Simulating the Effects of Urbanisation on Urban Flooding in Ashimowu Watershed, Lagos, Nigeria

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Abstract

The paper studied the effects of urbanization on the extent of urban flooding in Lagos by using System 6c (Ashimowu Watershed) as a case study. The study utilized a scenario approach to simulate flooding processes for different land use scenarios (1965, 1975, 1987 and 2005) and 13 storm events recorded in 2005. For each scenario, the peak flow and area inundated were assessed using Precipitation Water Inundation Model (PWIM), a bespoke simple catchment water balance model with three components (Infiltration, runoff and digital surface) developed as part of the study. The results show that runoff and peak flow from precipitation increased by more than 200% between 1965 and 2005, due principally to urban impervious developments, causing the inundated area to increase by about 10% over the same period. Finally, Sustainable Urban Drainage Systems, (SUDS) that encourages natural groundwater recharge was recommended.

***Key words**: Rainfall-runoff, Modelling; Inundation; Lagos (Nigeria).*

1. Introduction

Urban flooding has long been a major environmental issue for most cities of the world (Odunuga and Oyebande, 2005). In Lagos, rapid urbanization is exacerbating vulnerability of the inhabitants of the megacity to flooding through unplanned development in sensitive areas, particularly around the Lagos Lagoon and the adjourning wetlands. This has not only put more people and assets at risk, but has also, through sand-filling and loss of fringe vegetation, reduced the capacity of the lagoon and the wetlands to accommodate and buffer flood waters.

As a low-lying and rapidly growing coastal megacity, Lagos has a very high vulnerability to urban flooding. Much of the territory is spread over barrier islands located close to the seafront or the shoreline of the Lagos Lagoon and water channels connecting it to the sea. Some of Nigeria's most expensive real estates line the seafront which have undergone dramatic erosion in recent decades, whilst the lowest lying areas around the lagoon and its inlet channels frequently house the poor in informal settlements, thereby creating further land use crises. As development is intensified within the urban and peri-urban environments of Lagos, the impact of land use changes on hydrological fluxes has also increased. The severity of the effect of the changes on hydrological fluxes in urban environments has been more pronounced on the storm runoff because by converting previously pervious areas to compacted surfaces, infiltration will reduce and runoff will increase. In such situations, flooding will be rampant (Falconer, 2006). As noted by Odunuga *et al* (2011), System 6c falls within section 17 (1) b, of the Lagos State Town and Regional Planning Regulations, where building coverage should not exceed (60) % of the plot. However, field verification and image interpretation show that no single building meets this requirement as more than (95) % of most plots have been completely developed or paved. Also, the developed plots along the major channels course have less than 10m as setback which also contravene section (15) titled ‘Setback to public Utilities’, sub section (5) d ‘Gorge/Canal/Drainage’ of the same regulation. As a consequence of the above, even moderate rains in the study area frequently cause local flooding.

On account of climate change and sea level rise, increase in flood peaks and runoff volumes in the range of 15-25% for medium–sized coastal urban watersheds have been predicted for temperate climates (UN, 2002). These will be higher in tropical environments due to the prevailing convective storms, with its characteristically higher rainfall intensity when compared with the intensity of rainfall of similar duration and frequency in other regions of the world (Oyebande, 1990). Additionally, analyses of the monthly rainfall pattern for the sahelian zone of the West Africa sub-region have shown that although the mean annual storm rainfall varies little, the dry periods exhibits a decrease in the number of rain events (Le Barbé and Lebel, 1997) while the wet periods are recording higher numbers of rain events especially in the southern humid tropics (Ojo et al., 2001).All of this would imply a preponderance of flood generation, shorter duration and high intensity rainfall events in the wet periods. Effects of these changes in the rainfall patterns are believed to be aggravated further by a number of anthropogenic factors, the most significant being violation of planning regulations, indiscriminate erection of structures on wetlands, encroachments into flood plains, and inadequate hydraulic capacity, and refuse dumping into the drainage systems (Oyebande, 1990; Odunuga, 2010A; Adeloye and Rustum, 2011). Also, Nkwunonwo *et al* (2016) noted that the increasing densities of populations (particularly in the urban areas of most developing countries such as

Nigeria), alongside the poor level of awareness and the limited efforts of many stakeholders towards flood risk reduction are critical issues undermining possible efforts towards addressing the flood hazard.

However, huge amount of resources and efforts have been invested into solving the problem of flooding in Lagos by the three tiers of government (Federal, State and Local Governments), and the International Organizations such as the World Bank and Non-Governmental Organisations (NGOs). Rather than abating, recent experiences suggest that the problem of flooding is worsening. This however necessitated the scientific investigation of the factors that promote the growing problem of flooding in Lagos. Specifically, there is an urgent need to identify the key parameters that precipitate, exacerbate and foster flooding in the study area. Once identified, these variables can be manipulated to control the phenomenon of flooding, not only in the study watershed, but in the larger city of Lagos and other environments with similar characteristics. Also, one crucial issue to the amelioration of the effects of floods is the need to formulate a sound flood model, which is driven by knowledge of the rainfall characteristics.

The aim of this study, therefore, is to assess the effects of urbanisation on the extent of urban flooding in Lagos using system 6C, an arterial drainage system in the Ashimowu neighbourhood of Lagos as a case study. The objectives include:

- In the absence of reliable rainfall and flow data, instrumenting the watershed to measure short-term rainfall and the corresponding discharge hydrographs;
- Assessing changing patterns of imperviousness and land-use cover for the Ashimowu watershed over 40 years, from 1965 – 2005;
- Developing a GIS-based water balance model to predict the generated runoff for different measured rainfall events and prevailing land use scenarios and;
- Estimating the flood inundated areas for each land-use scenario.

In the next Section, further details about the case study location are provided. This is then followed by a description of the methodology. The results are then presented and discussed and finally the main conclusions are presented.

2. Lagos and the Watershed Study Area

Lagos occupies an undulating topography generally between 5m *above mean sea level (amsl)* and 15m *amsl*. Surface lithology is made up entirely of alluvium sedimentary formation, which is underlain by a middle age Eocene sedimentary of Ilaro formation (Federal Survey, 1978). The climate is humid tropics and experiences a contrast between dry and wet seasons (Ojo *et a*l., 2001). These two seasons are dependent on the two prevailing air masses blowing over the country at different times of the year, the first being the warm, dry and dusty tropical continental or the north easterly air mass of Saharan origin while the second is the warm and moist tropical maritime or the humid maritime from across the Atlantic. The mean annual rainfall is between 1500 mm and 2000 mm, falling during some 125 days on the average. The rainy season has two maximum peaks. The first is between April and July, followed by a short dry season in August while the second maximum comes up between September and November. Rainfall is highly torrential with short duration and high intensity that allow for rapid concentration of storm runoff. The more pronounced dry season is experienced generally between December and February.

Average daily temperature varies between 21°C and 24°C and could be as low as 18°C at night. The area is a region of high relative humidity of about 80% around the peak of the dry season in January and over 90% in the wet season around June/July. Cloud cover is usually stratiform in the morning and may later develop to cumulus in the late afternoon (Ojo *et al*., 2001). Although vegetal cover of the area must have been swamp forest that is typical of the barrier islands along the Nigerian coastline, it has since given way to urban developments, thereby rendering transpiration process insignificant, infiltration almost non-existent and runoff generation more rapid (Odunuga, 2009).

Residential development outside the old city of Lagos Island began after the annexation of the city by the British colonial government in 1851, but it was not until about 1930 that mainland parts comprising Yaba, Mushin and Idi-Araba where the study area lies (see Fig. 1) were fully developed. As noted by Oyeleye, (2001) the relocation of about 200,000 people from Lagos Island to Surulere and Yaba in the mainland between 1956 and 1959 by the Lagos Executive Development Board paved the way for the urbanization process within the mainland section of the metropolis. Since then, urbanization process has continued with rapid increase in population and socio-economic activities and by year 2000 most parts of Surulere / Mushin had been developed.

The study area (System 6C) covers an area of about 13.46 km^2 and is located in the central Surulere/Mushin axis of the mainland parts of the Lagos metropolis. The main stream (Ashimowu stream) is 4,810m long and has been greatly modified by human activities. It is drained by several artificial drainage networks. Its watershed extends from about latitude 6^0 $27^{'}$ to 6^0 $32^{'}$ $30^{''}$and longitude 3^0 21’ to 3^0 $24^{'}$ 42’ (Figure 1) and is named as system 6C in the Lagos Drainage Master Plan (Dar-Al-Handash, 1993).

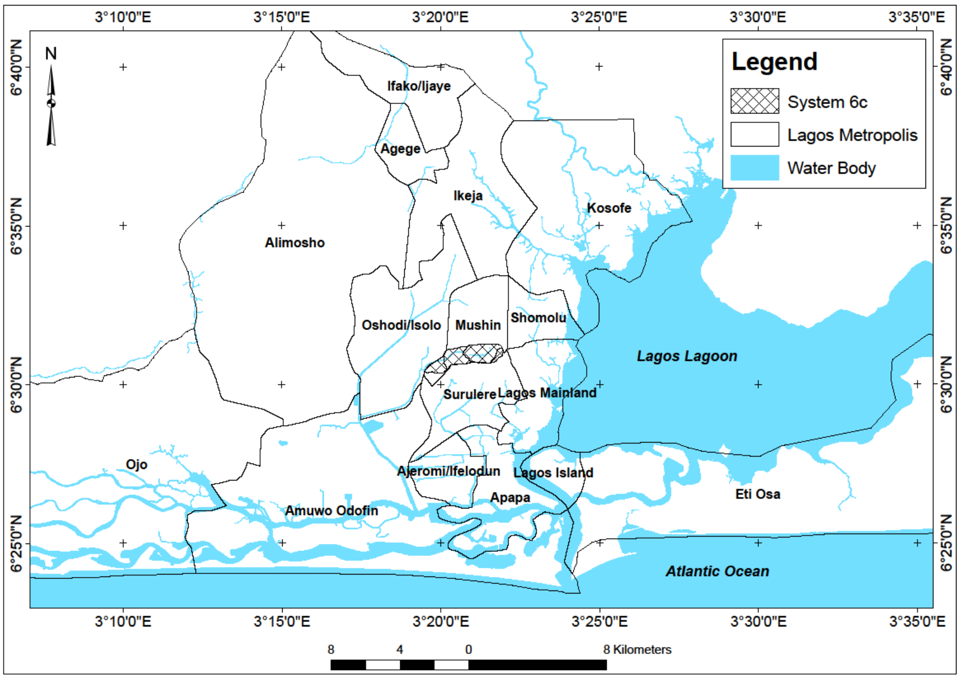


Figure 1: Lagos megacity showing the location of System 6c

3. Methodology

3.1 Land use and Land cover

Using the image elements such as tone, texture, shape, association, site, size, pattern and the local knowledge of the environment, the 1965, 1975 and 1987 aerial photographs as well as the 2005 Ikonos satellite imagery covering System 6C were interpreted and vectorized using on- screen digitization in the Arc-GIS environment. The 2005 imagery was found to be adequate because the analysis of Land use change by Odunuga, *et al*, (2011) shows that as at year 2005 over 90% of the watershed had been rendered impervious and no hydrological significant change was further expected from the watershed. In all, seven classes of land uses and land cover were identified, namely agricultural land use, built-up area (concrete and structures; CS), open bare surfaces, transportation, vegetal cover, water body and wetland.

3.2 Rainfall and Flow Measurements

A mini meteorological station was installed within the study area to monitor the storm rainfall between August and November 2005. This period was the second peak of the rainy season (October – November) in the Lagos metropolis as noted in Section 2. The station, which was certified by the Nigerian Meteorological Agency, was situated within the premises of the University of Lagos Staff School Annex within Lagos University Teaching Hospital (LUTH) premises, Idi-Araba, Lagos. The station was equipped with self-recording automatic rain gauge (Tilting siphon) that provides a continuous graphical record of rainfall against time. The unit siphoned each 25mm of rainfall amount for a vertical distance of 5cm on the chart while the horizontal distance provided the time in minutes. In all, eleven rainfall events were recorded during the 2005 study period with average intensity rain of 0.45 mm/hr to 32.96 mm/hr.

For flow measurement, a partial-width rectangular weir constructed according to recommended international standards (see UNESCO 1970; Shaw, 1994) was installed at a carefully selected location in the Ashimowu main channel. A self-recording gauge for water level (gauge) measurement was installed on the main channel to record the water level above an established datum within the channel bed continuously. That is, a base level for the water level was established while the variations from this stage are considered as the water level variation. The stage recorder allowed the measurement of up to 1m depth variation in the water level, which was charted on a rotating drum. The vertical scale on the chart was 10mm: 1m with horizontal scale of up to 8 days. The recorded weir heights were then converted to discharge using the weir equation (Shaw, 1994). This resulted in the complete hydrograph for each storm event from which the peak discharge could be read off.

3.3 Hydrological modelling

The rainfall-runoff modelling for the study employed the Precipitation Water Inundation Model (PWIM) (Odunuga, 2010B), a simple model developed as part of the study as an accounting method to determine loss due to infiltration, the runoff volume and the peak discharge during a storm. Because of its implementation within a GIS environment, it was also possible to delineate the areas of flood inundation and thus to identify vulnerable and risk zones of urban flooding for the area of study. The attractiveness of PWIM stems from its simplicity and parsimony in terms of the number of parameters, both of which make it a practical rainfall-runoff tool for a poorly gauged catchment such as the Lagos one under study. The PWIM has three major components as follows:

1. Infiltration Component: which determines the rainfall loss due to infiltration during a storm;
2. Runoff Component: which determines the excess rainfall (i.e. runoff) and peak flow during a storm;

3. Digital Surface Component which calculates the surface area within the watershed over which the peak runoff is spread.

3.3.1 Infiltration Component

Infiltration was modelled using Horton’s approach (Horton, 1939): defined as

$$f_p = f_c + (f_o - f_c)e^{-kt} \quad \text{……………………………………………………} (1)$$

where f_p is the infiltration capacity, i.e. maximum infiltration rate, at time t (mm/hr);
f_o = initial infiltration rate (mm/hr);
k = empirical coefficient for a particular soil and surface (min^{-1});
f_c = final constant infiltration rate as $t \rightarrow \infty$,
t = time since the start of rainfall (minutes).

To apply equation (1), the parameters f_o, f_c and k must be known. The parameters f_c and f_o were based on the guidelines of the U.S. Soil Conservation Service (SCS)Stephenson et al, (2001) as summarised in Table 1 for different soil types and antecedent soil moisture conditions (see also Beven, 2012). Soil group A in the table refers to soil of low runoff potentials and high infiltration rates; B is for moderate infiltration rates and well drained soils; C is for slow infiltration soils; and D is for very slow infiltration rates soils, such as clay or heavily saturated soils that potentially generate the largest runoff volume. As evident in Table 1, the initial infiltration rate, (f_o,) is affected by the antecedent soil moisture condition, with soils at or close to saturation having a much smaller f_o than dry soils.

Table 1: Parameters of Horton (1939) infiltration model based on US SCS guidelines

Horton’s Parameter	Antecedent Moisture Condition (AMC)	Soil Group (SG)			
		A	B	C	D
f_0 (mm/hr)	Bone dry	250	200	125	75
	Slightly wet	162	130	79	45
	Wet	83	65	36	8
	Saturated	34	32	11	4
(f_c (mm/hr)	All	25	13	6	3

Source: *Stephenson et al., (2001)*

Stephenson et al. (2001) established that the values presented in the table were too high for South African catchments because the runoff values generated using them were generally much lower than the observed runoff in the urban catchments they investigated in South Africa. They therefore recommended a value of f_o equal to a third and a value of f_c equal to a quarter of those in the table for South African catchments. These recommendations were followed in the current study, albeit with a further refinement that the infiltration was only considered for the pervious areas of a catchment rather than to the entire catchment. This latter refinement ensured that the runoff generated from the impervious areas of the significantly urbanised catchments is fully captured and the model becomes applicable to any urban catchment in the tropical environment where the current study is situated.

To accommodate the spatial variability within Ashimowu Stream, the System 6C watershed was divided into three sub-watersheds, namely LUTH, Lawanson and Itire as shown in Figure 2.

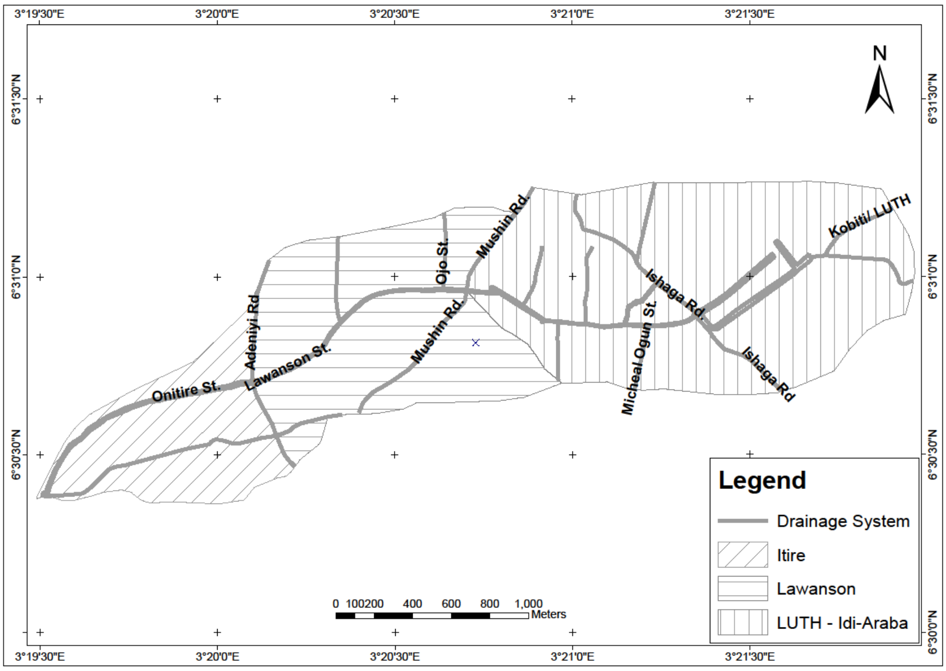


Figure 2: The Three Sub-watershed of Asimowu Stream Lagos treated for the study

Soil types for each of the sub-watersheds were determined using the particle size distribution analysis derived from particle size sieves. On the basis of this, the soils in the pervious areas at Itire were found to be predominantly grassland loamy (Soil group C in Table 1) while those for Lawanson were sandy loam supporting a lot of vegetation (soil group A). LUTH soils were mud clay (soil group D).

Antecedent soil moisture conditions to classify the level of soil wetness for use in Table 1 were determined by using soil moisture measurement (EA514-010 Quickdraw) probe. This was carried out at two places for each of the sub-watersheds. The values at both Itire and Lawanson were far from saturated because of their vegetation, with Lawanson being closer to “slightly wet” and Itire being “wet”. The generally high water table in the LUTH part of the studied watershed due to its wetland and extended floodplain of Ashimowu Stream morphology ensured that its soil was very close to saturation.

Thus, following the approach of Stephenson et al. (2001) and its refinement as applied in the current study, the initial infiltration capacity and terminal infiltration capacity of each sub-watershed were obtained using equations (2) and (3) respectively:

$$f_o' = (1-\alpha)\left(\frac{f_o}{3}\right) \qquad (2)$$

$$f_c' = (1-\alpha)\left(\frac{f_c}{4}\right) \qquad (3)$$

Where fo and fc are the values in Table 1;

f_o' *and* f_c' *are the corresponding modifications as applied in the current study; and*

α *is the proportion of the sub-catchment that is impervious, which comprises the built-up areas, transportation routes and concrete open spaces*.

For the soil types and antecedent moisture conditions in the various sub-watersheds as outlined above, the corresponding (f_o, f_c) pairs from Table 1 for each sub-watershed are as follows:

Itire: (36, 6); Lawanson: (162, 25) and LUTH (4, 3). Using these in equations (2&3) with the impervious fractions α in Table 4give the estimated values of f_o' and f_c'.

3.3.2 Runoff Generation

The runoff component was based on a number of assumptions that integrate land use, rainfall, infiltration and runoff. These assumptions include:

(a) Precipitation on the non-infiltration, i.e. impervious, surface will be fully converted to runoff (volume) as follows.

$R_N = \alpha (P) A$ ……………………………………………………….…… (4)

where R_N *is runoff volume produced on non-infiltration surface* (m^3);
P is precipitation (m); and
A is total area of the sub-watershed (m^2).

(b) Precipitation on wetlands will be held in storage and will not contribute to runoff.

(c) Runoff from the pervious (or infiltration) surfaces will be the precipitation minus the infiltration , i.e.,

$R_I = (1-\alpha)A(P)) - F_I$ ………………………………………………….. (5)

where R_I *is runoff volume from pervious surfaces* (m^3),
F_I *is the infiltration volume* (m^3) *and all other symbols are as defined earlier.*

The infiltration volume, F_I, can be estimated using:

$F_I = f_p (\Delta t) (1-\alpha)A$ ………….……………………………………… (6)

Where f_p *is average infiltration capacity over* Δt *(m/hr) (which can be obtained using equation 1); and* Δt *is the duration of the time interval (hr).*

Ideally, the area used in equations (4 – 6) should be the net area after deducting the area taken up by wetlands in each of the sub-watersheds. However, since except for the year 1965 the areas of wetlands are generally small, no allowance has been made for the wetlands areas. The effect of evapotranspiration on the runoff at such a fine temporal resolution will also be so small that it has been ignored.

The total excess rainfall (or runoff) volume during Δt thus becomes:

$R_T = R_N + R_I$……………………………………………………………………. (7)

where R_T *is the total runoff volume* (m^3).

The R_T was calculated for each of the three sub-watersheds and then added together to obtain the runoff for the entire System 6C. For such a small catchment, hydrograph attenuation and elongation due to storage and routing effects are likely to be minimal; consequently, the hydrograph of discharge was obtained directly from the excess rainfall hyetograph by dividing the R_T by Δt to give the discharge in m^3/hour. The peak discharge could then be read off the hydrograph. Thus, the model determines the runoff and peak flow from rainfall. The model efficiency criterion used to judge the model performance was the coefficient of determination, R^2, proposed by Nash and Sutcliffe (1970), Stevens (1996) and applied by Gadain *et al* (2006).

3.3.3 Flood Inundation Area

The surface areas required in equations (4-6) were determined using surface computation facility of the 3-D spatial analyst extension of Arc Map 10.3 software. Topographic map sheet 297 Ilaro SE.3 produced by the Federal Survey in 1985 at scale of 1:25,000 was the major source of data for the Digital Elevation Model (DEM). The extracted contour interval of feet from the topographic sheet was further interpolated to 1m interval using nearest neighbour spline power quadratic interpolation. The DEM was computed by using grid cell arrays of 300 rows and 100 columnson the interpolated contours. Each cell covered an area of $2.23m^2$ with a resolution of 10m posting (horizontal accuracy) and 1m between adjacent terrain measurements (vertical resolution). Each grid cell has eight neighbouring cells, and the slope was defined as the steepest descent among the eight permitted choices after (Chen, 2004).

The slope and terrain input were derived from the DEM. The measured hydrologic data including water level, flow and rainfall were integrated with DEM dataset in GIS environment. The PWIM – GIS based flood inundation model adopts the query functionality of the ARC-GIS 10.3 and searches starting from the water level at peak discharge for neighbouring cells that are below the water level at peak discharge. As a result, it was able to calculate the areas inundated at peak discharge / highest water level using the 2D plannimetric area (Chairat and Delleur, 1996). These inundated areas were evaluated for the measured rainfall using the PWIM estimated peak flow on the four land use scenarios for each of the study periods of 1965, 1975, 1987 and 2005.

4. Results

4.1 Land use and Land cover Analysis

The distribution of the various land uses in 2005 is shown in Figure 3 while Table 2 contains a comparison of the 2005 situation with the other years. The predominant land use class in 2005 was built-up which account for 1231 ha (over 91%) of the total land area as against 167 ha (a mere 12%) of the total land area in 1965. It actually ranked third in 1965, behind vegetation and wetlands (Table 2). This rapid expansion in built-up areas within the watershed drained by System 6c from about 166.88 hectares (12.40%) in 1965 to 1231.00 hectares (91.46%) in 2005 indicates an extensive anthropogenic activity, involving residential and institutional developments over areas covered by hitherto. The regression in wetland is not only typified by the study area but also in the entire lower Ogun River basin of which Lagos metropolis is a major settlement (Odunuga and Oyebande, 2007).

Table 2: Land use and land cover distribution of Ashimowu watershed in 1965, 1975, 1987 and 2005

	1965		1975		1987		2005	
Land use / Land cover	Area in hectare	% of total	Area in hectare	% of total	Area in hectare	% of total	Area in hectare	% of total
Agriculture	38.09	2.83	18.57	1.38	10.90	0.81	3.86	0.29
Built up Area (CS)	166.88	12.40	1045.54	77.69	1195.99	88.87	1231.00	91.46
Open Surfaces			23.15	1.72	14.94	1.11	6.03	0.46
Transportation			40.78	3.03	55.04	4.09	66.70	4.96
Vegetation	396.60	29.47	60.02	4.46	33.24	2.47	24.93	1.85
Water Body	35.26	2.62	25.84	1.92	6.86	0.51	6.16	0.46
Wetlands	708.96	52.68	131.89	9.80	28.80	2.14	7.10	0.53
Total	1345.78	100.00	1345.78	100.00	1345.78	100.00	1345.77	100.00

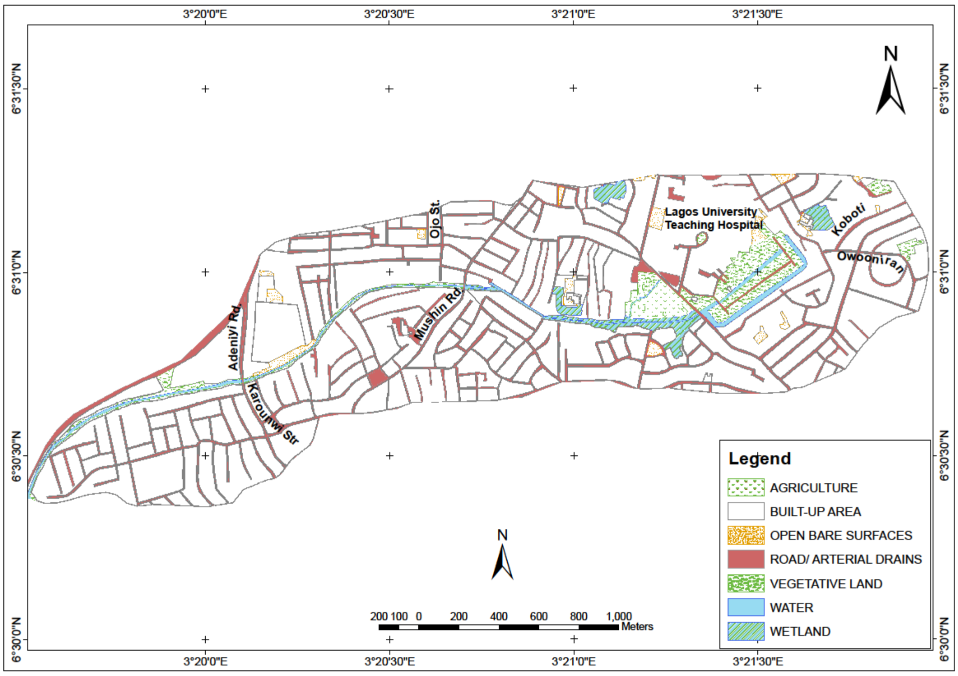


Fig 3: Lagos Megacity System 6C drainage area showing land use types (2005), the main and arterial drains

The continuous expansion of the built-up areas has led to the disappearance of what was hitherto the vegetative cover on the watershed. For example, there were no open surfaces in the watershed up till 1965; however, between 1965 and 1975, 23.15 hectares (1.72%) of land was converted to open spaces basically for recreational and institutional purposes, especially around LUTH/College of Medicine and by 2005 this decrease to 6.03 hectares (0.46%). In all these changes, the greatest victims are the wetlands that lost more than half of its areal extent in less than the half a century covered by the study. The consequence of continuous loss of the wetlands, especially in the urban setting, is degradation of the environment in various forms as earlier opined by (Selman 1996; Odunuga and Oyebande, 2007). This has been largely responsible for flooding (UN, 2004).

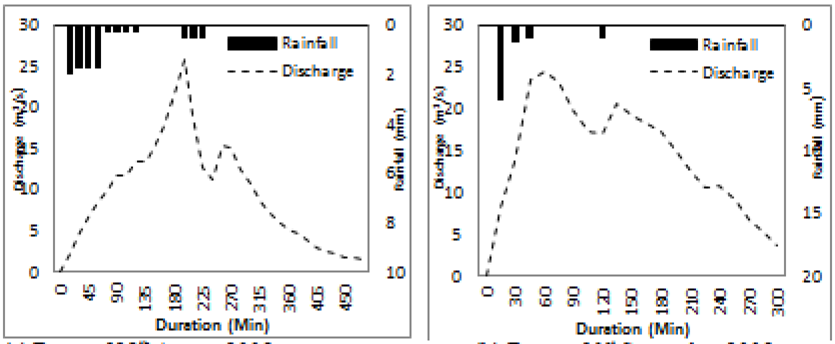
4.2 Rainfall-Runoff Modelling Performance by PWIM

Table 3 shows the amount, intensity and some statistics of the recorded storm events during the experimental field work for the data collection. The minimum amount of 1.25mm was recorded on 7th September while the maximum of 32.96 mm was on 3rd November. Variability of the rainfall amount during the experimental period was quite high, with a coefficient of variation of 71.9%. The average value of rainfall intensities during the storms reported in Table 3, has masked high temporal variability as shown by the sample hyetographs in Figure 4(a-e).

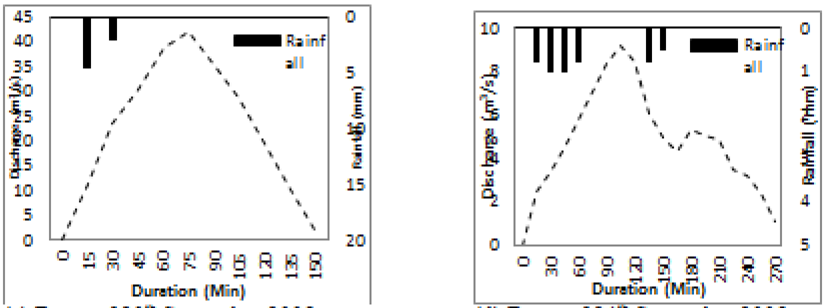
Table 3: Measured rainfall and peak flows during field work in 2005 for Ashimowu Watershed

Date	Rainfall Amount (mm)	Average Intensity (mm)/hr	Peak flow	
			Measured (m^3/s)	Simulated (m^3/s)
22/08/2005	4.75	0.61	1.59	2.09
28/08/2005	9.75	2.6	25.77	8.89
1/9/2005	9.25	4.63	24.46	15.83
7/9/2005	1.25	0.45	1.08	1.54
8/9/2005	2.25	9	5.44	30.78
20/09/2005	6.5	13	42.13	44.45
24/09/2005	4.75	1.9	9.23	6.50
27/09/2005	7.5	2.5	7.71	8.55
4/10/2005	2.25	3	5.83	10.26
11/10/2005	1.8	1.8	1.91	6.16

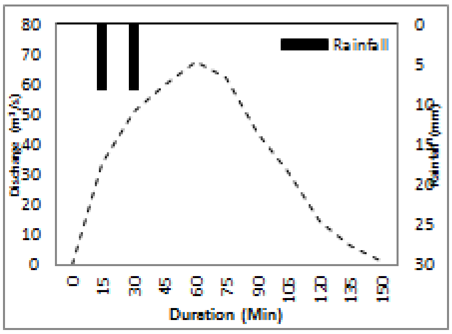
3/11/2005	16.48	32.96	67.42	112.70
Maximum	16.48	32.96		
Minimum	1.25	0.45		
Mean	6.05	6.59		
S/D	4.35	9.1		
CV(%)	71.9	138.09		



(a) Event of 28th August 2005 (b) Event of 1st September 2005



(c) Event of 20th September 2005 (d) Event of 24th September 2005



(e) Event of 3rd November 2005

Figure 4 (a-e): **Hyetographs and Hydrographs of measured rainfall events in Ashimowu watershed**

To test the performance of the PWIM, the modelled peak discharges are compared with the observed peak flows in Table 3for the 2005 rainfall and land use scenarios. In general, the observed and predicted peak flood discharges compare favourably, except for the storm events of 28/08/2005, 8/9/2005 and 3/11/2005 where there were significant discrepancies between the simulated and observed peak discharges. This can be attributed to the use of low infiltration rates adopted from Stephenson *et al* (2001) for the hydro-climatic environment. For example, both the events on the 8/09/2005 and 3/11/2005 occurred after a relatively dry intervening period and so one would expect that the infiltration occurring for these storms would be higher than that suggested by the adopted values of Horton's infiltration model parameters in Table 4. However, although the conceptualisation of the PWIM did consider antecedent soil moisture condition, in as far as the choice of the parameters of the Horton's infiltration model was concerned; this consideration was static in that a fixed antecedent condition was used for each sub-watershed irrespective of the actual situation prior to the onset of the recorded rainfall events. Consequently, there would be over-prediction of the runoff for a storm falling on a relatively dry soil and vice-versa. While a consideration of the dynamics of the antecedent conditions would have improved the performance of the PWIM, such a consideration would have also introduced a further layer of complexity into the analysis.

Table 4: Impervious fraction (α),f'_o (mm/hr) and f'_c (mm/hr) for Ashimowu sub-watersheds

Sub-watershed	Parameter	1965	1975	1987	2005
Itire (total sub-area = 282.9 ha)	α	0.03	0.85	0.89	0.91
	f'_o	11.64	1.8	1.32	1.08
	f'_c	1.46	0.23	0.17	0.14
Lawanson (total sub-area = 387.9 ha)	α	0.02	0.82	0.82	0.87
	f'_o	52.9	9.72	9.72	7.02
	f'_c	6.13	1.13	1.13	0.81
LUTH (total sub-area = 675.1 ha)	α	0.09	0.72	0.76	0.81
	f'_o	1.21	0.37	0.32	0.25
	f'_c	0.68	0.21	0.18	0.14

In terms of overall performance, however, the modelling skill of the PWIM is satisfactory. For example, Figure 5 is a scatter plot of the observed against the predicted peak discharges for all the events in 2005, together with both the 1:1 line and the line of best fit superimposed. In general, the scatter of the plotted points around the 1:1 line shows that the model has performed reasonably well and that the residuals are likely to be random. Using the regression analysis, the correlation between the observed and predicted was R = 0.892, indicating that almost 80% (R^2 = 0.795) of the observed variance was explained by the model.

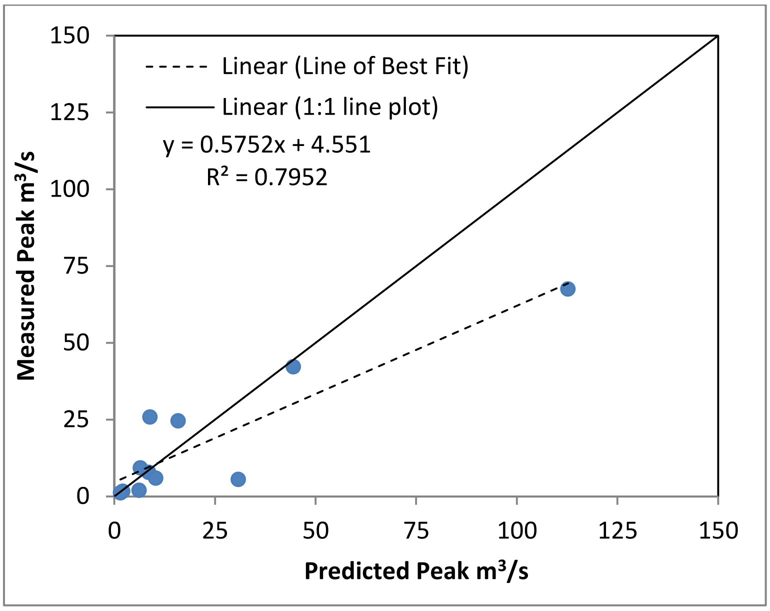


Figure 5: **Scatter plot of the observed against the predicted peak discharges of the 2005 storm events together with both the 1:1 line and the line of best fit**

4.3 Simulated Peak Flows for Historical Urbanisation Extents

With the PWIM shown to be capable of reasonably simulating the runoff response of System 6C to rainfall, it was then possible to simulate the effects of progressively rising imperviousness of the watershed that has occurred since 1965. Since the rainfall recorded was for 2005 and for the respective years of study, the land use rainfall simulation analysis and the responses obtained have not been affected by possible changes in precipitation caused by projected climate change. This is a good thing since otherwise it will be difficult to separate the confounding effect of variations in precipitation from those due purely to land-use changes in line with the main objective of the current study.

Table 5 shows how the simulated runoff depths and peak discharges have changed between 1965 and 2005. While runoff was generally small in 1965, this has more than doubled by 1975 for most of the events. As widely recognised, the 70's coincided with the huge influx of petro Dollars to the Nigerian economy and the associated massive migration to Lagos resulting in unprecedented growth in physical development in urbanization mostly on wetlands and other hitherto pervious land cover. The increases in the runoff and peak discharges recorded after 1975 have been more modest but still significant.

Table 5: PWIM simulated runoff and peak flow for 1965, 1975, 1987 and 2005 land use scenarios

	1965		1975		1987		2005	
Date	*RUNOF (mm)*	*Peak flow m^3s^{-1}*	*RUNOF mm*	*Peak flow m^3s^{-1}*	*RUNOF mm*	*Peak flow m^3s^{-1}*	*RUNOF mm*	*Peak flow m^3s^{-1}*
22/08/05	1.84	0.28	4.26	1.77	4.65	2.03	4.70	2.09
28/08/05	0.83	1.21	2.32	7.55	2.54	8.64	2.57	8.89
1/9/2005	3.96	2.15	8.31	13.45	9.06	15.38	9.16	15.83
7/9/2005	0.20	0.21	1.11	1.31	1.22	1.49	1.24	1.54
8/9/2005	0.67	4.17	2.01	26.14	2.20	29.90	2.23	30.78
20/09/05	2.67	6.03	5.83	37.76	6.36	43.19	6.44	44.45
24/09/05	1.84	0.88	4.26	5.52	4.65	6.31	4.70	6.50
27/09/05	3.14	1.16	6.73	7.26	7.34	8.31	7.43	8.55
4/10/05	0.67	1.39	2.01	8.71	2.20	9.97	2.23	10.26
11/10/05	0.46	0.83	1.60	5.23	1.75	5.98	1.78	6.16
3/11/05	7.36	15.28	14.81	95.72	16.14	109.50	16.32	112.70

Table 6 is a disaggregation of the runoff response into those from impervious (R_N) and the pervious (R_I) areas. While the runoff from the pervious areas was more than 2 times that from the impervious in 1965, It was almost non-existent in the post-1975 years. The loss is primarily caused by the disappearance of infiltration areas rather than the pervious areas becoming more pervious. This shows that more runoff volumes were being generated. Thus, although the urbanisation of the study areas appeared to have reached saturation in 1975, the gradual elimination of the remaining pervious surfaces in Lagos has continued to generate devastating consequences of flooding, infiltration, groundwater recharge and general ecosystem well-being.

Table 6: PWIM simulated runoff volume produced on non-infiltration surface (R_N) and runoff volume from pervious surfaces (R_I) for 1965, 1975, 1987 and 2005 land use scenarios

	1965		1975		1987		2005	
Date	R_N (*mm*)	R_I (*mm*)	R_N (*mm*)	R_I (*mm*)	R_N(*mm*)	R_I(*mm*)	R_N (*mm*)	R_I (*mm*)
22/08/05	0.57	1.27	3.85	0.41	4.42	0.23	4.56	0.14
28/08/05	0.31	0.52	2.11	0.21	2.42	0.12	2.50	0.08
1/9/2005	1.11	2.85	7.49	0.81	8.60	0.45	8.88	0.28
7/9/2005	0.15	0.05	1.01	0.09	1.16	0.05	1.20	0.04
8/9/2005	0.27	0.40	1.82	0.18	2.09	0.10	2.16	0.07
20/09/05	0.78	1.89	5.27	0.57	6.05	0.32	6.24	0.20
24/09/05	0.57	1.27	3.85	0.41	4.42	0.23	4.56	0.14
27/09/05	0.90	2.24	6.08	0.66	6.98	0.37	7.20	0.23
4/10/05	0.27	0.40	1.82	0.18	2.09	0.10	2.16	0.07
11/10/25	0.22	0.24	1.46	0.14	1.67	0.08	1.73	0.05
3/11/05	1.98	5.38	13.35	1.46	15.33	0.81	15.82	0.49

4.4 The Area of Inundation

Table 7 shows the calculated inundated areas for the different land use scenarios based on PWIM and GIS. It has increased successively from 1965, as a result of the increasing urbanisation within the watershed. As was the case with the runoff analysis, the results in Table 7 assume that the same rainfall as observed in 2005 fell in each of the scenario years. Reduced amount or intensity of rainfall will result in less runoff and inundated area; however, it is more than likely that any such reduction in rainfall would have been more than compensated for by the huge rise in the degree of imperviousness recorded within the watershed over the scenario years. On the other hand, where the rainfall amount and intensity to increase, the resulting inundated area will be far larger than those presented in Table 7.

Table 7: Estimated inundated areas in the watershed for 1965, 1975, 1987 and 2005 land use scenarios (in ha)

Date	1965	1975	1987	2005
22/08/05	120.67	126.22	129.48	130.3
28/08/05	214.56	225.7	238.87	241.69
1/9/2005	222.98	233.99	237.92	239.53
7/9/2005	19.47	24.56	28.92	30.88
8/9/2005	21.89	26.11	29.72	31.73
20/09/05	189.98	196.45	200.94	202.54
24/09/05	120.67	126.22	129.48	130.3
27/09/05	123.76	123.76	126.89	204.09
4/10/2005	22.14	26.11	29.72	33.76
11/10/2005	20.65	25.54	29	31.45
3/11/2005	271.89	278.89	284.76	297.05

4. Discussions

The analyses reported in this work have shown the rapid rise in urbanisation at mainland neighbourhood of Lagos and the flooding implications. They also show that the rise in proportion of imperviousness from about 12% of the catchment area in 1965 to 92% in 2005 was at the expense of other "greener" land use classes such as wetlands. This suggests that the study area is of high vulnerability to flood. The consequence of higher imperviousness is the increased runoff resulting from rainfall because infiltration will be almost nil. This was confirmed for system 6c of Lagos megacity drainage using the PWIM, a catchment water accounting tool utilising simple expressions to characterise losses due to infiltration and hence runoff. Extensive assessment of the performance of the PWIM using storm events measured during 2005 proved that the tool is very adequate in describing the runoff-runoff response for the catchment. Much more re-assuring was the high degree of accuracy associated with the predicted peak discharges. The implementation of the PWIM within a GIS environment also led to the delineation of the flood inundated area. Thus, the calibrated and validated model used to assess the impact of urbanisation on runoff and flooding based on four different land use scenarios of 1965, 1975, 1987 and 2005.

As expected, both the peak discharges and the inundated areas predicted with PWIM based on the measured 2005 rainfall were much higher in 2005 when compared with those for the earlier years. There is thus no doubt that the unplanned rapid expansion of the impervious areas in Lagos is having a profound effect on runoff and the incidence of flooding. The analyses carried out ignored the possible contribution of climate change and the anticipated increase in rainfall amount and intensity. When these issues are factored in, the flooding problems caused by the urbanisation of Lagos neighbourhood is bound to be intensified.

One possible long-term solution that has been demonstrated to work in other regions of the world is a shift from the over-reliance on structural approach that has characterised drainage plans in Lagos to its hybridization with sustainable urban drainage systems, SUDS (Martin, *et. al*, 2000). This as noted by WMO & GWP (2008) incorporates a number of different measures based on common principles of Run-off prevention and Source Control. The combination of these SUDS and the existing structural drainage systems will, in addition to helping to relieve the flooding problem, bring some other benefits including the enhancement of water quality protection, natural groundwater recharge and elimination of possible underground salt water intrusion. Some good practices of SUDS are currently being implemented in the megacity around the Lekki-Ibeju and Ikorodu axis. SUDS are not just for new-builds but can be retrofitted to existing and developed environments as well.

For already developed areas like Ashimowu, simple, source control interventions including rainwater harvesting from roofs (Al-Najar and Adeloye, 2005), can be more formalised as part of development regulations. This would imply existing structures have roof gutters that will drain rainfalls on roofs directly into small reservoirs (or cisterns) nearby for domestic uses. Thus, formalising rainwater harvesting will deliver the advantage of controlling the runoff at source and thus reducing flooding. However, in the end the only sustainable longer-term solution to the flooding problems in Lagos is the complete adoption of SUDS for the city! Embracing this practice must start now since with climate change, the problem is more likely to worsen rather than improve.

5. Conclusions

This study established that the rapid urbanisation in the study area over the last 40 years has been largely responsible for incessant flooding. The uncontrolled conversion of hitherto pervious surfaces and wetlands to concrete surfaces and building developments has reduced infiltration to almost nullity, resulting in much higher runoff. Consequently, even moderate storms are causing flooding, inundating large areas and paralysing socio-economic activities in addition to its direct and indirect effects on health as indicated by Odunuga (2012). Furthermore, increase in the frequency and number of extreme, high-intensity rainfall events as a consequence of climate change can only be expected to worsen an already intolerable situation. This calls for the adoption of holistic approach to containing flooding problems and integration of natural flood management approaches (e.g. SUDS) to structural flood control measures in the area.

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