Estimation of the Quantity of Surface Runoff to Determine Appropriate Location and Size of Drainage Structures in Jimeta Metropolis, Adamawa State, Nigeria

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Abstract

This study attempts to determine the appropriate locations and sizes of drainage structures that can handle surface runoff in all watersheds of the study area (i. e. Jimeta Metropolis) without endangering lives and properties. Surface runoff is the excess water that flows over the land after the soil is infiltrated as a result of heavy rainfall while a watershed is defined as the area of land that drains to a particular point. Among various methods of determining the quantity of surface runoff, rational method is considered for this study. This is because previous attempts have shown that the concept of rational method is simple and good for relatively small watersheds as those covered in this study. The data used are the rectangular coordinates of points and the rainfall data of the study area for the year 2011. The method includes the determination of the locations and volumes of the drainage structures, Time of Concentration (ToC), Rainfall Intensity (I), Runoff Coefficient (C) and hence the estimated quantities of the surface runoff. Analyzing the results obtained, it was observed that the locations of the drainage structures are appropriate. However, the drainage structures of some watersheds are smaller than the required sizes thereby posing the risk of endangering lives and properties. That is, the existing volumes of the structures are smaller than the estimated volumes of the surface runoff. Therefore, it is recommended that the estimated quantity of surface runoff in a particular watershed should serve as a bench mark for the determination of appropriate location and size of drainage structure to be constructed for such watershed.

Key Words: Surface runoff, Drainage structures, Watershed, GPS, Rational method and Jimeta Metropolis

Introduction

The flow of surface water which is of great concern to Geospatial Scientists generally results from excess water on the ground after the soil if infiltrated to full capacity due to melted water or heavy rainfall over the land.

Measures taken to control such surface flow of water is generally termed surface drainage system and the methods involved include construction of structures like culverts, bridges, gutters etc. That is, drainage systems are typically designed to carry surface water flow away from areas where it is not wanted. Flooding and/or erosion occur when volume of flowing surface water exceeds the capacity of the designed drainage system. Therefore, appropriate drainage structures should be designed to maintain compatibility with the existing drainage patterns of a particular community. This will minimize negative environmental impacts that lead to the destruction of lives and properties.

Surface runoff has led to the failure of many structures such as roads, buildings, culverts etc within Jimeta Metropolis in Adamawa State of Nigeria. Debris of solid wastes and pool of surface water are left on the ground after heavy rainfall. This, in some cases, has resulted into the loss of lives and properties. The failure of these structures and the severity of the hazard experienced in this Metropolis due to surface runoff might not be unconnected with the inadequacy of the sizes and/or poor locations of the drainage structures within the Metropolis.

Therefore, it is the objective of this study to estimate and utilize the quantity of surface runoff for the determination of appropriate locations and sizes of drainage structures that can handle the surface runoff adequately without endangering lives and properties within Jimeta metropolis in Adamawa State of Nigeria.

Study Area

Jimeta is a metropolitan city in Yola North local government area of Adamawa State in Nigeria as shown in figures 1, 2 and 3. It is located between longitudes 12^0 17' and 12^0 33' and latitudes 9^0 06' and 9^0 24' with an altitude of 185m above sea level (Amogu, 2001). It lies within the Sudan Savannah region with a tropical climate marked by wet and dry seasons. The wet season is from May to October with maximum rainfall around August while the dry season is from November to April. On the average, the minimum temperature is 35^0c while the maximum temperature is 44^0c per year (Amogu, 2001).

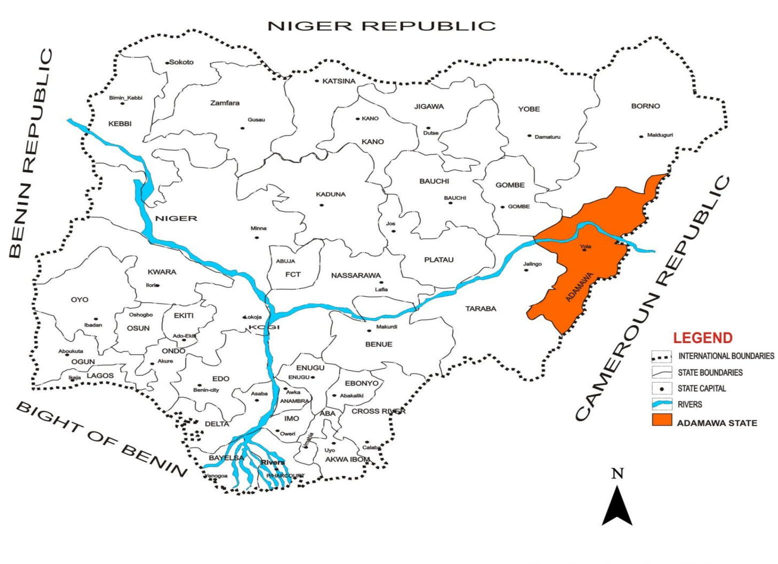

Figure 1: Map of Nigeria showing Adamawa State

Source: Adamawa State Ministry of Land and Survey (2006)

Figure 2: Map of Adamawa State showing Yola North LGA

Source: Adamawa State Ministry of Land and Survey (2006)

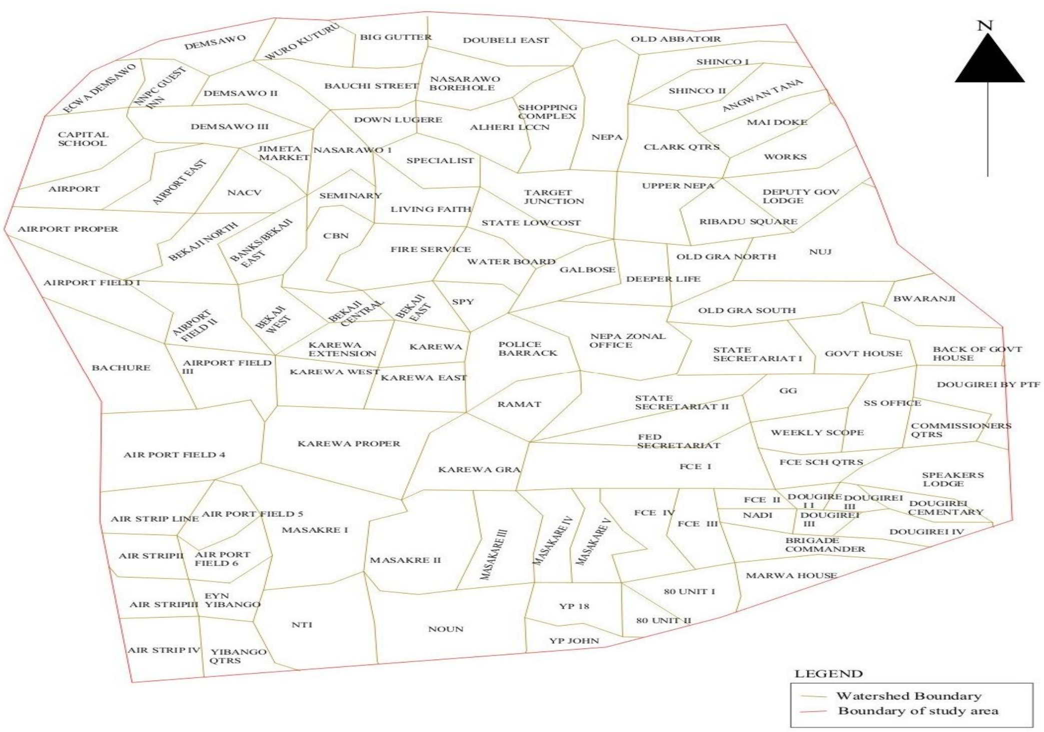

Figure 3: Map of Jimeta Metropolis showing watershed boundaries.

Source: Adamawa State Ministry of Land and Survey (2006)

Methodology

The procedure adopted includes acquisition of data, the use of rational method to determine the estimated quantity (Q) of surface runoff for each watershed, determination of the volumes (V) of existing drainage structures and comparison of Q and V to make appropriate recommendation on the locations and sizes of the drainage structures.

Data Acquisition

A real time kinematic Global Positioning System (GPS) survey was carried out to obtain the coordinates of points within the study area using GSR 2700 ISX GPS hardware. Other sets of data used were records of rainfall for the year 2011 collected from Nigerian Environmental Climatic Observing Program (NECOP) base station located at Modibbo Adama University of Technology, Yola in Adamawa State of Nigeria (MAUTECH, 2011).

Data Quality

The quality of data used for any experiment can be determined by the validity and reliability of such data based on the assumption that the observers of such data are trustworthy and experienced. The validity of the data can be determined by the precision of the instrument used. Precision is defined as the degree of closeness of repeated measurements of the same quantity to one another. The coordinates of each point were taken repeatedly and found to be closely clustered. The reliability of data is determined by the accuracy of the data. That is, the degree of closeness of the sets of data to another sets regarded as the true values, often referred to as 'Gold Standard Data' (Roos et. al., 1982 and Roos et. al., 1989). The GRS 2700 ISX used for data capture was used in differential mode to cancel the effect of selective availability.

Also, some control points were included in the observation and the results show insignificant differences between the original and observed coordinates of the control points. Furthermore, the station manager of NECOP gave an assurance that the rainfall data was declared reliable and hence ready for public consumption. Based on the above report, it can be inferred that the validity, reliability and hence the quality of the data used in this study are satisfactory.

Data Processing

Estimation of the quantity of surface runoff is the first stage of analysis for locating drainage facilities. There have been many different approaches leading to many different models for determining the surface runoff of an area. The method used for this study is rational method.

Rational method

Rational method is the process of determining the maximum surface runoff in a drainage area. Functionally, it relates the quantity of surface runoff (Q) of the watershed area (A), the rainfall intensity (I) and the runoff coefficient (C) as shown in equation (1). It has simplifying assumptions which include uniform rainfall with uniform intensity over the entire watershed for the particular time of rainfall concentration (Rossmiller, 1980). The runoff coefficient is determined based on land-cover, topography, soil type and storm period within the study area.

$$Q = 0.0028CIA \quad (1)$$

Watershed Area (A)

The administrative map of the study area was scanned, geo-referenced and digitized. Also, the boundaries of the existing drainage networks and watersheds were digitized.

The different layers of the digitized administrative map, watersheds and drainage network were overlaid in ArcGIS 9.3 environment leading to the determination of the locations and areas of the watersheds.

Runoff coefficient (C)

Runoff coefficient used for the study was extracted from Kuichling (1889) and presented in table 1. Generally, in this table, areas with permeable soils, flat slopes and dense vegetation are expected to have the lowest values of coefficients. Areas with dense soils, moderate to steep slopes and sparse vegetation should have highest values. Furthermore, if the types of soil cover are homogeneous for the entire watershed, then the average of the runoff coefficients is used. In a situation where there is multiple soil cover type in a watershed, the watershed will be divided into sections and the area calculated for each section.

Thereafter, the corresponding runoff coefficient for each section is extracted from coefficient table. Then, the product of each area and the coefficient is obtained. The total sum of the products obtained for the sections divided by the total area represents the coefficient of the watershed. In this study, it is assumed that the soil cover is homogeneous hence the average value of coefficient between the highest and lowest values was used for each watershed.

Table 1: Runoff coefficients for different soil cover (Kuichling, 1889)

Description	Runoff Coefficients
Business	
Downtown Areas	0.70 - 0.95
Neighborhood Areas	0.50 – 0.70
Residential	
Multi-family detached	0.40 – 0.60
Multi-family attached	0.60 – 0.75
Parks, cemeteries (lawn)	0.10 – 0.25
Playground (lawn)	0.20 – 0.35
Streets	
Unimproved areas	0.10 – 0.30
Drive and Walks	0.75 – 0.85
Roofs	0.75 – 0.95
Asphalt	0.70 – 0.95
Concrete	0.80 – 0.95

Rainfall Intensity (I)

Rainfall intensity is a measure of amount of rain that falls over time measured in millimeter (Bashir, 2001). Time of Concentration (ToC) of each rainfall is a determining factor for selecting rainfall intensity for each watershed. Rainfall intensity that is equal to or slightly less than the ToC is rainfall intensity that will have the full watershed contribution to the runoff at the outlet. Therefore, from the list of rainfall intensity that falls in a particular year, the one that is equal or slightly less than its ToC will be selected as the rainfall intensity that will be used in rational method for estimating quantity of surface runoff for the watershed.

Time of Concentration (ToC)

Time of Concentration is the time required for rainfall to reach the watershed lowest elevation from the highest elevation of the watershed. It is used as the duration of the storm for calculating quantity of surface runoff. It is given by equation (2).

$$ToC = T_1 + T_2 + T_3 \quad (2)$$

Where: T_1 = Travel time for overland sheet flow

T_2 = Travel time for shallow concentrated flow

T_3 = Travel time for open channel flow

T_1 is computed using equation (3) as given by Harlan (2007).

$$T_1 = 5.48\,(NL)^{0.8}/(P^{0.5}\,S^{0.4}) \quad (3)$$

N is the Manning coefficient that describes the nature of the surface. It is extracted from Harlan (2007) and presented in table 2, L is the Hydraulic length, P is the rainfall depth and S is the ground slope. Hydraulic length (L) is the distance from the highest elevation to the lowest elevation of each watershed. It is made of three regimes (i. e. overland flow, shallow concentrated flow and channel flow). Overland flow is the upper reaches of the hydraulic length, shallow flow begins where overland flow converges to form gullies while channel flow is available man made drains (Zelazinski, 1986). The hydraulic lengths and ground slopes were computed using the GPS coordinates obtained at the beginning and the end of the overland flow, end of shallow flow and outlet.

Table 2: Manning coefficient (Harlan, 2007)

Surface Description	N
Smooth surfaces (concrete, asphalt, gravel, or bare soil)	0.011
Fallow	0.05
Residue cover	0.06
Short grass prairie	0.15
Dense grasses	0.24
Bermuda grass	0.41
Range (natural)	0.13
Light underbrush	0.4
Dense underbrush	0.8

T_2 is obtained by dividing the travel length by the flow velocity of surface water as shown in equation (4) given by (Harlan, 2007).

$$T_2 = L/60V \quad (4)$$

Where $V = 4.9178\,S^{0.5}$ for an unpaved surface and $V = 6.1960\,S^{0.5}$ for paved surface

$$T_3 = L/60V_l \quad (5)$$

$V_1 = q/A$, $q = (1/n)WR^{2/3}S^{1/2}$

V_1 = the average open channel flow velocity, q = the flow rate in the open channel, R = the hydraulic radius of the open channel flow (R = W/P), W = the cross-sectional area of the open channel flow, P = the perimeter of the open channel flow.

Volume of existing drainages (V_2)

The volume of each existing drainage structure in the study area was obtained using equation (6).

$$V_2 = l \times b \times h \qquad (6)$$

Where: l, b and h are the respective measured length, breadth and depth of the drainage structure.

Size of drainage to be constructed (S_d)

The size of drainage structures to be constructed for each watershed should not be less than the estimated quantity of surface runoff in the watershed. This is to avoid over flooding the drainage structure. The constructed drainage structure should be at least 25% more than the estimated quantity of surface runoff (Al-Handasah, 1982). This is functionally given as equation (7).

$$S_d = 125\% * Q \qquad (7)$$

Location of drainage structures

A module in ArcGIS 9.3 was used to generate the water flow direction map. This map shows the direction of flow of water from higher gradient to the lower gradient in each watershed. The existing drainage network was superimposed on the flow direction map and the drainage network was observed to have been located appropriately to take care of the surface water flow.

Presentation of results

The computations were carried out for 108 watersheds. However, samples of the results of the computed values are presented in this section. Table 3 shows the computed runoff coefficients for the watersheds. Columns 1 and 2 of the table show the serial numbers and names of watersheds respectively while columns 3 and 6 show the areas and runoff coefficients of the watersheds respectively. Table 4 gives the quantities of surface runoff and recommended sizes of the drainage structures for the watersheds.

Columns 1 - 7 of the table show names, areas, rainfall intensity, runoff coefficients, estimated quantities of surface runoff, volumes of the existing drainage structures and recommended sizes of the drainage structures for the watersheds. Figure 4 is the map showing the change in elevations while figure 5 shows the drainage network and the direction of flow of surface water within the watersheds.

Table 3: Computed Runoff coefficients (C)

S/N	NAMES OF WATERSHEDS	A (Hectare)	landuse areas Asphalt A1 Roofs A2 Resident A3	landuse coefficient C1 C2 C3	C1xA1+ C2xA2+ C3xA3+ CA C = CA/A
			1.75	0.825	
			15.75	0.85	
1	DEMSAWO 1	35	17.5	0.675	0.76125
			1.08	0.825	
			9.72	0.85	
2	WURO KUTURU	21.6	10.8	0.675	0.76125
			1.18	0.825	
			10.58	0.85	
3	BIG GUTTER	23.5	11.75	0.675	0.76161
			1.79	0.825	
			16.11	0.85	
4	DOUBELI EAST	35.8	17.9	0.675	0.76125
			0.55	0.825	
			4.91	0.85	
5	OLD ABBATOIR	10.9	5.45	0.675	0.76202
			3.02	0.825	
			27.14	0.85	
6	NTI	60.3	30.15	0.675	0.76139
			3.99	0.825	
			35.96	0.85	
7	NOUN	79.9	39.96	0.675	0.76134
			1.17	0.825	
			10.53	0.85	
			11.7	0.675	
			5.4	0.85	
8	YP 18	23.4	6	0.675	0.76125
			1.3	0.825	
			5.85	0.85	
			5.85	0.675	
			5.89	0.85	
9	80 UNIT	13	5.89	0.675	0.76875

Table 4: Estimated Quantity of Surface Runoff (Q) and Expected Size of Drainage (S)

NAMES WATERSHEDS	A (hectare)	I (mm)	C	Q (m^3/sec)	V (m^3)	S (m^3)
DEMSAWO 1	35	100.6	0.76	7.50	4.56	9.38
WURO KUTURU	21.6	100.6	0.76	4.63	3.30	5.78
BIG GUTTER	23.5	100.6	0.76	5.04	12.00	6.30
DOUBELI EAST	35.8	100.6	0.76	7.67	4.64	9.59
OLD ABBATOIR	10.9	100.6	0.76	2.33	4.49	2.92
NTI AREA	60.3	115.65	0.76	14.86	4.50	18.58
NOUN AREA	79.9	115.65	0.76	19.69	3.45	24.62
YP 18	23.4	100.6	0.76	5.01	2.00	6.27
80 UNIT AREA	13	100.6	0.76	2.81	1.09	3.55

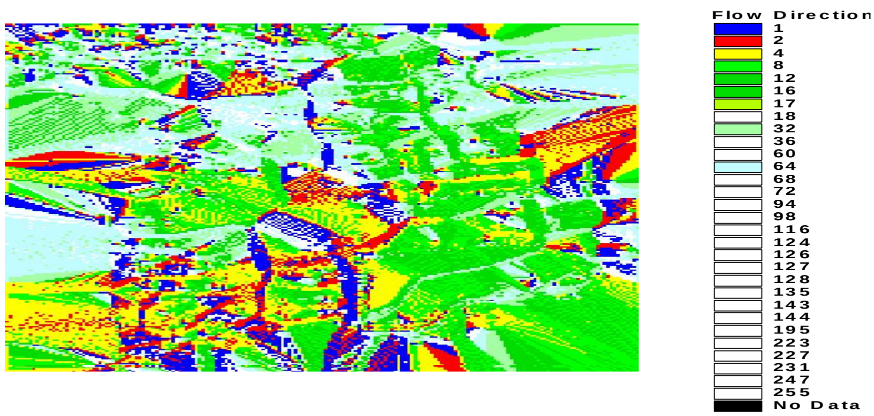

Figure 4: Map showing change of elevation in the study area

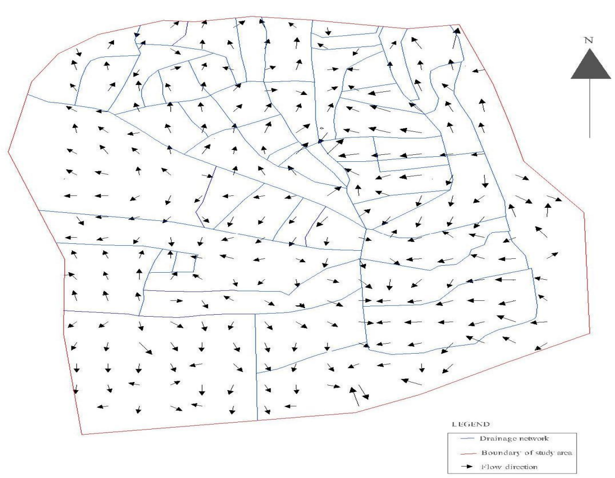

Figure 5: Map showing flow direction and drainage network in the study area

Analysis of Results

Results showed that areas of high density population have high runoff rate as a result number of roofs found in such areas compared to areas with low population density which have less number of roofs but more of asphalt roads. Also, the slope plays a vital role in surface water runoff. For instance, places with high slope have high runoff rate compared to places of relatively flat terrain. Furthermore, it was revealed that some of the watersheds have drainage structures volume greater than the quantity of surface runoff in their respective watersheds thereby making the area free from flooding while other watersheds have drainage structures volumes less than the quantities of surface runoff showing that the area is vulnerable to flooding.

In addition, some watersheds have no provision for drainage structures at all making the area flood prone. Furthermore, it was discovered that some existing drainage structures are appropriately located to take care of the water flow but their sizes are smaller than the quantities of the surface runoff thereby leading to chance for flooding during heavy rainfall.

Conclusion

This study focused on the determination and utilization of estimated quantity of surface runoff to determine the appropriate locations and sizes of drainage structures that can handle the water flow adequately without endangering lives and properties. Based on the analysis of the results obtained, it can be inferred that the locations of existing drainage structures are appropriate. Also, it was shown that the flood prone areas are the areas where quantities of surface runoff are more than the sizes of the existing drainage structures.

Therefore, it is recommended that the size of drainage structure to be constructed should be at least 25% more than the estimated quantity of surface runoff in the affected watershed to avoid flooding. Furthermore, Adamawa State Government should carry out expansion of the existing drainage structures based on the calculated sizes of drainage structures in the affected flood prone areas. In addition, government should always carry out surface runoff analysis as a feasibility study before embarking on drainage structures construction in future.

References

Adamawa State Ministry of Land and Survey (2006): Map of Nigeria showing States, map of Adamawa State showing Local Government areas and map of Jimeta Metropolis showing watershed boundaries.

Al – handasah, D. (1982): Master plan of Michika Local Government 1981-2011. A report presented to the Government of Gongola State, Nigeria.

Amogu, N. (2001): Spatial analysis of health facilities and health hazards. A B. Tech. degree project, Department of Geography, Federal University of Technology, Yola

Bashir, A. (2001): Water quality and occurrence of water borne diseases in Yola Area. M Sc. Thesis presented to the Department of Geography, Modibbo Adama University of Technology, Yola.

Harlan, H. B (2007): Rational method of hydrologic calculations with excels continuing education and development, incorporated New York.

Kuichling, E. (1889): The relation between the rainfall and the discharge of sewers in populous districts. Transactions, American Society of Civil Engineers, 20, 1(56)

MAUTECH, (2011): Records of rainfall data for the year 2011. Nigerian Environmental Climatic Observing Program (NECOP) base station located at Modibbo Adama University of Technology, Yola, Nigeria.

Roos, L. L., Roos, N. P., Cageorge, S. M. and Nicol, J. P. (1982): How good are the data? The Reliability of data bank. *Journal of Med. Care*. 20: 266-276.

Roos, L.L., Nicol, J. P. and Wajda, A. (1989): Assessing data quality: A computerized approach. *Journal of Soc. Sci. Med.* 28: 175-182.

Rossmiller, R.L. (1980): The Rational Formula Revisited. Proceedings of the International Symposium on Urban Storm Runoff, University of Kentucky, Lexington, KY.

Zelazinski, J.(1986): Application of the geomorphological instantaneous unit hydrograph theory to development of forecasting models in Poland, Journal of Hydrological Sciences, Vol.30, 165-174