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DEVELOPMENT OF STORMWATER DRAINAGE NETWORK MODEL: MODRAIN CODE

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ABSTRACT

The development of a storm drainage design and simulation model called MODRAIN is presented. The MODRAIN code is written in visual basic language, version 6.0 (VBL) as well as Fortran IV. It consists of two parts; the MAIN program and a subroutine, SDRAIN. In the MAIN program all the input data are entered on screen for VBL. The MAIN program simulates the catchment runoff while the subroutine, SDRAIN sizes the drain by computing depth and width values of each channel cross-section from simulated runoffs. The program was then validated against the prototype network cited in literature. The error range for the manually computed (textbook solution) and simulated depth and width values of drains as per cross sectional areas is between 0.0 and 18.4%. The modrain program was further applied to the design and assessment of existing drainage network of University of Port Harcourt Permanent site (Unipark) and thus, proved to be a reliable engineering design tool.

1. INTRODUCTION

Drainage is a high priority urban service and the associated problems are increasingly becoming a concern due to rapid urbanization and global climate change impacts. Consequently, a channel whose geometry minimizes the cost of excavation and linning is often desired. Therefore, for a given discharge, slope, and roughness, the designer aims to minimize the cross-sectional area, in order to reduce construction costs (Henderson, 1966). It has been shown that the most "efficient" cross-sectional shape is one that the wetted perimeter is also minimum (Streeter and Wylie, 1981; Nwaogazie and Uba , 2001).

Based on the existing literature review on the subject, one may infer that the progress in urban stormwater drainage modeling has not been uniform in time or across different countries or regions. Furthermore, the various models may give different solutions to the same problems; thus communities that are experiencing urbanization may develop their own urban storm drainage model and local drainage design practice (Viessman and Lewis, 2008).

The objective of this paper is to present the development of a drainage network analysis model (MODRAIN) using the basic approach: Rational formula method, rainfall Intensity-Duration-Frequency (IDF) versus time of concentration model and best hydraulic section for sizing of drains. Practical utility of MODRAIN include: assessment of performance of existing or proposed drainage system for flood mitigation, stormwater management and development of local drainage practice.

2. MATHEMATICAL DEVELOPMENT

The application of the concept of "best or most efficient hydraulic section" for gutter and culvert is necessary for cost reduction during actual construction (Nwaogazie and Uba, 2001). By the definition of hydraulic radius, R the minimization of wetted perimeter may be taken as the problem of maximization of R. Thus, a channel of maximum R not only results in

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optimum hydraulic design but also tends towards a section of minimum cost. The basic formula for best hydraulic section for trapezoidal or rectangular cross-section (see Fig 1) may be derived as follows:

For the trapezoidal section, hydraulic radius is given as:

$$R = \frac{A}{P} = \frac{by + zy^2}{b + 2y(1+z^2)^{1/2}} \quad \ldots\ldots\ldots \quad (1)$$

and

$$P = \left(\frac{A}{y} - zy\right) + 2y\sqrt{1+z^2} \quad \ldots\ldots\ldots \quad (2)$$

Where;

y = Hydraulic depth (m);
R = Hydraulic radius (m);
A = Cross-sectional area (m^2);
z = Channel side slope (see Fig 1);
b = Bottom width (m).; and

P = Wetted perimeter (m) , which assumes a minimum value when $\frac{dP}{dy} = 0$.

Differentiating Equation (2) with respect to y, we have:

$$\frac{dP}{dy} = \left(\frac{-A}{y^2} - z\right) + 2\sqrt{1+z^2} = 0 \quad \ldots\ldots\ldots \quad (3)$$

Solving for A, we have:

$$A = y^2\left(2\sqrt{1+z^2} - z\right) \quad \ldots\ldots\ldots \quad (4)$$

Equating Equation (4) with the area of trapezoidal channel (see numerator of Eq.1) gives the value of channel width as:

$$b = 2y\left(\sqrt{z^2+1} - z\right) \quad \ldots\ldots\ldots \quad (5)$$

Substituting Equation (5) into Equation (1), gives an efficient maximum hydraulic radius, R_{max} as:

$$R_{max} = \frac{y}{2} \quad \ldots\ldots\ldots \quad (6)$$

For uniform flow in a channel or prismatic section, Chezy-Manning's equation may be written as:

$$Q_p = \frac{1}{n} AR^{2/3} S_o^{1/2} \quad \ldots\ldots\ldots \quad (7)$$

Where n is Manning's roughness coefficient; S_o is normal channel slope; Q_p is peak discharge or flow rate; and other terms are as previously defined..

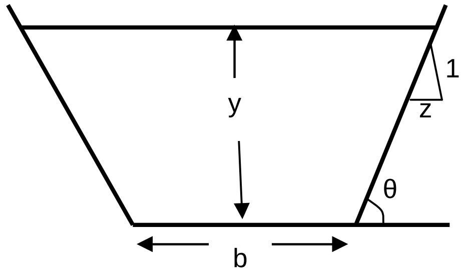


Fig. 1: Sketch of optimum trapezoidal section

For the depth of flow y, we substitute Equations (5) and (6) into Equation (7), which yields:

$$y = \left[\frac{1.587 n Q_p}{\left(2\sqrt{1+z^2} - z\right) S_o^{1/2}}\right]^{3/8} \qquad \text{(8)}$$

Equations (5) and (8) provide the hydraulic design models, while Equations (9)–(12) give the hydrologic aspects of runoff computation. The estimate of time required for runoff to travel from the most remote part of catchment to point of interest is given as (Agunwamba, 2001):

i) $t_c = 0.01947\, L^{0.77}\, S^{-0.5}$ ……………………………………………… (9)
Where t_c is time of concentration, L is length of channel (m); and S is average catchment slope (m/m).

ii) For IDF rainfall intensity-duration computation, we have the quotient model of the type (Nwaogazie and Duru, 2002; Nwaogazie and Nwadike, 2010):

$I = a_0 / (t_c + a_1)$ ……………………………………………… (10)

Where I is rainfall intensity (mm/hr); t_c is duration, in minutes (same as time of concentration); and a_0, a_1 are regional constants. The constants a_0, and a_1 are transferred to the MODRAIN program as COEF1 and COEF2, respectively, after Equation (9) is evaluated with field data.

iii) The computation of peak runoff, Q_p into the drain, we adopt the Rational formula:

$Q_p = CIA_1/360$ ……………………………………………… (11)

where Q_p is the peak runoff rate (m^3/sec); C is the runoff coefficient and A_1 is catchment area (ha). And I is the design rainfall intensity from Equation (10).

iv) Velocity of flow, v is given by:

$$v = \frac{1}{n} R^{2/3} S_o^{1/2} \qquad \text{(12)}$$

Where the terms are as previously defined.

3. COMPUTER AIDED DRAINAGE NETWORK SIMULATION

3.1 Modrain Program Development

MODRAIN computer code is written in Visual Basic Language, version 6.0 and it consists of two parts; the MAIN program and a subroutine, SDRAIN. In the MAIN program, all the input data are entered on the screen. Estimate of overland flow or catchment runoff for all drains are equally made in the main program. The sequence of computation begins with the estimate of time of concentration, t_c using Eq. (9), then the rainfall intensity via the evaluation of Equation (10) and thereafter, the computation of runoff flow into the drain, using Equation (11).

The subroutine SDRAIN sizes the drain by way of computing depth and width values of each channel cross-section. However, the choice of rectangular or trapezoidal section is made before hand via input data, before the subroutine SDRAIN is called. The velocity v for the designed drain is computed and checked if the velocity limits $v \leq 1.0$ and $v \geq 3.0$ are satisfied to avoid siltation or erosion, respectively.

If the velocity value is less then 1.0m/s, an upgrade of the estimated longitudinal slope, S_o is made by a given percent. This is to avoid siltation in the drain. This slope upgrade is repeated many times as necessary and velocity, v is correspondingly computed and checked until $v \geq 1.0$m/s. Similarly, if velocity, v is greater than 3.0m/s, then a reduction of slope, S_o is made to avoid erosion. In each cycle of slope reduction by a given percent, velocity is recomputed and compared with set limits. And it is terminated once v is ≤ 3.0

Once all the drains have been sized by the subroutine, SDRAIN, then the simulated results per drain are printed out and program is terminated. The flow chart (Fig.2). shows the development of MODRAIN, the order in which the computations are made in the code.

3.2 Input Data Structure

The input data entry requirement, and the sequence of operations necessary to run the MODRAIN program are:

i). On the Main Menu, Click the Drain Analysis Dialogue box, twice, to load the program.
ii). Click “OK” on the user Login Menu;
iii). Click “Compute” to compute Network and Display Results to screen; and
iv). Click “File” to compute Network and Write Results to File

The user decides between (iii) and (iv) above. An example of input data format on the dialogue box is illustrated in the model verification example problem in Section 3.3.

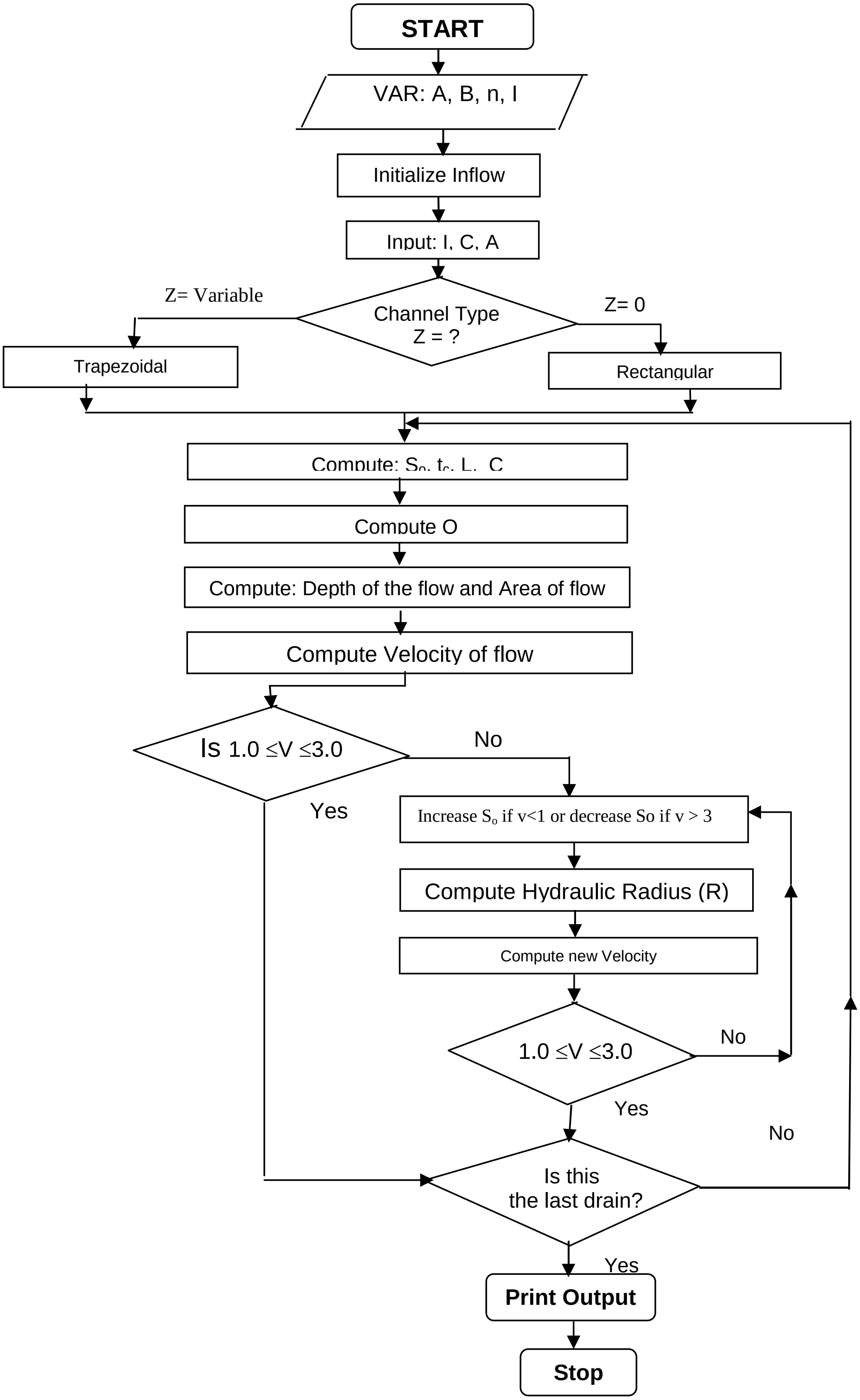


Figure 2: Flow Chart for Main Program

3.3 Example Problem for Model Verification

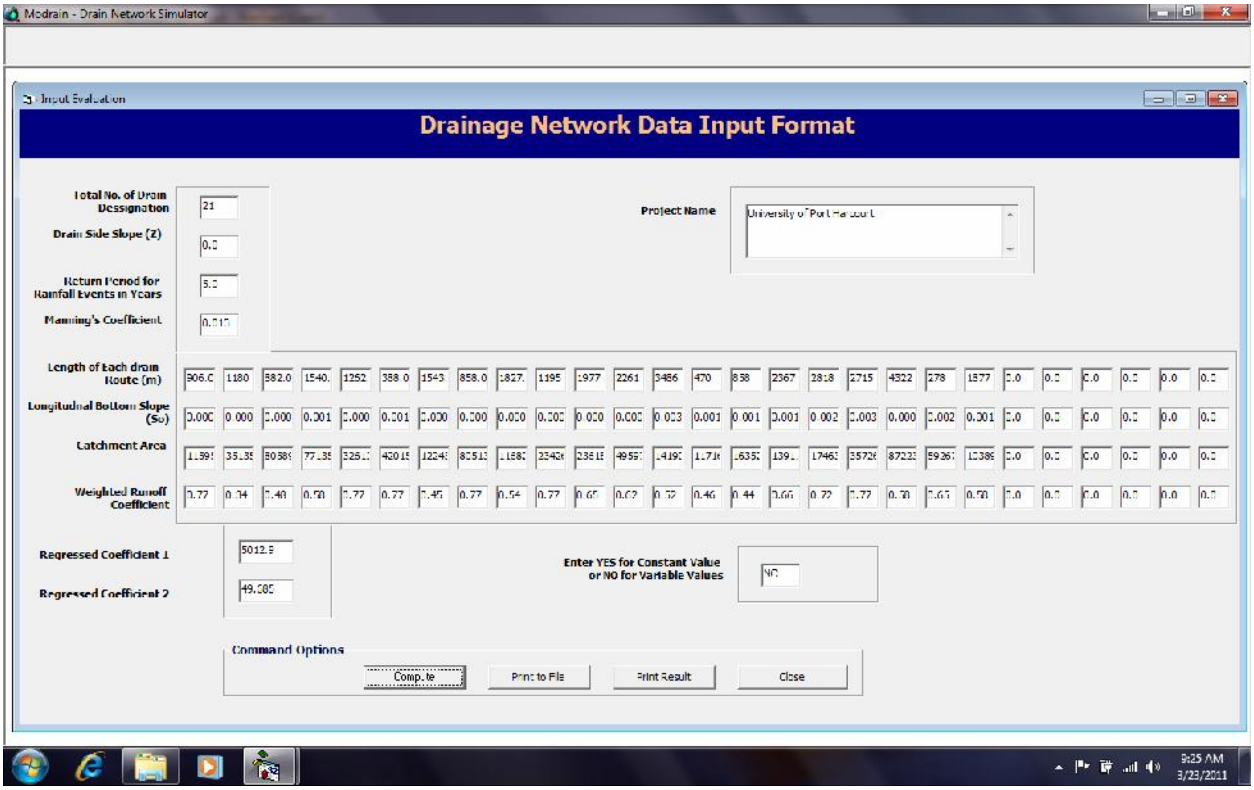
The MODRAIN code was verified using an example problem taken from Agunwamba (2001) and it states as follows: Design a drainage system for the area shown in Figure 3. The drains must be laid along one side of each street. Every street is 8m wide. Assume a return period of 5 years, Manning's roughness coefficient, n = 0.013 and rainfall intensity (mm/hr) versus duration (minutes) model of $i = 6994.235/(t_c + 39.865)$, respectively.

SOLUTION:

In Fig. 3, drainage layout is divided into 5No sub-catchment areas namely: City business area, residential, non-residential areas, Parks and cemeteries, and Farm land with corresponding runoff coefficients, C. The broken lines with arrow heads indicate flow directions in the drainage network while the distance inbetween two node numbers indicates length of a drain in metres. At node 12, drainage network discharges into a stream.

The input data for the example problem are as presented in Table 1, while in Table 2 the computer simulated results are compared and contrasted with the manually computed results in Agunwamba (2001). Likewise, the drain capacities (m^3/s) for the 13No. drains for both simulated and manually computed values are plotted (see Fig. 4) for sake of comparison.

Table 1: Input Data for Example problem 1



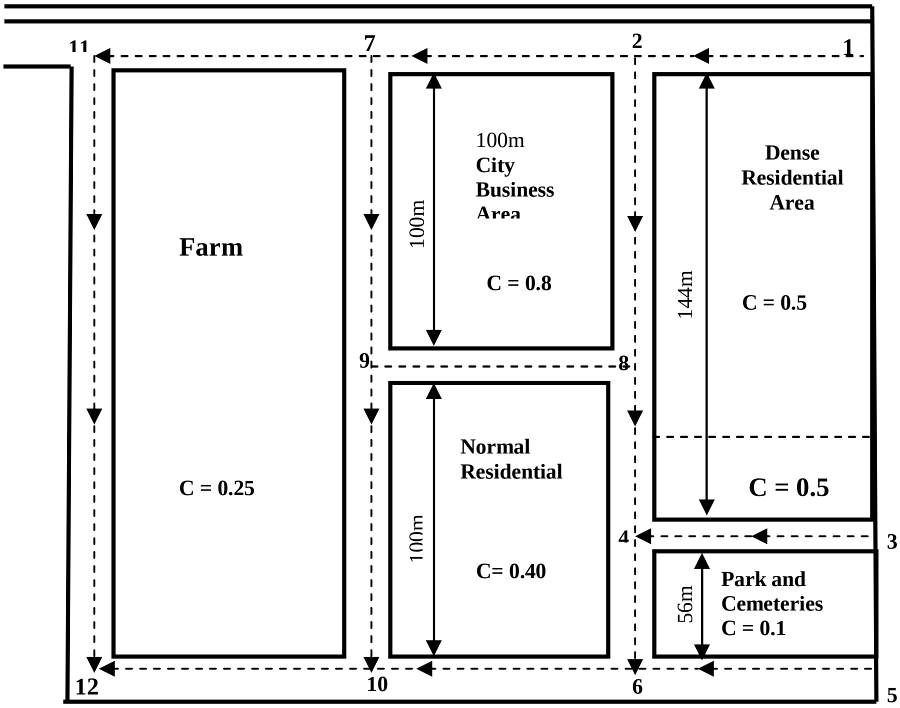


Fig. 3: Drainage Layout in Agunwamba (2001)

Table 2: Results of Model Verification

S/N	Computer Simulated Results			Manually Computed Results			% Error
	Depth (y) (m)	Width (b) (m)	Area (A_1) (m^2)	Depth (y) (m)	Width (b) (m)	Area (A_2) (m^2)	$\frac{(A_2 - A_1) \times 100}{A_2}$
	1	2	3	4	5	6	7
1	0.1714	0.2958	0.0507	0.1713	0.2928	0.05016	-1.08
2	0.3718	0.6935	0.2578	0.3951	0.7402	0.29245	11.85
3	0.2909	0.5318	0.1547	0.2909	0.5318	0.1547	0.0
4	0.3921	0.7342	0.2879	0.3921	0.7342	0.2879	0.0
5	0.1714	0.2928	0.05019	0.1714	0.2928	0.05019	0.0
6	0.3474	0.6448	0.2240	0.3833	0.7165	0.27463	18.44
7	0.1817	0.3133	0.05693	0.1827	0.3160	0.05773	1.39
8	0.3890	0.7280	0.2832	0.412	0.774	0.31889	11.19
9	0.1637	0.2770	0.04534	0.1644	0.2788	0.04583	1.07
10	0.3975	0.7451	0.29618	0.4294	0.8089	0.34734	14.73
11	0.3717	0.6934	0.25774	0.3947	0.7394	0.29184	11.68
12	0.1753	0.30064	0.05270	0.1753	0.3006	0.05270	0.0
13	0.2566	0.4633	0.1189	0.2614	0.4729	0.1236	-5.3

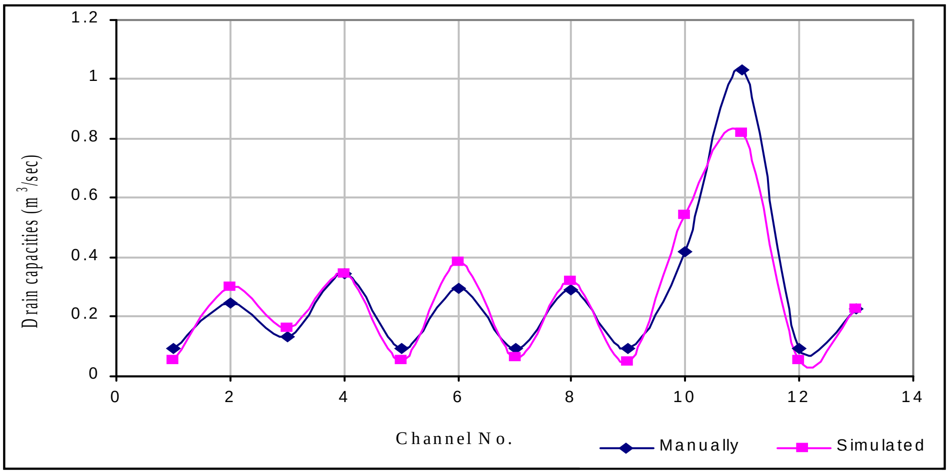


Fig. 4: Comparison of simulated with manually Computed Drain Capacity

4. APPLICATION OF MODRAIN TO UNIPARK DRAINAGE NETWORK

The University of Port Harcourt Permanent Site (Unipark catchment) is divided into eight sub-catchments with areas A_1 to A_8. The degree of urbanization in each sub-catchment is represented by the runoff coefficient. The rainfall is assumed to be distributed uniformly over the entire catchment. The directly connected paved areas are mainly streets. The additional paved areas are the roofed areas, parks, mini-stadium and so on. The input data for modrain code are as presented in Table 3, while the simulated results are presented in Table 4, respectively. Results in both Tables 3 and 4 are that of Fortran IV code.

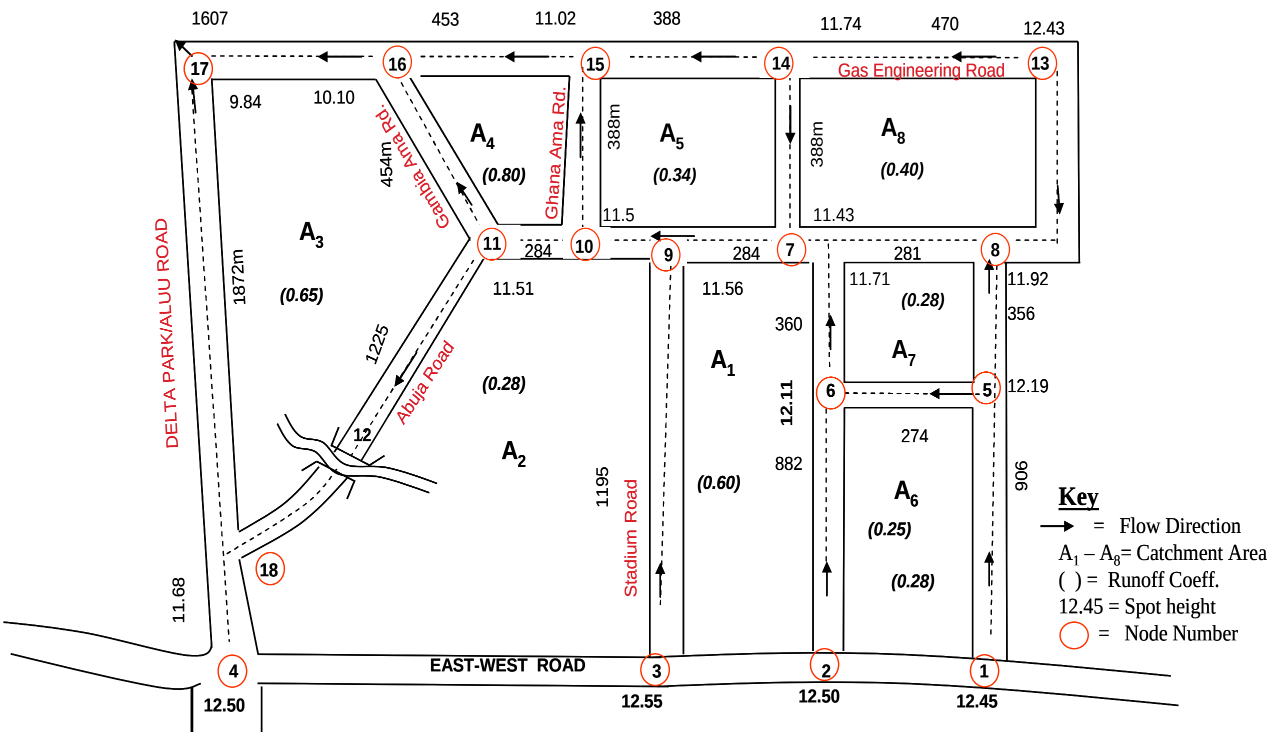


Fig. 5: Drainage Layout of University of Port Harcourt main campus (Unipark)

Project Name: University of Port Harcourt

DRAINAGE NETWORK ANALYSIS USING RATIONAL FORMULA, RAINFALL INTENSITY VERSUS TIME OF CONCENTRATION MODEL AND BEST HYDRAULIC SECTION FOR SIZING OF DRAINS DEVELOPED **BY ENGR. ITOLIMA OLOGHADIEN** UNDER THE SUPERVISION OF **ENGR. IFY L. NWAOGAZIE, (PhD, FNSE, FNICE)** PROFESSOR OF CIVIL ENGINEERING, UNIVERSITY OF PORT HARCOURT. DRAINAGE NETWORK DESIGN FOR UNIPARK, UNIPORT

TABLE 3: INPUT DATA FOR UNIPARK NETWORK OF DRAINS

TOTAL DRAIN DESIGNATIONS = 21
RETURN PERIOD = 6.0 YEARS
MANNINGS COEFFICIENT = 0.013
DRAIN SIDE SLOPE = 0.0

S/No.	LENGTH	S_o(Slope)	A_c	t_c	I	Runoff
01	906.00	0.00029	11595	217.4772	0.0000521	0.04653
02	1180.00	0.00022	35135	303.067	0.00000395	0.04716
03	882.00	0.00044	80589	171.6586	0.00000629	0.24335
04	1540.00	0.00111	77135	166.3778	0.00000644	0.28833
05	1262.00	0.00076	32612	172.6762	0.00000626	0.15725
06	388.00	0.00131	42015	52.98229	0.00001356	0.43878
07	1543.00	0.00075	122434	203.0768	0.00000551	0.30352
08	858.00	0.00093	80513	115.9784	0.00000841	0.52109
09	1827.00	0.00053	1168212	275.1615	0.00000429	2.70411
10	1195.00	0.00079	234262	162.3307	0.00000657	1.18471
11	1977.00	0.00033	236182	368.1874	0.00000333	0.51157
12	2261.00	0.00004	495978	1255.758	0.00000107	0.32801
13	3486.00	0.00344	1419053	177.2878	0.00000613	4.52704
14	470.00	0.00147	117161	57.97258	0.00001293	0.69708
15	858.00	0.00186	163528	81.9209	0.00001058	0.7613
16	2367.00	0.00124	139110	219.1734	0.00000518	0.47552
17	2818.00	0.00203	174639	195.9172	0.00000567	0.7129
18	2715.00	0.00311	357265	153.8114	0.00000684	1.8824
19	4322.00	0.00016	872234	964.0193	0.00000137	0.69492
20	278.00	0.00295	59267	27.313	0.00001808	0.69668
21	1877.00	0.00115	1038946	190.3639	0.0000058	3.49549

Where S_o = natural slope, A_c = catchment area, t_c = time of concentration, i = rainfall intensity.

TABLE 4: SIMULATED RESULTS ON DESIGN OF RECTANGULAR SIZED DRAINS

LOCATN	DEPTH	WIDTH	VELOCITY	DRAIN CAPTY	ADJ. SLOPE
01	0.31282	0.57564	1.00376	0.18075	0.00213832
02	0.32716	0.60433	1.01829	0.20133	0.00206754
03	0.50074	0.95147	1.10303	0.52552	0.00134888
04	0.45417	0.85833	1.04629	0.40787	0.00138750
05	0.39581	0.74163	1.09951	0.32276	0.00185156
06	0.50862	0.96724	1.22839	0.60432	0.00163750
07	0.49375	0.93750	1.01644	0.47050	0.00116766
08	0.57183	1.09366	1.12004	0.70046	0.00116000
09	1.12551	2.20102	1.09156	2.70411	0.00052800
10	0.78198	1.51397	1.00068	1.18471	0.00078900

LOCATN	DEPTH	WIDTH	VELOCITY	DRAIN CAPTY	ADJ. SLOPE
11	0.67803	1.30606	1.05298	0.93247	0.00081299
12	0.86018	1.67035	1.09811	1.57776	0.00064028
13	0.96818	1.88635	2.47878	4.52704	0.00344000
14	0.58390	1.11780	1.06803	0.69708	0.00147000
15	0.57802	1.10604	1.19081	0.76130	0.00186000
16	0.52755	1.00510	1.22537	0.64974	0.00155000
17	0.55679	1.06358	1.20382	0.71290	0.00203000
18	0.72332	1.39665	1.86334	1.88240	0.00311000
19	0.85638	1.66277	1.07560	1.53161	0.00061798
20	0.51843	0.98686	1.36171	0.69668	0.00295000
21	1.07337	2.09675	1.55314	3.49549	0.00115000

NOTE THE FOLLOWING UNITS OF MEASUREMENTS:

Depth and width: metres; velocity: metre per second; discharge and drain capacity: m^3/s; time of concentration: minutes; rainfall intensity: m/s; length of drain: m; catchment area: m^2; fall, natural slope dimensionless.

5. DISCUSSION OF RESULTS

In order to establish the accuracy of MODRAIN code to model a network of drains, an attempt was made to solve an example problem (drainage design) with known solution. Thus, a network of rectangle drains shown in Fig. 3 was modeled using Modrain code and simulated results were compared and contrasted with manually computed results (Agunwamba, 2001) as shown in Table 2. Out of 13No. drains in the network we have the following % error distributions: 0.0 – 1.4% for 7No. drains; 5.3% for 1No. drain; 11 – 15% for 4No. drains; and 18.4% for 1No. drain, respectively. The margin of error of 0.0 – 18.4% are mainly due to round-off error in manually computed results; which can be minimized by retaining upwards of five decimal figures in manual computations.

Similarly, a comparison of simulated drain capacities (m^3/s) for the 13 No. drains were made with manually computed equivalents as shown in Fig. 4. The distribution of drain capacities (Fig. 4) by the two methods of computation are in good agreement. The slight variation is the effect of round-off error.

The MODRAIN code was subsequently applied to model the network of drains in University of Port Harcourt main campus (Unipark) as shown in Fig. 5. A total of 21 No. drains are involved. Table 3 displays both the input data set (see columns 2-4) as well as computed parameters (columns 5-7) such as time of concentration, $t_{c;}$ rainfall intensity values,i; and corresponding runoff flow (m^3/s), Q_p for each drain. The computed parameters are essentially the hydrologic aspect of the drainage design, that is, overland flow computation via the Rational formula approach (Nwaogazie and Uba, 2001).

The hydraulic aspect of the design of Unipark network of drains are as presented in Table 4. Noticeable in column 4 (Table 4) are the computed velocity values greater than 1.0 to avoid siltation and less than 3.0 to prevent erosion. The MODRAIN code has an inbuilt adjustment mechanism to update velocity values for each drain by decreasing or increasing the bottom slopes of the drains. Column 6 of Table 4 is the adjusted slope values while column 3 of Table 3 is the guessed values entered as input data. The resulting adjusted slopes are essential for drain construction for the realization of velocity values in column 4 (Table 4).

MODRAIN code has proved to be a handy tool for design of network of drains. It is possible to use MODRAIN code for design of single drain (rectangular or trapezoidal). The option for single or network of drains is achieved by indicating in the input data slot for the number of drains to be simulated. The MODRAIN code is available on request at a price.

6 CONCLUSION

The computer program, MODRAIN for designing of drainage system network consists of two parts: the MAIN program and a subroutine, SDRAIN. The Main program simulates catchment runoff while the subroutine SDRAIN sizes the drain by computing depth and width values of each channel cross-section. Results of model verification with textbook example problem showed that the model predicted the prototype network with high degree of accuracy. The margin of error as per the cross-sectional areas for the manually computed (textbook) and computer simulated solutions is between 0.0 and 18.4%.

On the average, the agreement between the textbook and MODRAIN's results was very good. The field application using University of Port Harcourt main campus (Unipark) showed that the MODRAIN simulator is capable of being used to adequately simulate the process of runoff generation and sizing of drains. Thus, the MODRAIN is a reliable engineering design tool, and can be applied in the design and assessment of existing and/or proposed drainage network system.

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