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COMPARISON AND SENSITIVITY ANALYSIS OF TWO RAINFALL-RUNOFF MODELS IN THE CALABAR METROPOLIS, SOUTH-SOUTH, NIGERIA

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ABSTRACT

Two models were developed for the Calabar Metropolis catchment and subsequently applied in the study of the catchment so as to determine the influence of some hydraulic and hydrologic parameters on the rainfall-runoff processes in the Catchment. The models centered on the multiple regression and the finite difference approaches. The two models were compared by the application of the root mean square error (RMSE) and the Pearson correlation approach. Sensitivity analysis was equally conducted on the models using the standardized regression coefficient and the cubic regression coefficient. The results gave a root mean square error of 1.22 and 0.46 for the regression and finite difference models respectively.

Keywords: *sensitivity, analysis, catchment, cubic, regression, urbanization, pearson, impervious,discharge*.

I. INTRODUCTION

It is generally accepted that the contemporary trend towards more urbanization in the world today will continue. As a consequence, urban problems associated with the hydrologic aspects of water management should become increasingly more acute. Effective disposal of storm water has become very essential. Urban storm water management is no longer based on the interception, collection and disposal of storm water only, but also on the application of workable rainfall-runoff model approaches in storm drainage designs.

In 2004, the Vision 20/20 Water Quality Planning Group recognized the role sound water engineering design principles and practices play in defining the quality of life for South West Missouri (Storm Water Drainage Criteria Manual, 2008). Sound storm water design practices help to maintain compatible drainage systems, minimize disturbance to existing drainage patterns, control flooding of property, structures, and roadways, and minimize environmental impacts of storm water runoff. Urbanization tends to increase downstream peak flows, runoff volumes, and runoff velocities. These changes can cause the capacity of adequately designed downstream systems to be exceeded and disrupt natural waterways. The impacts of new urbanization must be reduced through the use of structural and non-structural Best Management Practices (BMPs) that usually include storm water detention.

In Calabar Metropolis, rapid and largely unplanned urban growth has, over the years, resulted in land use changes and modifications, which have resulted to changes in the hydrological fluxes in the urban watershed.

Over the past thirty-eight years, the area of impervious surfaces in Calabar Metropolis has significantly increased. This has resulted from the several activities of man to foster urbanization and expedite development. In 1972 for instance, the city had an area of about 120.8sqkm. At the end of 2006 however, the area had expanded to encompass not less than 380sqkm, (The Calabar Master Plan, 1972 in Ugbong, 2000). As urbanization continues, there is increased population density. This means that more areas have been devoted to housing and businesses. This, in turn results in an increase in the area of ground covered with impervious surfaces. This should also mean that a good portion of the right-of-way of water, specifically overland flow, would have been tampered with. Accordingly, as there are more impervious surfaces in the ever-spreading urban area, threat of flooding is bound to increase during any major storm event. This should be expected because water runs off quickly and there is an increase in peak discharge rates. This, of course overwhelms the various hydrological structures and systems across the entire metropolitan area.

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The objectives of this study is to

(i) Review,
(ii) compare and
(iii) conduct sensitivity analysis on existing rainfall-runoff models in the Calabar Metropolis catchment.

II. MATERIALS AND METHODS

Description of Area of Study

Calabar Metropolis lies between latitudes 04° 45' 30" North and 05° 08'30" North of the Equator and longitudes 8° 11' 21" and 8°27'00" East of the Meridian. The town is flanked on its eastern and western borders by two large perennial streams viz: the Great Kwa River and the Calabar River respectively. These are aside from the numerous ephemeral channels which receive water after storm events to drain the area of study (Antigha, et al, 2014, Antigha, 2017).

It occupies an area of about 223.325 sqkm with major clans being Efut Uwanse, Obufa – Esuk, Old Calabar, Mbukpa, Anantigha, Archibong Town, Cobham Town, Henshaw Town, Old Town, Essien Town, Ikot Ansa, Ikot Effanga, Ikot Omin, Ikot Nkebre, Akim Qua Town, Big Qua Town, Kasuk,Satellite Town, Nyakasang etc.(Antigha and Ogarekpe, 2013, Antigha et al,2015)

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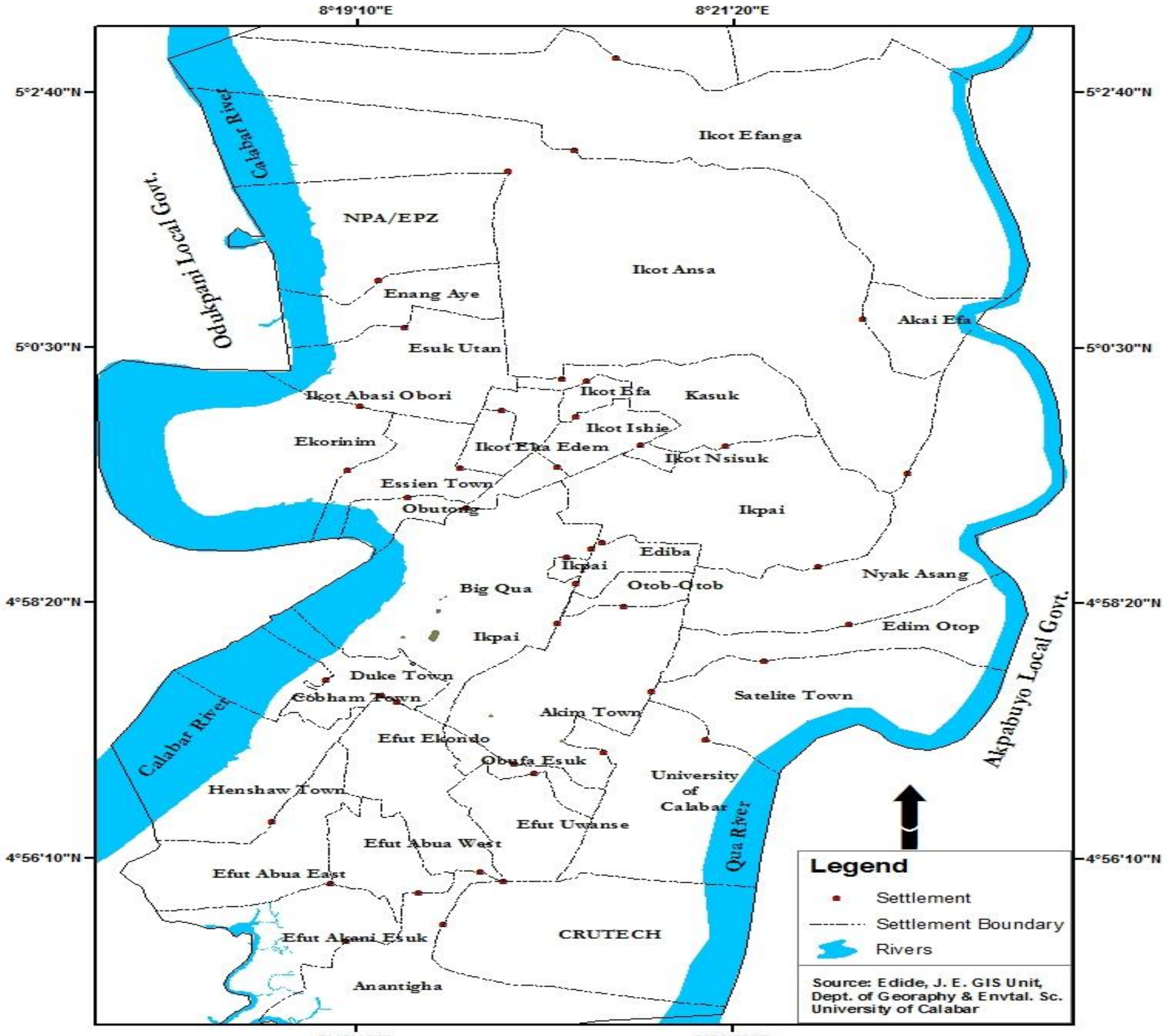

Fig. 3.1: Layout of Calabar Metropolis

As a coastal town in Nigeria, Calabar metropolis has a high relative humidity, usually between 80% and 100%. Relative humidity drops with the rise in temperature to about 70% in the afternoon during the dry season. Vapour pressure in the air averages 29 millibars throughout the year (CRBDA Report, 1995**).**

The Calabar River is about 7.58 metres deep at its two major bands (Tesko-Kutz, 1973). The city lies in a peninsular between the two rivers, 56km up the Calabar River away from the sea. Calabar has been described as an inter-fluvial settlement (Ugbong, 2000).

The present conditions as seen in terms of road network and settlements are as follows: The Calabar Road cum Murtala Muhammed Highway form the main artery of the city's roads network, running from north to south, linking all other major lines. Other major routes are the Ndidem Usang Iso Road, which runs parallel to the Highway, and MCC Road which runs perpendicular to both the Highway and Usang Iso Roads. Other streets spread like branches of a tree throughout the city (Antigha, et al 2015 a&b).

The urban structure can best be explained in terms of the Hoytes (1939) as captured in Ugbong (2000) sectoral model. Population and settlements are concentrated in zones inhabited by the three ethnic groups-, the Efuts to the south, the Efiks to the west and the Quas to the east.

With a population of 202,585 in 1991, it now has a population of over 400,000, (C.R.S Ministry of Land and Housing, 2008).This shows a growth or an increase in population of 49.4% or an average annual population increase of 2.9%.

All the year round, temperature rarely falls below 19^0C and average 27^0C. The average daily maximum is above 24^0C with a range of 6^0C, and a seasonal variation of the same amount, between the hottest month (March) and the coolest month (August). Expectedly therefore, evaporation will be high (Antigha *et al*, 2014).

III. RESULTS AND DISCUSSIONS

1. Comparison of the Developed Models

Two models were developed to attempt a solution to the perennial flooding in the Calabar Metropolis catchment. One was a conceptual model while the other was an empirical. The target was to show how each model directly or otherwise, explicates and quantifies flooding in the catchment. The multiple regression and the finite difference approaches were employed.

Multiple Regression Approach

Based on the multiple regression approach, for the prediction model to be validly applied, the following assumptions must hold.

1. The dependent variable y should be approximately normally distributed i.e.
   $$y \sim NID(\mu_1 \sigma^2) \quad - \quad (1)$$
2. The observation on y and x^s should be independently collected.
3. Measurement of the variables should be at least at interval level.
4. The inter-correlations among the independent variables should be close to zero

$$\curlyvee x_{ij} \doteq 0\ (\neq j) \quad - \quad (2)$$

These assumptions can be tested or taken care of in the design of the study, in which case testing becomes optional. For assumption (1) this can be overcome by a large number of observations on y such that n $\geq$ 30. In this study this was done but the values for the variables became too close to one another. To avoid what Draper (1981) called "repeat run" which might lead to an exaggerated R^2, the closed readings were averaged out, reducing the number of observation points to 10. Though this reduced the value of R^2, the resulting R^2 is much more meaningful than that obtained with "repeat runs".

Assumption (2) was attained by design. All observations on all the variables in the study were independently obtained.

For assumption (3) all measurements had a meaningful zero, which means measurement is at ratio level. The issue of units and their effect on the efficiency of the model has attracted the attention of statisticians for some time now. However, recent works by Kerlinger (1986) have handled this issue by providing a parallel model that utilizes normalized standard scores of the variables that showed that the differences in the R^2 is not significant. Thus the prediction model could be that in which x^s and y are converted to z scores thus

$$Z_x = \frac{x-\mu_x}{\sigma_x} \quad - \quad (3)$$

$$Z_y = \frac{y-\mu_y}{\sigma_x} \quad - \quad (4)$$

The resulting prediction model

$$\hat{y} = \beta_1 Zx_1 + \beta_2 Zx_2 + \ldots \beta_5 Zx_5 \quad - \quad (5)$$

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has no intercept or
$y = \hat{\beta}_0 + \hat{\beta}_1 x_1 + \hat{\beta}_2 x_2 + \ldots . . \hat{\beta}_5 x_5$ - (6)

which has an intercept and the units of measurement are primary. The assumption 4 was ascertained by examining the inter-correlation matrix. Clearly none of the inter-correlation coefficients is significant. Even if it were, the multiple collinearity can be removed by an appropriate combination of two or more variables involved into one composite variable.

Applying regression analysis on the data obtained using SPSS (17.0), it was observed that a linear correlation existed between the dependent variable, y, and the set of independent variables $(X_1, X_{2,} X_3, X_4, and X_5)$. The model developed gave a good multiple regression coefficient of 0.982 with a standard error of 0.709 at a significance level of 0.05

The equation below is obtained as an empirical regression model for the prediction of discharge of storm water for Calabar metropolis.

$$\hat{Y} = -113.8973 + 6.055X_1 + 1.739X_2 - 685.912X_3 + 0.006X_4 + 0.001X_5 \quad (7)$$

where;

Y = Discharge (m^3/s)
$X_1 =$ Cross sectional area (m^2)
$X_2 =$ Degree of imperviousness (%)
$X_3 =$ Gradient (m/m)
$X_4 =$ Sum of channel length (m)
$X_5 =$ Basin area (ha)

Multiple Regression Approach
For the finite difference model, the proposed flow equation was given as shown below. (Note that the detailed derivation of the model has been skipped).

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = f\,\frac{\phi}{2z_e}(r_e - T) \quad (8)$$

But $Q = V_k A$ and $f = az^b$

(9)

Where V_k is the celerity and A is the cross sectional area, then

$$A = \frac{Q}{V_k} \quad (10)$$

Substituting equation (11) into equation (9), gives the following,

$$\frac{\partial Q}{\partial x} + \frac{\partial}{\partial t}\left(\frac{Q}{V_k}\right) = \frac{a\phi}{2z_e}(r_e - T)z^b \quad (11)$$

$$\frac{\partial Q}{\partial x} + \frac{1}{V_k}\frac{\partial Q}{\partial t} = \frac{a\phi}{2z_e}(r_e - T)z^b \quad (12)$$

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Using the method of characteristics to solve for V_k

$$Q(x,t) = Q[x(s),t(s)]$$

$$\frac{d}{ds}Q[x(s),t(s)] = \frac{\partial Q}{\partial x}\frac{dx}{ds} + \frac{\partial Q}{\partial t}\frac{dt}{ds} \quad (13)$$

Comparing equation (14) with (13), the following relationship is obtained

$$\frac{dx}{ds} = 1 \text{ and } \frac{dt}{ds} = \frac{1}{V_k} \quad (14)$$

$$\frac{dt}{ds} = \frac{1}{V_k}, \Rightarrow \frac{dQ}{ds} = \frac{a\phi}{2z_e}(r_e - T)z^b \quad (15)$$

$$ds = V_k dt \quad (16)$$

Integrating both sides

$$S = V_k t + c \quad (17)$$

Using the initial condition t (0) = 0, c = 0

Then

$$S = V_k t \quad (18)$$

$$V_k = S/t \quad (19)$$

$$\text{But } \frac{dx}{ds} = 1 \quad (20)$$

$$dx = ds$$

$$\int dx = \int ds$$

$$x = S + C$$

Where C is the integral constant

Also, using initial condition

$$x(0) = 0, C = 0$$

$$x = 0 \text{ and } x = L \Rightarrow S = L$$

$$\text{Then } V_k = S/t = \frac{L}{t}$$

Therefore, the celerity V_k can be obtained the formula

$$V_k = \frac{L}{t} \quad (21)$$

Where L is the channel length and t is travel time to the outlet. An expression for t has been derived from overland flow model as

$$t = \left(\frac{L}{\alpha r_e^{\beta-1}}\right)^{\frac{1}{\beta}} \quad (22)$$

Where α can be obtained from equations depending on the shape of the channel.

$\beta = \frac{5}{3}$ and r_e is the rainfall intensity

From the foregoing, the model derived therefore is given as,

$$\frac{\partial Q}{\partial x} + \frac{1}{V_k}\frac{\partial Q}{\partial t} = \frac{a\phi}{2z_e}(r_e - T)z^b \quad (23)$$

Where

Δt is change in time,

Δx is change in length along the path of flow(from inlet to outlet),

ϕ is a catchment constant defining the channel finish.

V_k is the celerity,

Q is the discharge,

r_e is the rainfall intensity

T is the catchment losses (evapotranspiration).

z is the time from the onset of infiltration

α and b are infiltration constants.

z_e is a time constant assumed as unity.

The solution to this model was done using the numerical approach of solving partial differential equation. The finite difference method was used. Finite difference formulation for runoff through the channel is given as

$$\frac{Q_{i+1}^{j+1} - Q_i^{j+1}}{\Delta x} + \frac{1}{V_k}\frac{Q_{i+1}^{j+1} - Q_{i+1}^{j}}{\Delta t} = \frac{a\phi}{2ze}(r_e - T)z^b \quad (24)$$

$$\frac{v_k\Delta t\left(Q_{i+1}^{j+1} - Q_i^{j+1}\right) + \Delta x\left(Q_{i+1}^{j} - Q_i^{j+1}\right)}{\Delta t\Delta x v_k} = \frac{a\phi}{2z_e}(r_e - T)z^b \quad (25)$$

$$v_k\Delta t\left(Q_{i+1}^{j+1} - Q_i^{j+1}\right) + \Delta x\left(Q_{i+1}^{j} - Q_i^{j+1}\right) = \frac{a\phi}{2z_e}(r_e - T)z^b v_k\Delta x\Delta t \quad (26)$$

$$v_k\Delta tQ_{i+1}^{j+1} - v_k\Delta tQ_i^{j+1} + \Delta xQ_{i+1}^{j+1} - \Delta xQ_i^{j+1} = \frac{a\phi}{2z_e}(r_e - T)z^b v_k\Delta x\Delta t \quad (27)$$

$$v_k\Delta tQ_{i+1}^{j+1} + \Delta xQ_{i+1}^{j+1} = v_k\Delta tQ_i^{j+1} + \Delta xQ_i^{j+1} + \frac{a\phi}{2z_e}(r_e - T)z^b v_k\Delta x\Delta t \quad (28)$$

$$Q_{i+1}^{j+1}(v_k\Delta t + \Delta x) = Q_i^{j+1}(v_k\Delta t + \Delta x) + \frac{a\phi}{2z_e}(r_e - T)z^b v_k\Delta x\Delta t \quad (29)$$

Dividing both sides by $(v_k\Delta t + \Delta x)$ to make Q_{i+1}^{i+1} the subject, yields the following,

$$Q_{i+1}^{j+1} = Q_i^{j+1} + \frac{\frac{a\phi}{2z_e}(r_e - T)z^b v_k\Delta x\Delta t}{v_k\Delta t + \Delta x} \quad (30)$$

The target in model comparison is to ascertain which of the two or more equations appropriately fits the model data. The goodness-of-fit as quantified by the sum-of-squares is one scientifically reasonable approach in achieving this. For this work, a correlation was first run on the calculated data for both the regression and the conceptual models before fitting the data. The results of the correlation and the root mean square errors analyses are as shown on Tables1-4 and Figures 1- 4

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Table 1: Multiple Regression Approach.

Location	Measured Discharge	Estimated Discharge
SB1	4.85	4.69
SB2	13	10.63
SB3	1.8	1.49
SB4	1.94	2.94
SB5	0.69	-1.03
SB6	32.2	32.16
SB7	1.94	3.26
SB8	9.7	11.31
SB9	0.66	1.58
SB10	4.4	4.16

The fitted regression model is

$$\hat{Y} = -113.8973 + 6.055X_1 + 1.739X_2 - 685.912X_3 + 0.006X_4 + 0.001X_5$$

$$R^2 = 0.982.$$

where,

X_1 = Cross Sectional Area

X_2 = Degree of imperviousness

X_3 = Gradient

X_4 = Sum of channel

X_5 = Basin Area

Y = Discharge

The result showed that the five independent variables accounted for 98.2% of the variation in discharge. The graph of the measured and estimated discharge are shown in Figure1 below.

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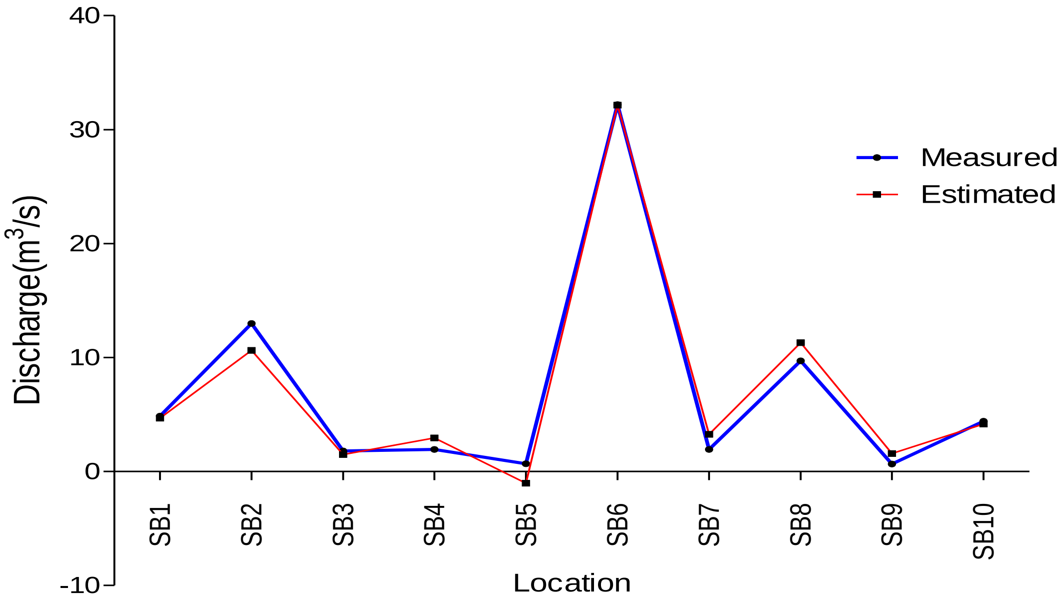

Fig 1: Measured and Estimated Discharge using Multiple Regression Approach.

Table 2: Rainfall-Runoff Conceptual Model Results

Location	Measured Discharge	Estimated Discharge
SB1	4.85	4.57
SB2	13	12.19
SB3	1.8	1.67
SB4	1.94	1.88
SB5	0.69	0.65
SB6	32.2	33.29
SB7	1.94	1.81
SB8	9.7	9.42
SB9	0.66	0.58
SB10	4.4	4.23

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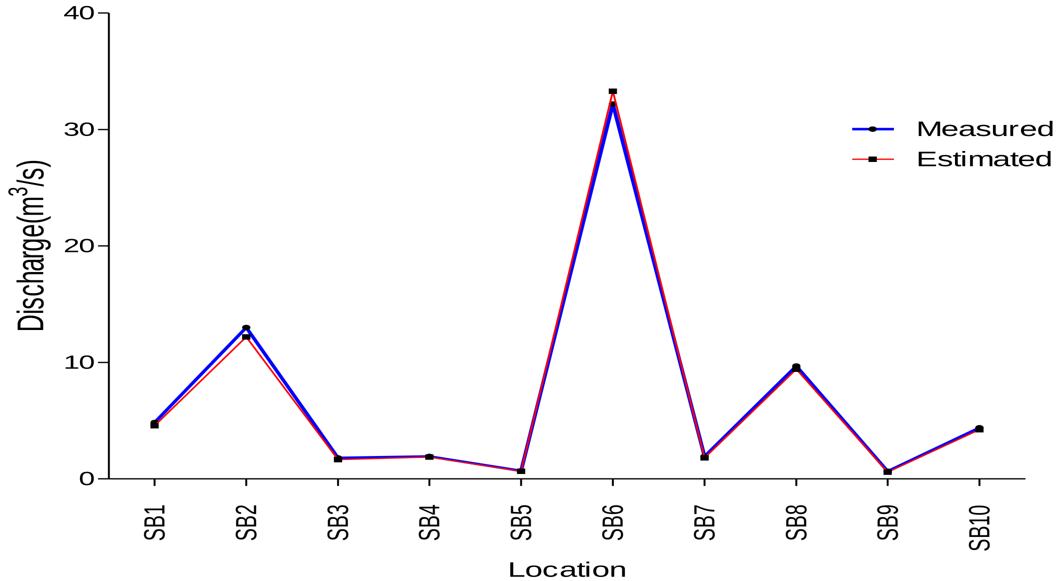

Fig 2 : Measured and Estimated Discharge using the Conceptual Rainfall-Runoff Model.

Table 3: Comparison of the Two Models

		Regression approach		Conceptual model	
Location	Measured Discharge	Estimated Discharge	RMSE	Estimated Discharge	RMSE
SB1	4.85	4.69	1.22	4.57	0.46
SB2	13	10.63		12.19	
SB3	1.8	1.49		1.67	
SB4	1.94	2.94		1.88	
SB5	0.69	-1.03		0.65	
SB6	32.2	32.16		33.29	
SB7	1.94	3.26		1.81	
SB8	9.7	11.31		9.42	
SB9	0.66	1.58		0.58	
SB10	4.4	4.16		4.23	

The result in Table3 above showed that the Root Mean Square of 1.22 was obtained when the regression approach was used while 0.46 was obtained for the conceptual model. Based on the Root Mean Square Error, it can be concluded that the conceptual rainfall-run off model gave a better model of discharge than that of the regression approach.

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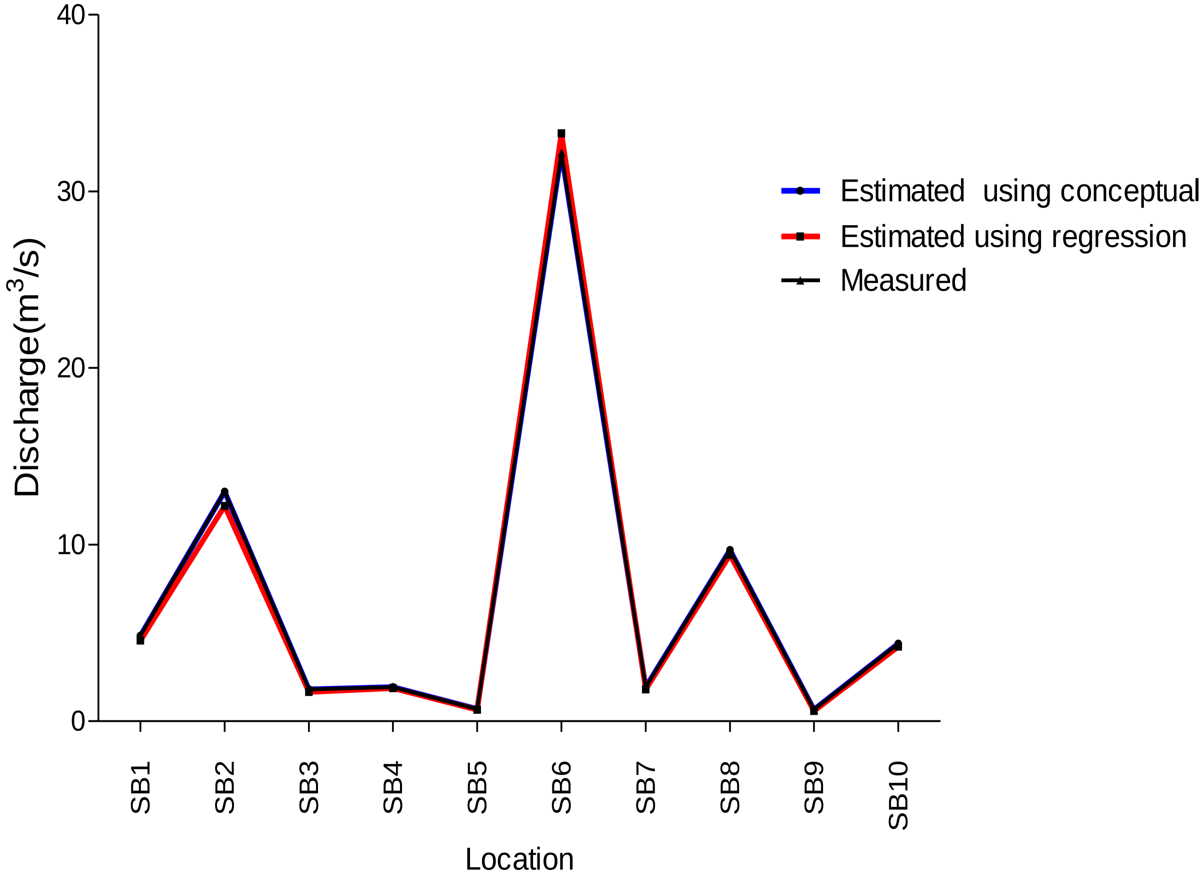

Fig 3 : Measured and Estimated Discharge based on Regression Method and the Conceptual Model.

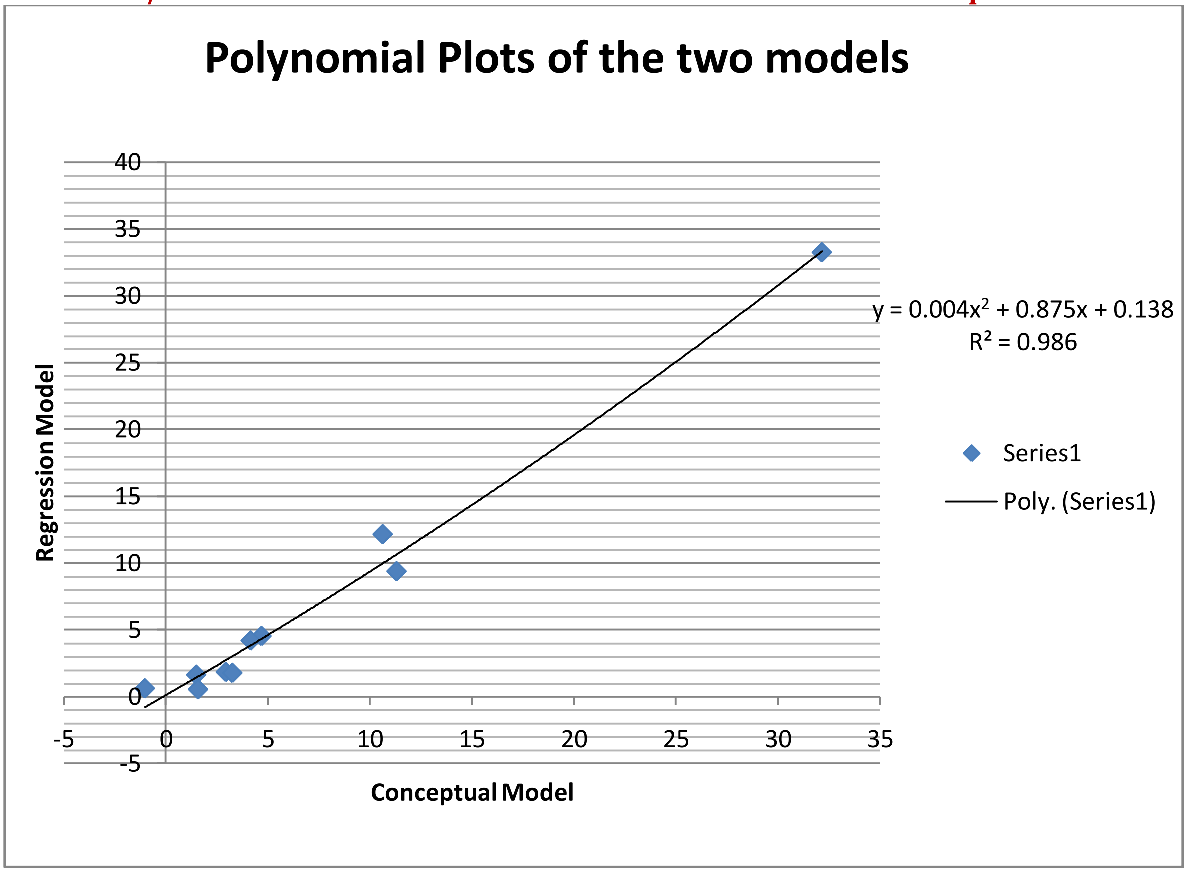

Fig.4: Scattered Polynomial Plots for the Regression and Conceptual Models

Table 4: Correlation Matrix Showing Relationship between the Measured and Estimated Discharge using the Conceptual Approach and Regression Approach.

Correlations

		Measured	Estimated conceptual	Estimated regression
Measured	Pearson Correlation	1	.999**	.991**
	Sig. (2-tailed)		.000	.000
	N	10	10	10
Estimated_conceptual	Pearson Correlation	.999**	1	.993**
	Sig. (2-tailed)	.000		.000
	N	10	10	10
Estimated_regression	Pearson Correlation	.991**	.993**	1
	Sig. (2-tailed)	.000	.000	
	N	10	10	10

**. Correlation is significant at the 0.01 level (2-tailed).

As shown on the table above, the correlation between measured discharge and estimated discharge using conceptual model was obtained as 0.99 ($r = 0.99$, $p<0.05$) while that of the regression yielded 0.991 ($r = 0.991$, $p<0.05$). Hence, the two models showed a significant relationship between the measured and estimated discharge. The correlation

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value of the conceptual model was more significant than that of the regression method. This also supports the result obtained using the Root Mean Square method.

2. Sensitivity Analysis of the Rainfall-Runoff Models Developed

Sensitivity analysis in any model development and application involves the study which shows how the uncertainty in a given mathematical model output can be apportioned or distributed to various sources of uncertainty in its input. This may involve the testing of the strength of the results of a model in the incidence of ambiguity. It can equally be useful in the increased understanding of the relationships between input and output variables in a model or in a given system. Additionally, the process helps in the reduction of uncertainty by identifying model inputs that cause significant uncertainty in the output. This, undoubtedly, helps minimize errors.

Multiple Regression Approach Model

For this work, the sensitivity analysis of the model was examined using the standardized multiple regression coefficient. The regression approach was used because it explores the entire interval definition of each factor, each factor effect is averaged over that of the other factor and that the standardized regression coefficient give also the sign of the effect of an input factor on the output.

Table 5: Results of Sensitivity Analysis Using Standardized Regression Coefficients

Model Input	Standardized Regression Coefficient	Relative Contribution %	Contribution Sign	Rank	R	R^2
Cross-Sectional Area	1.14	53	+ve	1		
Degree Of imperviousness	0.480	22	+ve	2	0.991	0.982
Gradient	0.383	18	+ve	3		
Sum Of channel length	0.079	4	+ve	4		
Basin Area	0.074	3	+ve	5		

The result of sensitivity analysis above shows relative contribution of each of the input variable to the output. The result reveals that cross-sectional area has the highest contribution to discharge follow by degrees of imperviousness, gradient, sum of channel length and basin area. All the input variables have positive standardized coefficient with the exception of gradient which has negative contribution.
Therefore, sensitivity analyses results have shown that cross-sectional area is the most important variable in the model and is ranked 1. For any 1% change in cross-sectional area, the discharge increased by 1.130 and for 1% change in degree of imperviousness, sum of channel length and basin area, the discharge increased by 0.476, 0.078 and 0.074 respectively.

The Conceptual Model Approach

In order to examine the sensitivity of the conceptual rainfall-runoff model to changes in time, the standardize regression coefficient approach was used.

Table6: Sensitivity Analysis of the Conceptual Rainfall - Runoff Model based on the Standardized Cubic Regression Coefficients using time as the independent variable.

Model Input	Standardized Coefficients	% Contribution	Sign	Rank	R	R^2
T	7.436	23.10	+ve	3		
t^2	- 16.071	49.93	-ve	1	0.942	0.887
t^3	8.679	26.97	+ve	2		

The results showed a coefficient of determination of 0.887 (R^2= 0.887). This means that 88.7% of the total variation in discharge was accounted for by time using the cubic regression model. The result also revealed that at the initial

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time t, the runoff increased by 7.436 m^3/s but when the time was doubled, the runoff reduced by 16.071 m^3/s and then picked up again by 8.679 m^3/s when the time was tripled.

Summary Output

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.991[a]	.982	.960	1.93360

a. Predictors: (Constant), X3, X5, X1, x4, X2

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	832.877	5	166.575	44.553	.001[b]
	Residual	14.955	4	3.739		
	Total	847.832	9			

a. Dependent Variable: Y

b. Predictors: (Constant), X3, X5, X1, x4, X2

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-113.873	50.114		-2.272	.086
	x4	.006	.010	.078	.643	.555
	X5	.001	.001	.074	.734	.503
	X2	1.739	.795	.476	2.186	.094
	X1	6.055	.866	1.130	6.992	.002
	X3	-685.912	310.319	-.380	-2.210	.092

a. Dependent Variable: Y

IV. CONCLUSION AND RECOMMENDATIONS

The perennial flooding in some parts of the Calabar Metropolis drainage basin has been a thing of grave concern to all residents and stake holders in recent times.

In urban storm drainage systems studies, rainfall-runoff processes are normally analysed by the application of mathematical models sometimes in combination with other various water quantity and quality sampling techniques. Urbanization has been shown to increase surface runoff, by creating more impervious surface such as pavement and structures that impede percolation. When this happens, the water instead is forced to flow directly into streams or storm water runoff drains, where erosion and siltation can be major problems, even when flooding is not.

A well-designed storm water system will improve the effectiveness of the natural system, rather than negate, replace, or ignore it. Urbanization in the Metropolis, as well as in other areas of the world, tends to increase downstream peak flows, runoff volumes, and runoff velocities. Consideration should therefore be given to the importance of reducing erosion because of the potential for public and private property damage.Storm water system planning and design for a new development must be compatible with watershed master plans and objectives and must be coordinated with plans for land use, open space, transportation and other community objectives

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