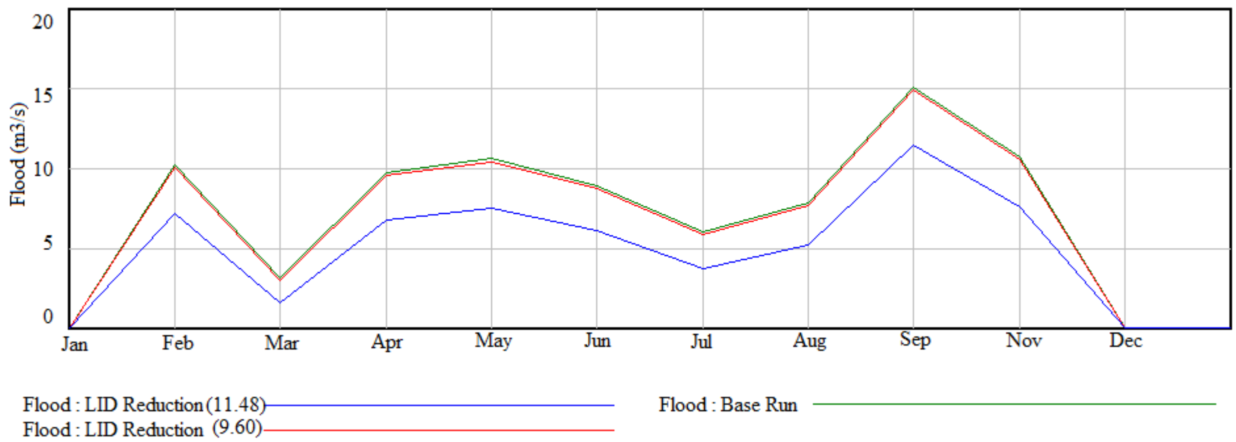

Figure 11: Simulated Peak Flood for Three Scenarios

In situations where data is scare, dynamic models have been found to be a useful innovation. This study examined the effect of installing Low Impact Development (LID) facilities for the reduction of peak flood in the study area. As a result of lack of ground based meteorological data within the study area, satellite derived data were adopted. The satellite derived daily rainfall that was utilized for the study was found to depict a double modal seasonal pattern, which is the usual pattern of monthly rainfall in Southwest Nigeria. This corroborates Adejuwon and Odekunle (2006) who asserted that Southwest Nigeria experiences wet and dry seasons associated with, moist Tropical Maritime and dry Tropical Continental currents, respectively.

One of the common land use changes associated with urban space is the pavement of urban space and roads making them impermeable. Unplanned urbanization also results in property development in marginal areas and the unhealthy practice of dumping refuse into drains (Amangabara and Gobo, 2007). According to Njoku *et* al. (2013), this practice has led to urban flooding in some Nigerian cities like Port Harcourt, Aba, Lagos and Ibadan. As a result, the factors responsible for the magnitude of runoff at the outlet of a basin must be well considered; which include climate and physiographic. Major physiographic factor that have been found to affect the magnitude of flood in the study area includes land use, soil type, slope, elevation, area and shape of the basin. In order to simulate peak floods in the study area, a basin model was developed by applying the HEC-geoHMS software functionality within the ArcMap GIS environment. The upper Opeki sub basins was delineated for the study area while its physical characteristics were computed (table 1), which served as input for the system dynamics simulations.

This study adopts the simple concept that the decrease in CN (which represents the installation of infiltration and storage facilities) would decrease flood (Sin et al., 2014). This is because it is not easy to measure how a given storage and infiltration facility would reduce peak flood (Sin et al., 2014). Sin et al. (2014) asserted that by installing infiltration collectors and storage facilities, floods in Pyeonghwa district in Korea were reduced as a result of CN reduction of 9.6. As result, this study endeavored to quantify how peak flood will respond to CN reduction of 9.6 based on the assumption that storage and infiltration facilities were installed, using system dynamics simulations.

The result of the various scenarios shows that an introduction of LID would reduce the peak flood. However, CN reduction of about 9.6 by installing LID would cause a 1.4% reduction in peak flood of the area. As a result of this insignificant reduction, further reduction of CN was simulated, which revealed that 11.48 reductions in CN will lead to 24% reduction of peak flood. Therefore, in order to install Low Impact Development (LID) facilities in the study area, CN value of 68.75 may be considered.

The study presents SD as a simple and efficient tool for modeling flood, based on the SCS CN method; and serves as decision support for formulating its hazard reduction policies in the study area. However, future investigations are to focus on determining the quantity and designs of storage and infiltration facilities required to reduce CN of the study area from 80.23 to 68.75.

4. CONCLUSION

System dynamics tools are versatile for studying the interaction between systems and its environments in situations where data is limited. Based on the outcome of the study, it has been established that an introduction of LID would reduce flooding effect in the study area. Therefore, techniques that promote infiltration and storage of water in the soil column, such as infiltration trenches, permeable pavement and conservation of forest should be employed in the study area.

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