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Assessment of Hydraulic Adequacy of Selected Culverts for Effective Flood Management in Ibadan Southwest Nigeria

[1*]Adeogun A.G., [1]Sule B.F., [1]Samson I.O., [2]Bawa S.M., and [3]Ayeh A.A.

[1]*Department of Civil Engineering, Kwara State University, P.M.B 1530 Malete Kwara State, Ilorin Nigeria,*
adeniyi.adeogun@kwasu.edu.ng , yehmeeeeee@gmail.com , ayomide.ayeh17@kwasu.edu.ng

[2]*Department of Civil Engineering, University of Ilorin P.M.B. 1515, Nigeria,*
bfsuleiman@gmail.com ,

[3] *Department of Civil Engineering, Joseph Saruwan Tarka University, P.M.B 2373, Makurdi, Bemue State, Nigeria,*
sheriffbawa@gmail.com

**Corresponding Author: Ayeh Ayomide;* ayomide.ayeh17@kwasu.edu.ng *(09131444365)*

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Abstract: This study assesses the hydraulic adequacy of selected culverts for flood management in Ibadan, Southwest Nigeria. The surface runoff potential and inflow at various culvert sections were analysed to determine their capacity to handle stormwater discharge. The Rational Method, which establishes a direct rainfall-runoff relationship, was employed to estimate storm discharge at different locations along the road alignment. For the hydraulic analysis, the HY-8 tool was used to simulate water profiles, applying the direct step method to calculate the sequent depths. A total of 17 box culverts, varying in number of cells and dimensions, were analysed. The hydrological analysis revealed that the lowest estimated flow occurred at culvert ID 73 with a value of 15.29 m^3/s, while the highest flow was observed at culvert ID 40 with 52.78 m^3/s. Overall, all 17 culverts were found to have sufficient capacity to convey the design flow. The study concludes that the culverts analysed are hydraulically adequate for managing flood events in the study area, thereby contributing to improved flood control and infrastructure resilience.

Keywords: *Hydraulic adequacy, HY-8 tool, Hydrological Analysis, Flood Management, Rational method, Stormwater discharge.*

INTRODUCTION

Flooding is a serious problem affecting urban areas all over the world. To build efficient flood management infrastructure, thorough hydrological and hydraulic assessments are required (Butler & Davies, 2011; Palla & Gnecco, 2015). Urban flooding can cause significant economic damage and grave risks to public safety. Studies show that urbanization exacerbates the effects of heavy rainfall by raising flood peaks and surface runoff (Palla & Gnecco, 2015). Various factors contribute to urban flooding, including poorly constructed channels with flat or uneven slopes, an insufficient drainage network where larger drains discharge into smaller ones and undersized culverts (Nwaogazie *et al.,* 2015). Determining the design flows for drainage systems and comprehending the dynamics of surface runoff require an understanding of hydrological analysis.

The rational method (Chow *et al*., 1998, Maidment & Mays, 1988) is one of the important procedures for estimating the peak flow in small catchments. It links rainfall intensity to runoff by taking land use and catchment features into account. When suitable rainfall intensity-duration-frequency (IDF) curves are utilized, the rational method, although straightforward, yields dependable estimates of design flows (Oyebande, 1982). Salami *et al.* (2017) studied how people who live in flood-prone areas of Ibadan perceive flood risk and how they respond to it. The study found that although residents were highly aware of the potential of flooding, they were unable to take appropriate action because of limited resources. The authors suggested that to promote the use of flood mitigation techniques, there should be more community involvement and financial support. Raji *et al.* (2017) analysed and designed a stormwater drainage system for Olu Daramola Road, University of Ilorin, Nigeria to prevent flooding. Using a discharge rate of $2.15m^3/s$, Hy-8 and AutoCAD tool were used to design a trapezoidal drain (800mm depth, 250mm width). The elevation and water profile for the culvert to be used were determined using Hy8.

Daramola *et al.* (2016) examined how urban planning in Lagos and Ibadan can reduce the risk of flooding. The research discovered that increasing urbanization without comparable infrastructural improvement increased the danger of flooding. The study suggested using sustainable urban development techniques and integrating flood risk assessments into urban planning procedures would lessen vulnerability to floods. The economic effects of urban flooding in African cities, such as Ibadan, were examined by Lamond *et al.* (2015). The analysis underlined the necessity of investing in flood mitigation infrastructure and the significant financial losses brought on by recurrent floods. The writers emphasized how crucial it is to incorporate financial factors into flood control strategies to guarantee sustainable urban growth. Aderogba (2012) examined the impact of recent floods on sustainable growth in Ibadan, Nigeria. The study identified deforestation, poor drainage systems, urbanization, and inadequate urban planning as key factors that contributed to the city's flooding. The floods caused health risks, economic disruptions, and infrastructure damage, hindering sustainable development. The study emphasized the need for improved urban planning, enhanced drainage infrastructure, and the use of advanced hydrological models like SCS-CN and HEC-HMS for effective flood prediction and management. Adelekan (2010) investigated how susceptible Ibadan's urban population were to floods, focusing on the socioeconomic effects of flooding on households. The study discovered that improper waste management and insufficient urban infrastructure are major causes of urban flooding. To lower flood risks and increase urban population resilience, the study also emphasized the need for community-based flood management strategies and improved urban planning.

The ability of drainage infrastructure, like bridges and culverts, to operate hydraulically is essential for maintaining safe passage during periods of high flow and preventing overtopping of the road. By calculating tailwater conditions, flow regimes, and water surface profiles, hydraulic modelling tools like HY-8 make it easier to analyse culvert performance (Rowley, 2006). For the design and assessment of highway drainage structures, the Federal Highway Administration (FHWA) advises utilizing HY-8 (Federal Highway Administration, 1996). Jones (2014) discusses improvements made on HY-8, the program boasting its multi-barrel analysis and designing for aquatic organism passage (AOP). The application of design tool HY-8 by Weaver and Bartolo (2011) in the design of small structures emphasizes the versatility of the tool, from rudimentary standard culvert shapes to more complex ones, in several settings as remains illustrated in this article. The study emphasizes the role of the program in modernizing the engineering designs of structures and the waterway environment as well as ensuring the conservation of the environment and assesses the hydrological and hydraulic performance of selected culverts and bridges in Ibadan using the rational technique and HY-8 software. The accuracy of catchment parameter assessment, including size, length, and slope, is improved in hydrological research by integrating Geographic Information Systems (GIS) with Digital Elevation Models (DEM) (Maidment, 2002). For accurate hydrological and hydraulic evaluations, these technologies allow for the precise definition of watersheds and the extraction of crucial hydrological information. By ensuring the structures can transmit design flows without toppling over, the analysis seeks to increase the overall flood resistance through adherence to the Federal Ministry of Works Highway Design Manual (2013) rules and utilization of advanced modelling tools.

MATERIALS AND METHODS

2.1 Description of Study Area

The study area for this research is Ibadan, the capital city of Oyo State, southwestern Nigeria. It is one of the largest cities in the country and serves as a commercial, cultural, and educational hub. The study area lies between latitude 7°23′47″N and longitude 3°55′0″E. The city receives an average annual rainfall of about 1,200 mm (47 inches) and the average temperature in Ibadan ranges from 22°C (72°F) to 28°C (82°F) throughout the year, with relative humidity levels being high, particularly during the wet season. The natural vegetation falls within the tropical rainforest and savanna transition zone. Historically, the area was covered by dense rainforest, but urban development and agricultural activities have significantly altered this landscape. In regions where the rainforest has been cleared, secondary vegetation comprising savanna grasslands and scattered trees is common. These areas are often utilized for farming and other land use activities. The hydrological setting of Ibadan is significant, given its network of rivers and streams that flow through the city. The Ogunpa River, a prominent watercourse, flows through the metropolis and has historically been prone to flooding, affecting many areas during heavy rains. Efforts have been made to manage and control these flooding events through various urban planning and engineering interventions. The city's topography, with its undulating terrain, contributes to the drainage patterns and impacts flood management strategies.

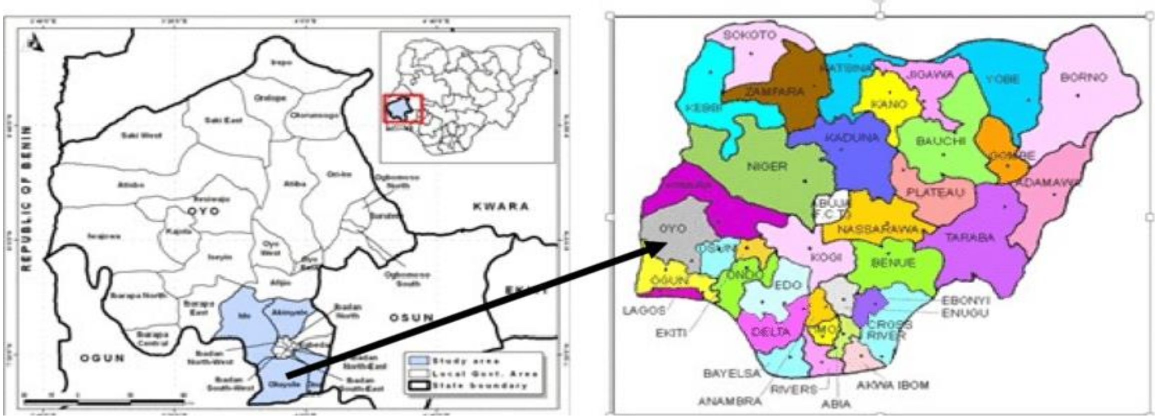

Fig 1. Map of Nigeria showing the location of the study Area source: Olubanjo (2016)

2.2 Modelling using HY-8 Software Package

HY-8 is a hydraulic modeling software specifically designed for culvert analysis, originally developed by Philip Thompson and later distributed by the Federal Highway Administration (FHWA). It is recommended for use in culvert analysis by the Ministry of Works, as outlined in Volume IV of the Drainage Design Manual. The tool allows for detailed analysis of culverts, including inlet control, outlet control, and the calculation of water surface profiles. One of its key features is the ability to estimate tailwater conditions downstream of the culvert based on the channel's dimensions and slope. Additionally, the software facilitates the determination of flow regimes and water surface profiles within the culvert. Fig. 2 illustrates the software interface used for hydraulic sizing of the culverts at the project site.

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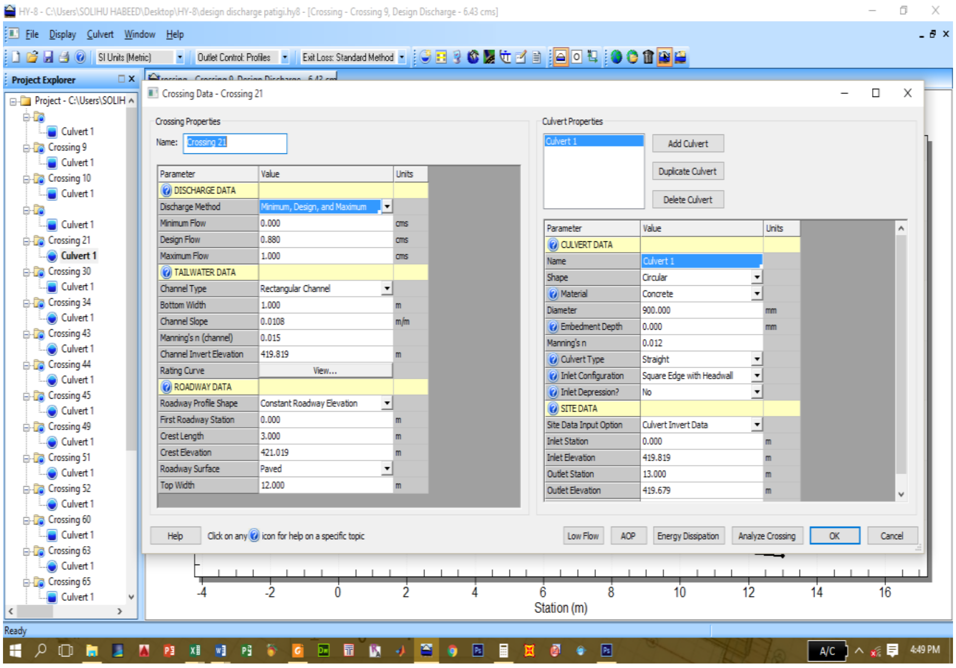

Fig 2. Interface of the HY-8 Software used for the hydraulic Analysis of the Culverts

2.3 Hydrological Study

The main objective of this study was to evaluate the surface run-off potential of stormwater and to determine the inflow at the various culvert sections. A hydrological analysis of the road is necessary for the design of the highway drainage structures. From such a study, information on the amount of rainfall in that area is needed which was used in the design of culverts to check whether the existing ones are adequate and to propose new ones where necessary. Hydrological study is an integral part of the preliminary design of highway hydraulic structures. It provides information on runoff and stream flow characteristics, which is required to estimate the design flow which is used as a basis of the hydraulic design of the system elements. The hydrological study for this project was carried out in line with the provisions of the Highway Design Manual Part 1, Volume IV (2013). Based on the available data, different methods of estimating storm discharge are reported in literatures. For this study, the rational method which utilizes a direct rainfall-runoff relationship was deemed adequate to determine the storm discharge expected at the various locations and stretch of the road alignment. The rational method, as outlined in the Highway Design Manual (2013), operates on several key assumptions. It assumes that the peak runoff rate at any given point is directly related to the average rainfall intensity during the time of concentration to that point. The frequency of peak discharge is identical to the frequency of the average rainfall intensity. Additionally, the time of concentration refers to the time it takes for runoff to become established and flow from the furthest part of the drainage area to the design point. Finally, the method assumes that the runoff coefficient remains constant for all storms, regardless of recurrence probability. The rational method used is of the form:

$$Q = 0.278\,CIA \tag{1}$$

where.

Q = Storm runoff (m^3/s)

C = Coefficient of runoff expressed as a percentage of imperviousness of the watershed surface.

I = Intensity of rainfall expressed in millimetres per hour for a certain time of concentration.

A = Area of the watershed in square kilometers.

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2.4 Runoff Coefficient

The run-off coefficient, "C" is the variable of the rational method that is least precisely determined. Its value gives the proportion of rainfall, which becomes run-off. It depends on such highly varying factors as vegetation, topography of the catchment, type of soil, infiltration rate, land use and drainage. Catchment runoff coefficients of the culvert locations were estimated based on the recommended Guide on the Value of C in Rural Areas as contained in the Highway Design Manual (2013).

2.5 Rainfall Intensity

Determination of rainfall intensity for hydraulic design requires consideration of factors such as average frequency of occurrence (also referred to as "return period"), intensity duration characteristics of rainfall for the selected return period, as well as the time of concentration (T_r). The approach for determining rainfall intensity, as presented in the Highway Design Manual (2013) which was developed by Oyebande (1983) was adopted for this study. The model is of the form given in equation (4)

$$I = \beta + y(1/\alpha) \tag{2}$$

Where α and β are the scale and location parameters. The parameters were derived from the reference manual for a given time of concentration. The parameter y is as expressed in equation (3).

$$y = In\ (T_r) - \frac{1}{(2T_r)} - \frac{1}{(24T_r^2)} - \frac{1}{(8T_r^3)} \tag{3}$$

Where Tr is the return period in years.

The design frequency adopted for this flood computation is a 50-year return period and a check flood of 100 years.

2.6 Time of Concentration

The time of concentration (t) was derived from the formula recommended for its estimation in the (Highway Design Manual Part I, Volume III) and is of the form:

$$t = \left(\frac{0.87L^2}{1000s}\right)^{0.385} \tag{4}$$

Where,

t =Time of Concentration in (hrs)

L = Hydraulic length of catchment measured along the flow path from the catchment boundary to the point of interest.

S = Average slope of the catchment in m/m

2.7 Catchment Parameters

The approximate area contributing to each of the culvert watersheds was estimated from the ArcGIS mapping. The delineation process of the watershed at each culvert location was carried out using the Automatic Watershed Delineation (AWD) procedure as embedded in the MapWindowGIS interface. The Digital Elevation Model (DEM) of 30m resolution data used for AWD was extracted from the Shuttle Radar Topography Mission (SRTM) final version from the US Department of Agriculture website. The SRTM digital elevation data provided has been processed to fill data voids and to facilitate the ease of use by a wide group of potential users.

The DEM was geo-processed and re-projected to Universal Traverse Mercator (UTM) Zone 31 Northern Hemisphere and was used to produce the spatial location of the subbasins of the attributed stream network in the project area (Fig. 3). More details about the spatial location of the subbasins of the culvert location are shown in Figs. 4 and 5. To identify the corresponding sub-basins for each of the bridge locations, the coordinates (Longitude, Latitude) of the locations obtained from the field survey were merged with the corresponding sub-basins. The value of the area of the watershed, length and average slope of the catchment obtained from the model were used for the hydraulic sizing of the bridges (See Table-1).

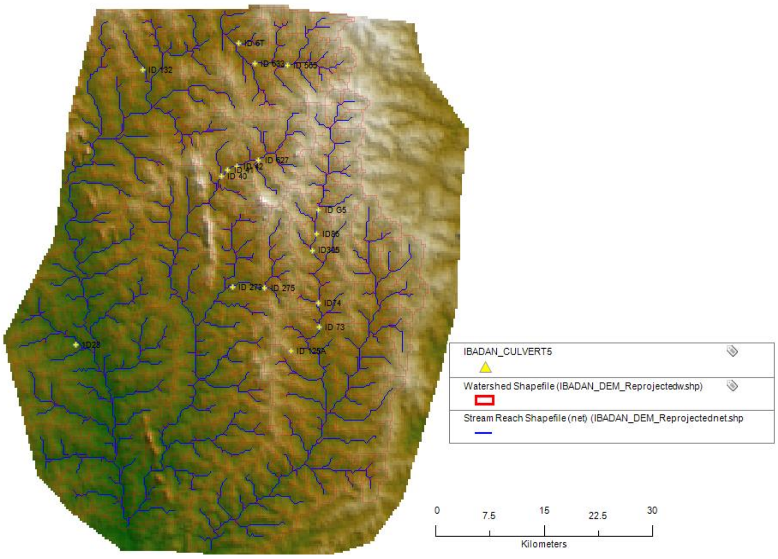

Fig 3. Digital Elevation Model of the Project Area

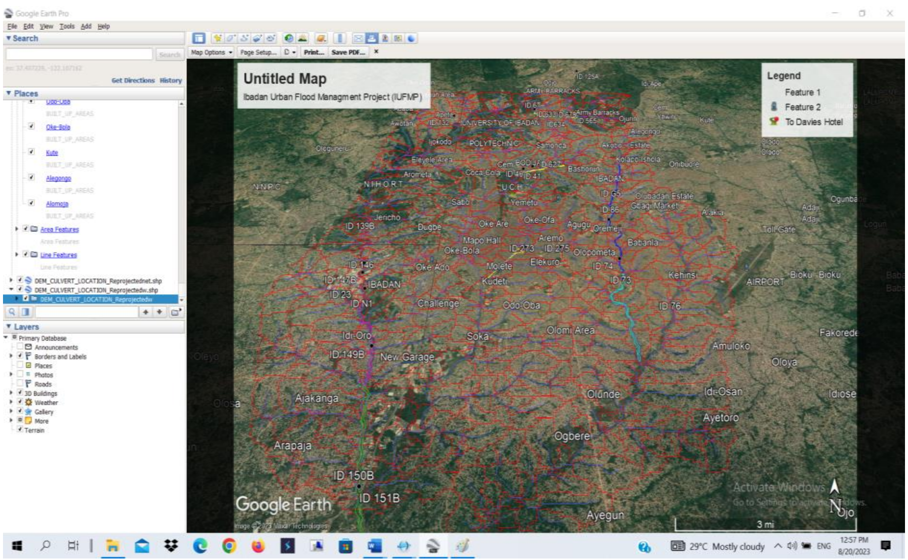

Fig. 4 Subbasins of the culvert locations overlaying the Google Earth Imagery Project Area

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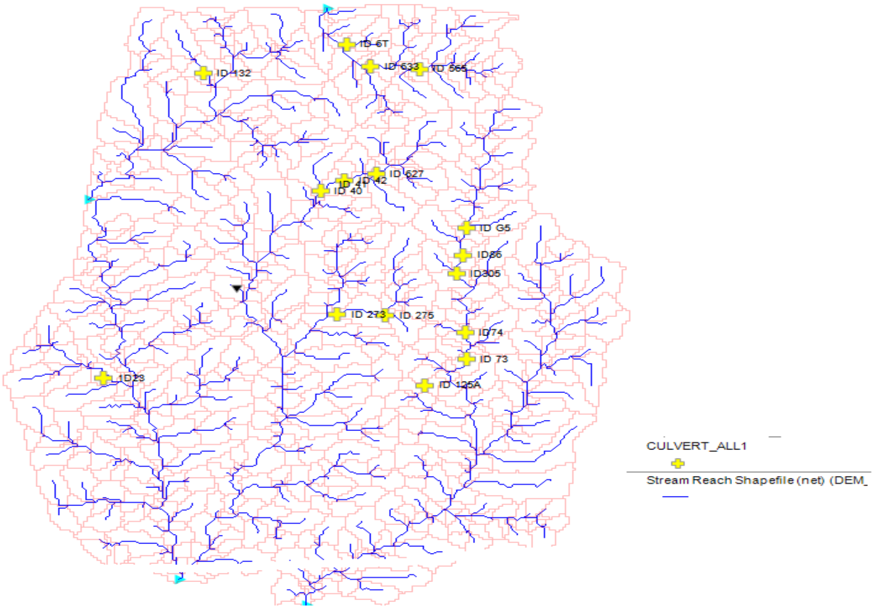

Fig. 5 Delineation of the Study area into subbasins attributed to culvert locations

2.8 Hydraulic Analysis

2.8.1 Data Requirements

The use of Hy-8 software for hydrologic and hydraulic analysis of culverts involved the collection of a range of data which will serve as input data before the running of the model. These data defined the culvert barrels and the surrounding site condition at each of the analyzed crossings. A crossing is defined as the location where a channel crosses a roadway, floodplain or other embankment. The software allows for the definition and modelling of up to six culverts at each crossing. Data requirements include Discharge Data, Tail water Data (including Channel type, Bottom width, channel slop, the manning's consultant and channels, in and out elevation.

2.8.2 Discharge Data

The model requires data such as the minimum, design and maximum discharge data before analysis can be performed. The minimum discharge is usually taken on zero while the design discharge is placed between the minimum and maximum discharge values. In plotting the rating curve, the value of the design discharge is always included as one of the flow values and is used for the value when default drawings and plots are created in the graphic window.

2.8.3 Tail water Data

These include the channel type, bottom, width, channel slope, Mannings 'n' constant in the channel and channel invert elevation. The tailwater data is used to define the water surface profile downstream of the channel crossing.

2.8.4 Roadway Data

It is required to provide and populate the model with data relating to the roadway at a crossing. These data will be used by the software to perform an overtopping analysis of the roadway and embankment. Two options are available for the road profile. These are constant roadway elevation or irregular profile shape. The former entails the user to provide information regarding crest length and crest elevation of the road, the latter (irregular profile shape) involves definition of up to 15 cross-section points (station and elevation). Other data in this category include the surface condition (pared, gravel) and the top width of the road.

2.8.5 Culvert Data

Information on the shape of the culvert, the material, span specification (the rectangular box culvert), and the pipe dimension (for the pipe culvert) was required. Also, the type was inlet configuration, and the embedment depths were required for the group of data.

RESULTS AND DISCUSSION

3.1 Hydrological Analysis

The hydrological analysis for the 17 selected culverts shows significant variations in design flow. The flow estimates range from 15.29 m^3/s at Culvert ID 73 to 52.78 m^3/s at Culvert ID 40, reflecting the differences in watershed characteristics, including area, slope, and runoff potential. The Rational Method, employed for calculating storm discharge, demonstrated that all culverts could convey their respective design flows without overtopping. The Rational Method calculations revealed that larger catchment areas, such as Culvert ID 40 (with a catchment area of 2.54 km^2), generate higher runoff volumes compared to smaller catchment areas like ID 73 (0.89 km^2). These results align with the principle that catchment size and slope significantly influence surface runoff potential and flow rates. Additionally, differences in land use, vegetation, and soil infiltration rates likely contributed to the variation in runoff coefficients across the study area, further affecting discharge values.

Table-1 Catchment Characteristics of the Culvert Locations

S/N	Culvert ID	Details of Hydraulic Structure & Dimensions	Easting(E)	Northern(N)	Length of catchment(m)	Slope (S)
1	ID 627	Box Culvert 2 cells (4.0x2.5x) m	600952.49	819918.06	2577	0.003537
2	ID 40	Box Culvert 4 cells (6.0x2.5x12.70) m	599430.75	819284.74	4593	0.003537
3	ID 41	Box Culvert 2 cells (6.0x2.5x10.10) m	599696.86	819517.59	4593	0.003537
4	ID 42	Box Culvert 2 cell (6.0x2.5x10.6) m	600081.11	819673.03	3390	0.003537
5	ID 633	Box Culvert 1 cell (7x2.5x17) m	600790.15	823710.03	3761	0.00151
6	ID G5	Box culvert 2 cells (6x2.5x 11) m	603406.7	817966.21	4825	0.00331
7	ID 565	Box Culvert 2 cells (2.5x1.8x19) m	602134.86	823640.47	4503.52	0.003537
8	ID 6T	Box Culvert 1 cell (4x2.0x17) m	600125.28	824520.46	2230.66	0.003537
9	ID 132	Box Culvert 1 cell (6x2.0x14) m	596221.91	823479.67	4483	0.00151

10	ID 273	Box Culvert 1 cell. (8x2.5x14) m	599882.37	814898.31	7817	0.003537
11	ID 275	Box Culvert 1 cell (7x2.5x17) m	601199.89	814881.57	7811	0.003537
12	ID 73	Box Culvert 1 cell (6x3.0x26) m	603416.45	813322.57	9392	0.00331
13	ID 125A	Box Culvert 1cell. (7x2.5x17) m	602281.48	812385.95	10481	0.00331
14	1D23	Box Culvert 4 cells (6x3x17) m	593483.69	812639.41	7490	0.004007
15	ID305	Box Culvert 4 cells (6x3x17) m	603132.11	816359.49	7490	0.003006
16	ID86	Box Culvert 4 cells (6x3x17) m	603326.15	817015.72	5090	0.003006
17	ID74	Box Culvert 4 cells (6x3x17) m	603385.07	814272	7110	0.003006

Table-2 Summary of Hydrological Analysis of Culverts

S/N	Culvert ID	Details of Hydraulic Structure & Dimensions	Rainfall Intensity (mm/hr)	Catchment Area (A) Km2	Design Flow (m3/s)
1	ID 627	Box Culvert 2cells [4.0x2.5x10.8] m	132.852	1.92	48.57
2	ID 40	Box Culvert 4 cells [6.0x2.5x12.70] m	118.158	2.54	57.14
3	ID 41	Box Culvert 2 cells [6.0x2.5x10.10] m	132.852	2.02	51.1
4	ID 42	Box Culvert 2 cells [6.0x2.5x10.6] m	126.804	1.85	44.67
5	ID 633	Box Culvert 1 cell [7x2.5x17] m	124.18	1.25	29.55
6	ID G5	Box culvert 2 cells [6x2.5x 11] m	115.774	2.42	53.35
7	ID 565	Box Culvert 2 cells [2.5x1.8x19] m	119.024	1.92	43.51
8	ID 6T	Box Culvert 1 cell [4x2.0x17] m	136.286	0.92	23.87
9	ID 132	Box Culvert 1 cell [6x2.0x14] m	105.186	0.99	19.83
10	ID 273	Box Culvert 1 cell [8x2.5x14] m	99.954	0.99	18.84
11	ID 275	Box Culvert 1 cell [7x2.5x17] m	99.954	0.9	17.13
12	ID 73	Box Culvert 1 cell [6x3.0x26]m	98.282	0.89	16.65
13	ID 125A	Box Culvert 1 cell [7x2.5x17] m	99.322	0.91	17.21
14	1D23	Box Culvert 4 cells [6x3x17] m	98.51	3.56	66.77
15	1D86	Box Culvert 2 cells [6X2.5X63] m	90.253	4.7	80.77
16	ID305	Box Culvert 1 cell [3.5x2x63] m	112.502	3	64.26
17	ID74	Box Culvert 1 cell [4x3x10] m	101.289	2.05	39.54

3.2 Hydraulic Analysis

The hydraulic analysis conducted using HY-8 software confirmed the adequacy of all 17 culverts in managing the design flows at each location with no instances of overtopping or inadequate conveyance capacity. The analysis of headwater and tailwater elevations provided insights into the culverts' ability to manage stormwater without causing road overtopping.

The analysis at Culvert ID 40, which had the highest design flow of 52.78 m^3/s, showed that its four-cell configuration (dimensions: 6.0 x 2.5 x 12.70 m) was capable of managing the inflow without exceeding the road elevation. Similarly, the single-cell culvert at ID 73, with a much lower design flow of 15.29 m^3/s, was also found to be sufficient, underscoring that culvert dimensions and design must match the specific hydrological conditions of the area.

3.3 Water Surface Profile and Rating Curves of Analyzed Bridges

The water surface profiles, and rating curves generated using HY-8 illustrate the performance/rating of the culverts under varying flow conditions. For instance, typical water surface profile and rating curves of Culvert ID 305 and ID 74 (Figs. 6 and 7 respectively) show that the hydraulic jump occurred within acceptable limits, maintaining a stable flow regime. The rating curves further demonstrate that the culverts maintain the desired headwater elevation across a wide range of flow rates, ensuring efficient water passage even during high-intensity rainfall events. The findings of the manuscript align well with existing literature on hydrological and hydraulic analysis, urban flood management, and infrastructure design. The study demonstrated significant variations in design flow among culverts, ranging from 15.29 m^3/s for Culvert ID 73 to 52.78 m^3/s for Culvert ID 40. These results align with the principles outlined by Oyebande (1982), who emphasized the effectiveness of the Rational Method when paired with intensity-duration-frequency (IDF) curves for hydrological calculations. Similarly, Raji *et al.* (2017) highlighted the importance of tailoring drainage designs to specific hydrological contexts using tools like HY-8, which was also employed in this study for hydraulic modeling. The manuscript's findings on the hydraulic adequacy of culverts resonate with prior studies that stress the importance of well-designed infrastructure for urban resilience. For instance, Adelekan (2010) and Aderogba (2012) identified urbanization, poor drainage, and inadequate planning as key factors contributing to flooding in urban areas. This study reinforces these insights by demonstrating that appropriately designed culverts can effectively manage stormwater flows, thereby mitigating flooding risks. The findings also echo Daramola *et al.* (2016) advocacy for integrating flood risk assessments into urban planning and infrastructure development. The study's use of HY-8 for detailed hydraulic analysis is consistent with Jones (2014) and Weaver & Bartolo (2011), who emphasized the software's capability for assessing complex drainage systems. Additionally, the Federal Highway Administration's (1996) recommendation of HY-8 as a standard tool for culvert analysis further validates the study's approach. By confirming the hydraulic adequacy of all analyzed culverts, the research supports the premise that advanced modeling tools enhance the accuracy and reliability of infrastructure assessments. Finally, the manuscript's emphasis on investing in flood mitigation infrastructure aligns with Lamond *et al.* (2015), who highlighted the economic benefits of resilient urban systems. The findings emphasized the need for continuous maintenance and monitoring of drainage structures to sustain their performance, particularly in light of urbanization and climate change. Overall, the study provides valuable insights that contribute to the ongoing discourse on effective flood management strategies in urban environments.

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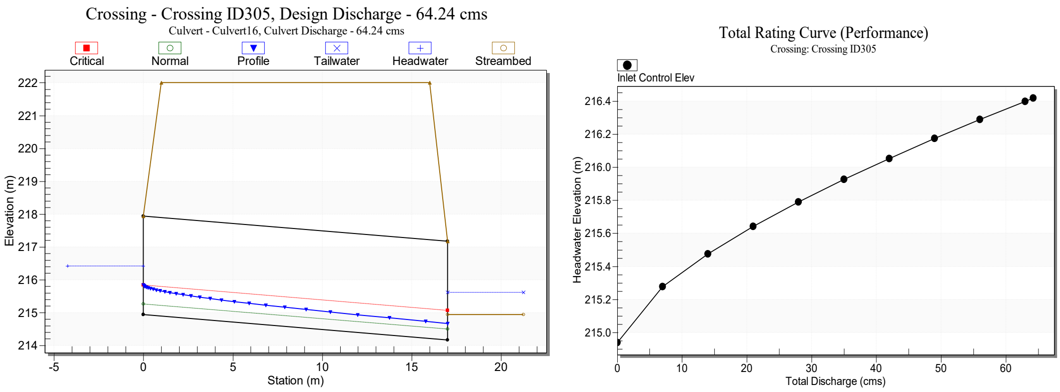
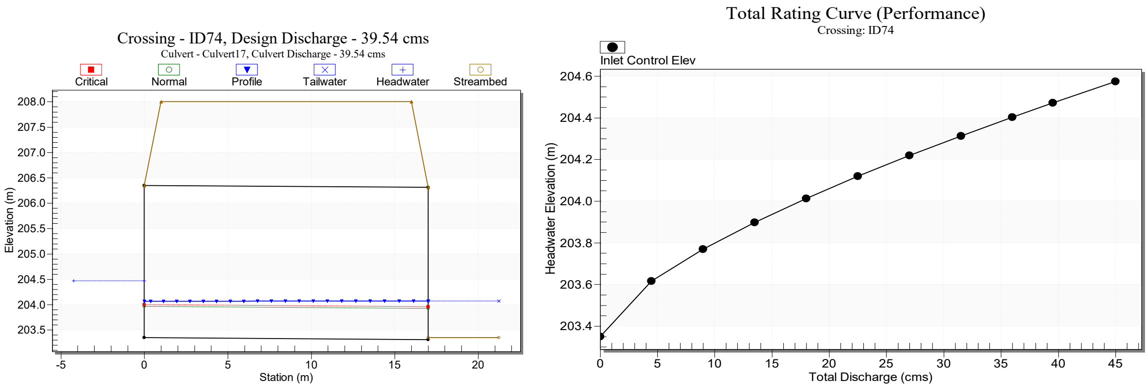


(a) (b)

Fig. 6 Water surface profile (a)and rating curve (b) of culvert with ID 305



(a) (b)

Fig 7. Water surface profile (a) and rating curve (b) of culvert with ID 74

CONTRIBUTION TO KNOWLEDGE

In summary, this research contributes valuable knowledge to the field of civil engineering and flood management, demonstrating that well-designed culverts are integral to effective stormwater management systems. Future studies could explore the long-term performance of these structures and assess the impact of extreme weather events on their functionality, thereby ensuring the continued safety and reliability of urban infrastructure.

CONCLUSION

This study comprehensively assessed the hydraulic adequacy of 17 selected culverts in Ibadan, Southwest Nigeria, as part of flood management efforts. Through rigorous hydrological analysis using the Rational Method and hydraulic modeling with the HY-8 tool, the research demonstrated that all culverts can effectively convey their respective design flows without the risk of overtopping. The hydrological analysis revealed significant variations in estimated flow rates, ranging from 15.29 m^3/s at Culvert ID 73 to 52.78 m^3/s at Culvert ID 40. These findings underscore the importance of understanding catchment characteristics, including area, slope, and land use, which directly influence surface runoff potential. The ability of each culvert to manage expected stormwater inflows reflects the appropriateness of their design dimensions and configurations. Hydraulic assessments confirmed that all analyzed culverts maintain adequate capacity under various flow conditions, reinforcing their role in mitigating flooding risks in the study area. The successful integration of advanced modeling tools like HY-8 facilitated a detailed examination of water surface profiles and rating curves, providing insights into the dynamic flow behaviors of the culverts. Furthermore, the study highlights the critical need for continuous monitoring and maintenance of these culverts to ensure sustained hydraulic performance, especially in light of ongoing urbanization and climate change challenges. By investing in the enhancement of existing drainage infrastructure and adopting innovative flood management strategies, local authorities can significantly improve urban resilience against flooding.

CONFLICT OF INTEREST

There is no conflict of interest for this research work.

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