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Modeling the Effect of Depression Areas on Outflow Hydrograph

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Abstract— The peak discharge value of any basin is the most important hydrological parameter and should be calculated accurately to determine the suitable protection strategy and perform suitable design for any proposed hydraulic structures.

Many factors affect these peaks values; meteorological factors (mainly rainfall characteristics) and basin morphological characteristics such as size, slope, cover, shape, soil type, and depression/surface storage. This research discusses the reduction factors at the peak values due to the existence of depressions/surface storage along the watershed main stream using HEC RAS 5.03-2D hydrodynamic modelling. The analysis of this research has considered different characteristics of the depressions with respect to the location, return period and depression area as categorized by NRCS (1975).

The analysis results of this research have been compared with the adjustment factors for ponding and swamp areas developed by NRCS (1975). The research showed that the peak reduction may reach 90% of the watershed original peak flow if the depression is located along the watershed main stream and with depression area equals to 20% of watershed area.

The lower locations along the main stream are the most effective on reducing peak flow values and there is a proportional relation between depression area with reduction percentage. As well the results showed that the watershed shape factor is one of the most important factors to be considered as it may change the reduction factors globally.

Index Terms— 2D Hydrodynamic Modeling, HEC RAS, Depressions, Surface Storage, Reduction Factor, Shape Factor, Ponding Areas.

1 Introduction

Flood management in arid region became a very important issue. Government planning for urban development must conduct flood studies when planning for development. As the flood attack, doesn't have specific behavior known till now to be avoided, so many studies have been started and are still ongoing for estimating the flood peaks and defining flood plains to avoid/reduce damage associated with floods.

In order to perform successful flood management many studies should be undertaken such as topographic analysis, morphologic analysis… etc. One of the most important items in flood management study is the hydrologic analysis; that is used to estimate the flood flow values at any time after the start of the storm.

Depression storage is the term applied to water which is lost because it becomes trapped in the numerous small depressions which are a characteristic of any natural surface. When ponded water accumulates in a low point with no possibility for escape as runoff, the accumulation is referred to as depression storage. The amount of water which is lost due to depression storage varies greatly with the land use as defined in [1].

Many studies have been performed to determine the reduction percentage due to depressions within the watershed, such as the wetlands in the Eagle Creek Watershed near Indianapolis which reaches to 20% peak flow reduction. In addition, those wetlands can be applied within the landscapes and could reduce the peak flows by 29% as per "Babbar-SebensMaghna [2]". The reduction factors depend on many factors such as locations of depression storage, size, return period, dry pond or filled with water. "Klingner [3]"

Consequently, HEC-RAS 5.03-2D hydrodynamic modeling has been used to simulate the effect of depressions existence within the upper areas, central areas and lower areas of the catchment for different return periods with respect to constant depth considering the factors affecting the efficiency of the depression areas, then the results have been compared and analyzed with respect to NRCS

2 DATA COLLECTION

The study area is in Ibadan, Nigeria. Ibadan is the capital city of Oyo state is characterized by rugged terrain with wide valley plains. The watershed area is about 655 square kilometers, located between Latitudes 7.225º, 7 .645º N and Longitudes 3.75º, 4 .05º E. Fig. 1.

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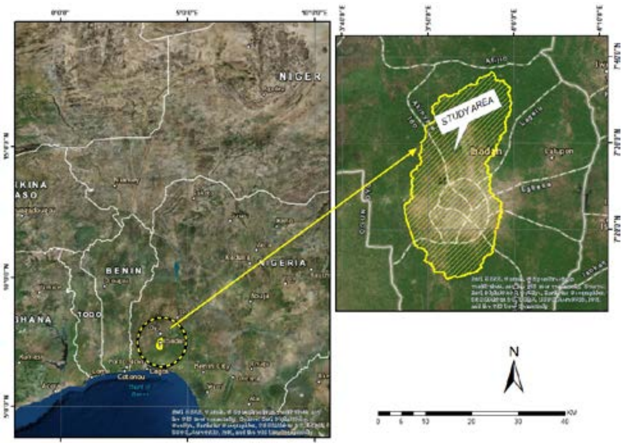

Fig. 1; Study Area Limits and Location

2.1 Topographic Data

Digital Elevation Model with cell size 10m x 10m has been used in the modeling and considered the base surface data for the analysis scenarios. It worth mentioned that Grid DEMs are readily available and simple to use and hence have seen widespread application to the analysis of hydrologic problems, "MooreI.D. [4]". However, they may suffer from some drawbacks that arise from their gridded nature which may cause some numerical errors.

Fig. 2, shows the DEM model as well as the main topographic information of the study watershed area.

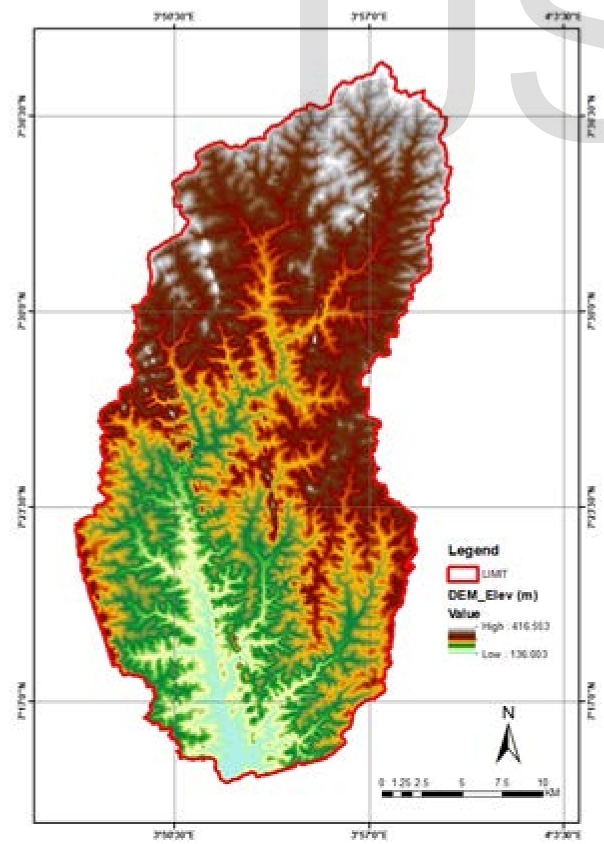

Fig. 2; Study Watershed Digital Elevation Model

2.2 Rainfall Data

The rainfall data have been collected from different sources and have been used in the frequency analysis, the data from four stations within the city (Ibadan New Airport, IITA, Horticulture, and Ibadan Old Airport) have been collected, in addition to others station outside the city (Abekouta, Ijebo Ode, and Iseyin). The rainfall data have been used in the frequency analysis generating the design depths for different return periods shown in Table 1.

Return Period (yrs.)	*5*	*10*	*25*	*50*	*100*
Design Depth (mm)	122	146	180	208	240

3 METHODOLOGY

Due to the effect of the different characteristics of the depression areas within the watershed on the peak discharges, many scenarios of different depression areas have been simulated. The area of the depression, location, and the return period are the main characteristics that have been evaluated under the below assumptions;

- The depression depth is constant for all scenarios.
- The rainfall used in the hydrodynamic modeling is the excess rainfall depths (R) resulting for the watershed due to uniform curve number (CN) equals to 80, R can be deduced from the NRCS runoff equations.

- Topographical analysis has been carried out using the natural DEM data as base topographic data (depressionless surface). In order to produce the analysis scenarios DEMs; multi depressions with different areas and locations have been burnt within the base DEM.
  Three main locations of the depression are considered in the analysis; lower, upper and central areas along the watershed longest flow path (LFP).
  For the lower areas, the center of depression areas is located on a distance equal to 10% of LFP length measured from the watershed outlet. Where for the central areas the depression areas center is located on a distance equal to 50% of LFP and equal to 85% of LFP for the upper areas.
  The depression is created by lowering all levels inside the depression boundary to the depression bottom level, which is assumed as 1.0m below the lowest level within the depression boundary.
  The resulting topographic scenarios are 30 DEMs due to 10 different depression areas equal to (0.2, 0.5, 1, 2, 2.5, 3.3, 5, 6.7, 10, and 20) % of watershed area in each of the above mentioned three location, in addition to the depressionless DEM (base DEM). Fig. 3, shows samples of resulted DEM with specific depression area in the main three locations.

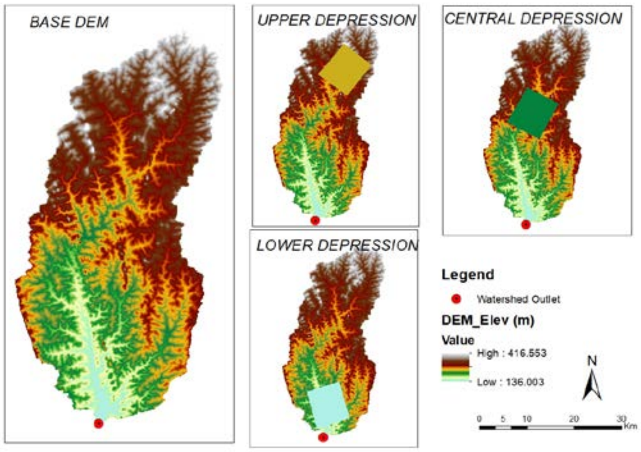

Fig. 3; Samples of Resulted DEMS with Depression Area in Different Locations

- In the absence of short duration records or any similar information, the temporal rainfall distribution could be estimated as a ratio of the daily rainfall depth for 24-hr based on the ratios stated by the Soil Conservation Service of the USA through their SCS type II dimensionless rainfall curve shown in Fig. 4. "TR-55 [5]"
  So, the design rainfall depths resulted from frequency analysis have been distributed using the max. 24hrs rainfall distribution of SCS assumptions (SCS type-II storm).
  Applying storms depth (P) with different return periods and NRCS runoff equations previously mentioned; the excess rainfall depths (runoff depths) were calculated. The resulted excess rainfall depths have been used in the 2D hydrodynamic modeling for the different scenarios DEMs.

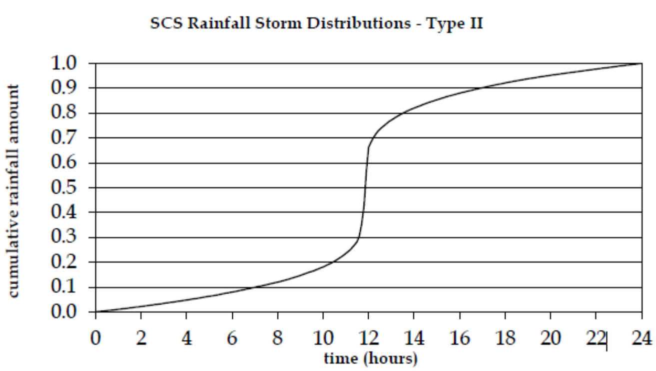

Fig. 4; SCS Type II Dimensionless Rainfall Curve (24hrs)

- The hydraulic analysis has been carried out using HEC-RAS 2D model which can perform 1D, 2D only or combined 1D/2D hydrodynamic modeling. The 2D solver uses implicit finite volume algorithm including the solving of 2D diffusion wave as well as 2D Full Saint Venant Equations which has been adapted in all analyzed scenarios in the present study.
  HEC-RAS 2D is an intuitive, low cost yet capable 2D modelling package. Available in the public domain, the program can now be used for a wide range of 1D and 2D modelling applications without the license constraints typical of many other software packages. "Lintott [6]"

4 Discussion of Results

- The watershed study area has been simulated in its natural condition (depressionless condition) at each return period, and the flow hydrographs at the watershed outlet were plotted, Fig. 5.

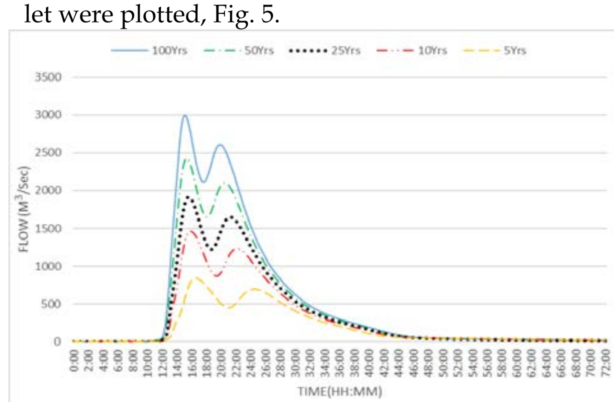

Fig. 5; Base (depressionless) Flow Hydrographs of the Watershed Study Area

The resulted flow hydrographs are generated due to hydrodynamic modeling of the base DEMS (depressionless DEMs), and will be considered the base hydrographs and peaks that other scenarios hydrographs and peaks will be compared with. Table 2, summarizes the peak flow values at the watershed study area outlet for each return period.

Table 2: Peak flow values for base (depressionless) condition.

Return Period (yrs.)	5	10	25	50	100
Peak Flow (m^3/sec)	844	1461	1913	2430	2987

- The depressions scenarios analyzed in the present study were chosen as the same cases developed by NRCS (1975) mentioned in [7], these scenarios are for the different depression areas are simulated for return periods (5, 10, 25, 50, and 100) years.
- The assumed depression scenarios have been simulated by the 2D hydrodynamic model, it is expected to get new peak flow value due to the existence of the depressions within the watershed area. The new peak flow values at the watershed outlet of each scenario was recorded and summarized in Table 3.
- Also, the resulted flow hydrographs due to the depressions existence within the watershed have been plotted and analyzed herein Section 4.

Table 3; Resulted Peak flow values for Analysis scenarios

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	Q peak Due to Depressions Existence at Each Return Period				
	RETURN PERIOD				
Percentage of Depression Area **(%)**	**RESULTED** PEAK FLOWS				
	100 (Years)	50 (Years)	25 (Years)	10 (Years)	5 (Years)
	Ponding occurs only in lower areas of LFP (10 % LFP)				
	m3/sec	m3/sec	m3/sec	m3/sec	m3/sec
0.2	2623	2119.61	1652.8	1225.44	676.34
0.5	2390.8	1861.84	1368.7	939.75	407.93
1	1440.7	1020.11	659.91	468.43	280.45
2	862.38	725.75	589.92	462.14	276.03
2.5	862.29	725.42	589.39	461.64	276.1
3.3	860.95	725.14	588.96	461.19	275.47
5	376.71	317.83	258.12	200.66	116.07
6.7	377.29	316.36	258.41	202.23	116.35
10	369.47	311.21	252.64	196.52	112.35
20	293.33	246.9	200.34	154.81	90.94
	Ponding occurs only in upper areas of LFP (85% LFP)				
0.2	3070.7	2504.28	1969.2	1509.6	872.39
0.5	3070.6	2504.49	1971.1	1510.51	872.48
1	3052.8	2503.03	1969	1509.23	872.29
2	3077.1	2505.74	1971.4	1510.64	872.81
2.5	3047.7	2505.74	1971.9	1509.3	872.67
3.3	3072.9	2509.44	1970.2	1509.14	872.22
5	3072.5	2504.16	1970	1509.77	872.43
6.7	3073.4	2513.68	1971.4	1510.87	872.74
10	3074.9	2505.85	1970.9	1510.62	872.52
20	3069.2	2507.83	1969.5	1510.31	872.7
	Ponding occurs in central areas of the LFP (50 % LFP)				
0.2	3070.7	2504.28	1969.2	1509.6	872.39
0.5	3070.6	2504.49	1971.1	1510.51	872.48
1	3052.8	2503.03	1969.0	1509.23	872.29
2	3077.1	2505.74	1971.4	1510.64	872.81
2.5	3047.7	2505.74	1971.9	1509.3	872.67
3.3	3072.8	2509.44	1970.2	1509.14	872.22
5	3072.5	2504.16	1970.0	1509.77	872.43
6.7	3073.3	2513.68	1971.4	1510.87	872.74
10	3074.9	2505.85	1970.9	1510.62	872.52
20	3069.2	2507.83	1969.5	1510.31	872.7

- The peak reduction factors for all cases have been calculated in comparison with the base case for the watershed study area. For the three main locations, lower, upper and central areas, the reduction factor (R.F) has been calculated according to the following equation;

$$R.F = \frac{Q_R}{Q_B}$$

Where;
R.F = Reduction Factor, dimensionless.
Q_R = Reduced Peak Flow (m3/sec).
QB = Base Peak Flow (m3/sec).

- For the lower areas, the reduction factors at the watershed outlet range from 0.87 to 0.09 for the different return period, Fig. 6. While the effect of the depressions is almost none for the upper and central areas as the reduction factor approximate 1.0.
- The peak discharge reduction is proportionally increasing with the depression area for all return periods, In the meanwhile it is inverse with the return period only in the small depression areas where the effect of return period reduces gradually with the increasing of depression areas.

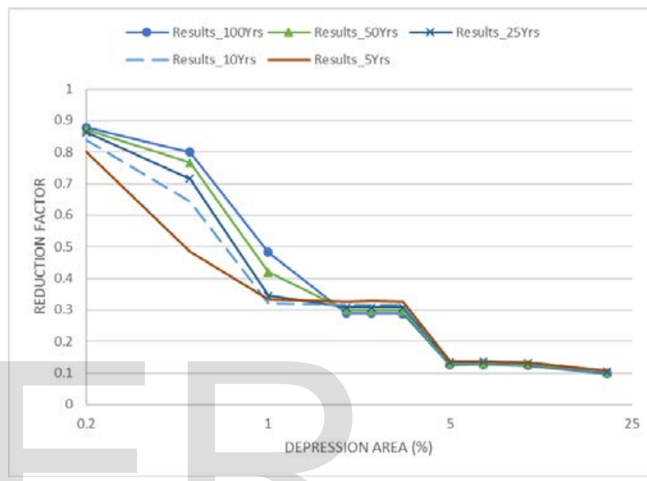

Fig.6; Resulted Reduction Factors within Lower Areas for Different Return Periods

No doubt that the effect of the depressions on the peak discharges depends on many factors such as depression area, location, and the return period, however the results show that there are many other factors that have great effect on the peak flow reduction factors. One of these factors is the watershed shape. As it has a great effect on the peak flow value, it has a great effect on the reduction of that peak flow values also. The modeling results, show the effect of depression characteristics on the reduction factors, and the difference about the values provided by NRCS (1975). So, those other factors have been discussed and analyzed within the modeling results as below;

4.1 Effect of Depression Location & Watershed Geometry

The results indicate that the lower locations of the depressions have the greatest effect on peak flows reduction while the upper and central locations approximately have no effect. The results showed that the watershed study area has a multi peaks hydrograph at the watershed outlet. Two peaks; the first one is generated due to the lower basin of the watershed while the second one is due to the upper basin runoff, Fig. 7 lower right. The highest peak is generated from the less elongated basin, as the fan shaped basins generates higher flood intensity since all the tributaries are nearly of the same length and hence the time of concentration is nearly the same. While for fern shaped basins, the time of concentration is more than the fan shaped catchment and the discharge is distributed over a longer period, "Soliman, [8]". Consequently, although the depression location affects generally the flow hydrograph, it may not affect the highest peak based on the watershed shape. As in Fig.7, upper right, the resulting hydrograph due to depression existence in the lower areas is broken down and reduced to 0.09, where the existence of the depression in the upper areas or the central areas does not affect the highest peak value (design value) yet they have a noticeable effect on the other peak flow. This is strongly related to the basin shape either it is elongated or squatty which can be determined using Form Factor, defined as a ratio of watershed area to the square of the length of the watershed. There are some different value ranges of form factor. The range values for form factor are < 0.78 (elongated) and > 0.78 (circular). There are also other range values for Form factor classification, i.e., elongated (0 or low value) and circular (1). An elongated watershed means it has low peak flows for longer duration while a circular watershed means it has high peak flows for a shorter duration. "S Sukristiyanti, R Maria, & H Lestiana, [9]"

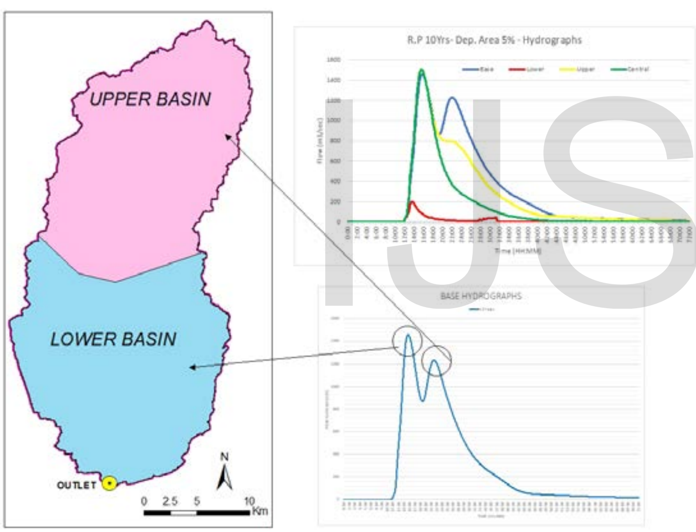

Fig.7; Study Watershed with Multi Peaks Hydrograph

5 Conclusion

Despite that the research results of this paper depends on one watershed case study; the results indicate that the NRCS reduction factor values can't be used without considering other factors that may lead to underestimate or overestimate the resulting hydrograph. On the other hand, the results affirm that the lower locations of the depression areas along the main stream is the most effective on peaks reduction, and there is a proportional relation between the peaks reduction percentage and depressions area/return period.

As the depression location with respect to the watershed outlet is important to determine the reduction factor (according to NRCS classification); the watershed shape factor is more important to be taken into account. The research results show that although the depression existence within the upper and central areas has no effect on the highest peak of the watershed, it affects other hydrograph's peaks. As well the depression area has a proportional relation with the watershed hydrograph reduction.

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