LAUTECH Journal of Civil and Environmental Studies
Volume 10, Issue 1; March 2023

DOI: 10.36108/laujoces/3202.01.0110

One-Dimensional Hydraulic Modelling of River Ona Bridges, Ibadan, South-Western Nigeria

[1,]* Ganiyu, H. O., [1] Adeogun, A.G., [1] Sheriff, B. and [2] Na'allah, A.

[1]Department of Civil & Environmental Engineering, Kwara State University, Malete, Kwara State, Nigeria
[2]Department of Civil Engineering, Kwara State Polytechnic, Ilorin, Kwara State, Nigeria

*Corresponding Author: habeeb.ganiyu@kwasu.edu.ng; Tel: 08069039551

Submitted on: 27/01/2023 *Accepted on: 21/03/2023*

Abstract

Bridges are crucial for transporting people and goods, but their failures can be catastrophic, resulting in loss of life and property. This study assessed the flood stage of selected bridges (Alaafin Avenue, Seven-Up, and Oluyole) along the Ona River, Ibadan, Nigeria, using a one-dimensional model called the Hydraulic Engineering Center-River Analysis System (HEC-RAS). The model requires two major input data: geometric and steady flow data. The geometric features of the study area (stream centerline, riverbanks, flow paths, cross-sections, and bridges) were generated from the Digital Elevation Model (DEM) in HEC-GeoRAS, an extension of ArcMap GIS. The MapWindow Soil and Water Assessment Tool (MWSWAT) was used to predict flow. The input data for the model include DEM, Land use, soil map data, and meteorological data obtained from the Nigerian Meteorological Agency (NIMET). The flood stages of the three bridges were predicted in the HEC-RAS model and the results showed that Alaafin Avenue, Seven-Up and Oluyole bridges had predicted flood stages of 1.5 m, 1.6 m, and 2.5 m and a freeboard minimum clearance of 2 m, 0.3 m, and 0.5 m respectively. However, the predicted flow (75.25 m³/s) was compared with the corresponding value of the flow in ERA (2002) for a free board minimum clearance. It was shown that only Alaafin Avenue Bridge is safe while Seven-Up and Oluyole bridges are prone to inundation by approximated values of 0.3 m and 0.5 m respectively. Therefore, regular inspection and maintenance of bridges are recommended to prevent inundation.

Keywords: HEC-RAS, Bridge, MWSWAT, Ona River, Flood Stage

Introduction

Bridges are costly to construct, and the cost per kilometer of a bridge is higher than that of the roads approaching the bridge. This is a major investment and should be properly planned because of insufficient funds allocated to the transportation system (Birhanu and Vijaykumar, 2020). When a bridge spans a river, there is a need for hydraulic and hydrological analyses of the bridge before construction to effectively serve its purpose (Amulya *et al*., 2018). There are different bridge designs, each serving a particular purpose and applicable to different situations. According to Balasubramanian (2017), bridge design varies depending on several factors, including the purpose of the bridge, the terrain nature where the bridge is constructed and anchored, the material used, and the financial resources available for its construction. Current bridge design specifications deal with various extreme hazards independently, which may lead to less economic design and construction practices and may underestimate failure probabilities (Wang *et al*., 2014). However, civil engineers need to be familiar with and continuously learn from the different failures of hydraulic structures (Delatte, 2010). Bridge failure occurs when the primary load-carrying portions of a bridge can no longer serve their purpose, and collapse occurs on the entire bridge or a main component when a partial or total replacement is required (Chavel and Yadlosky, 2011).

Choudhury and Hasnat (2015) classified bridge collapses globally into natural and human factors. Natural factors are caused by the occurrence of wind, earthquakes, cyclones, floods, bridge scour, and landslides, whereas human factors are caused by design and construction errors, overloading, collision, fire, lack of inspection, and improper maintenance. These factors individually may not cause collapse; however, collapse may occur because of the interaction of several events. Ede *et al*. (2019) reviewed the prevalent causes of the collapse of bridges in Nigeria between 2010 and 2018. The study presented forty-five bridge collapse cases and identified flooding, overloading, terrorist attacks, design and construction errors, and a lack of proper maintenance and inspection as the major causes of failure, with floods having the highest percentage. Meanwhile, floods due to rapid catchment response to an increase in rainfall intensity, breaches of flood defenses, and inundation of river natural banks may induce high-impact forces on structures, causing structural damage or even failures leading to loss of lives and properties (Siregar, 2018).

Moreover, the rate of flood vulnerability in developed and developing countries is unprecedented. This situation is of global significance, although it seems that the perception of flooding in developing countries, particularly Nigeria, is being nuanced by obvious limitations in research, economy, and policy frameworks (Isreal, 2017). The flood simulation presents two representations of bridges, including a novel and simple empirical formulation for the total head loss caused by bridges. This covers all flow regimes, free water surfaces, and partially or fully submerged flows (Heilemariam *et al*., 2013). The extent of the expected flood-affected areas and the increase in water surface elevation are highly dependent on the river morphology, bridge geometry, flow, and floodplain characteristics that may originate from upstream flooding (Brandimarte and Woldeyes, 2013). However, floods induced by climate change are natural events that cannot be prevented but can be mitigated to reduce the accompanying destructive impacts. Therefore, more specific and scientific work must be developed to provide a better understanding of flooding phenomena and their related geographical, hydrological, and geomorphological causes. Thus, it is important to define a strategic means that includes a combination of structural and non-structural measures, based on a careful analysis of past floods and improvements in flood forecasting (Sina, 2009).

According to the literature, there are limited studies on bridge modelling assessment, particularly those using a hydraulic model. In Nigeria, Oliver *et al*. (2021) assessed the hydraulic geometry of River Yedzeram at Lokuwa, Wuro-Gude, and Wuro-Bani Bridges in Adamawa State. The result showed that the discharges (velocities) of the three bridges were estimated at 691.136 m^3/s (109.78 m/s), 951.424 m^3/s (120.264 m/s), and 196.752 m^3/s (93.4 m/s) respectively. It was also revealed that the Wuro-Bani Bridge had the highest daily water level. The 1-D hydraulic HEC-RAS model is widely used for various water systems modelling including bridges. (Patra *et al*., 2022; Pochpande *et al*., 2019; Siregar, 2018) have applied this model to assess bridges in their respective regions with satisfactory output. It is on this note this study applied the 1-D HEC-RAS model to predict the flood stage of selected bridges along Ona River, Ibadan.

Materials and Methods

Description of the study area

The river Ona is situated upstream of Eleyele reservoir and continued downstream of the reservoir, in the city of Ibadan within geographical coordinates: Latitude 7º20’-7º25’N and Longitude 3º51’-3º56’ E. River Ona spans within the Ido and Ibadan North-West Local Government Areas of Oyo State. The Eleyele Reservoir was formed from the confluence of the Ona and Alapata River areas. The downstream of the reservoir is called River Ona. The river is further dammed at the National Horticulture Research Institute (NIHORT), Idi-Isin, and traverses many locations within the Ibadan Metropolis such as Odo-Ona Apata, Oluyole Estate, Odo-Ona Elewe and New Garage Challenge (Elufioye, 2016). Three prominent bridges

(Alaafin Avenue, Seven-Up, and Oluyole) around the Oluyole Estate were hydraulically modelled to evaluate the bridge flood stage. Figure 1 shows a map of the study area.

Model input data

The model input data were categorized as spatial and temporal data. The spatial data included a Digital Elevation Model (DEM), soil map, and land use/land cover map of the study area. The temporal data were precipitation, solar radiation, relative humidity, wind speed, and minimum and maximum temperatures. A 90 m × 90 m resolution DEM of the study area was obtained from the Shuttle Radar Topography Mission (SRTM) website (CGIAR, 2016). The DEM was processed and used to delineate the watershed and analyze the drainage patterns of the land surface terrain. Sub-basin parameters (such as slope gradient and slope length of the terrain) and stream network characteristics (such as channel slope, length, and width) were derived from DEM. The DEM of the study area watershed is shown in Figure 2.

The land use map of the study area was extracted from the Global Land Cover Characterization (GLCC) database and used to estimate vegetation and other parameters representing the watershed area (Adeogun *et al*., 2020). The GLCC database was developed by the United States Geological Survey (USGS) and has a spatial resolution of 1 km and 24 classes of land use representation (GLCC, 2020). Table 1 shows the land use of the study area.

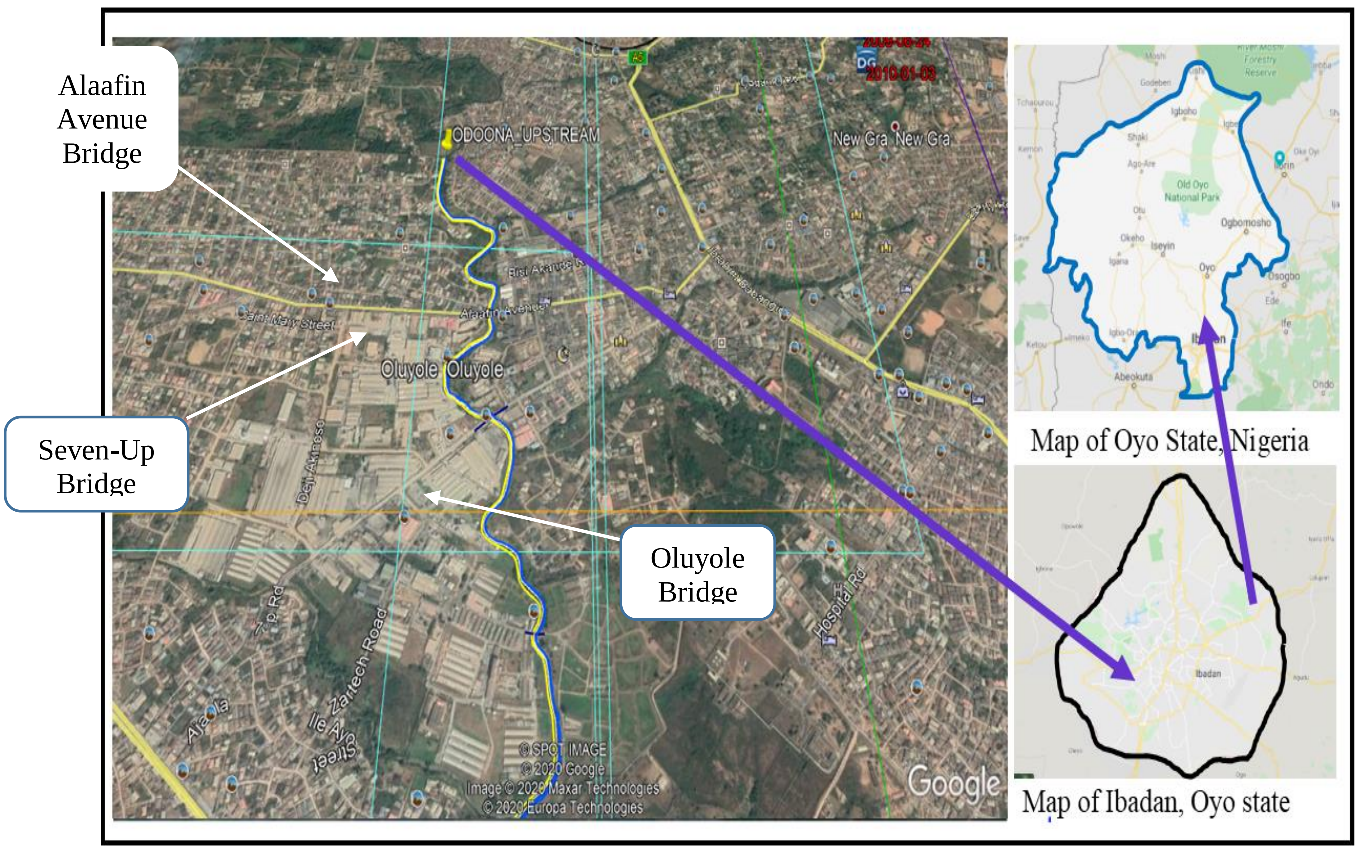

Figure 1: Map of the study area

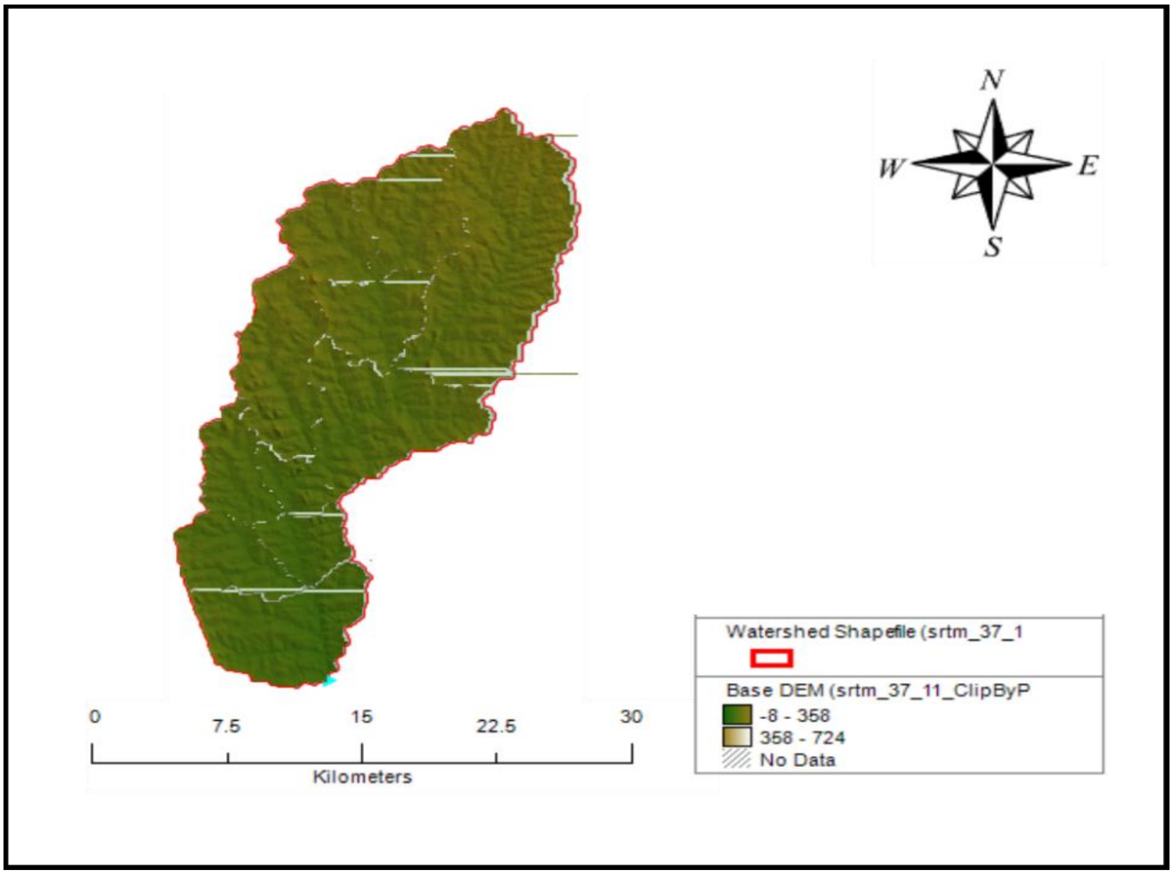

Figure 2: DEM of the Study Area

Table 1: Information on Land use of the Study Area

S/N	SWAT Code	Description	Area (Ha)	Percentage (%)
1	CRWO	Cropland/Woodland	17856.66	44.65
2	FOEB	Evergreen Broadleaf Forest	4933.83	12.34
3	CRDY	Cropland/Woodland mosaic	3019.84	7.55
4	SAVA	Savana	10416.80	26.05
5	WEWO	Wooded Wetland	1827.38	4.57
6	GRAS	Grassland	420.47	1.05
7	CRGR	Cropland/Grassland Mosaic	717.33	1.79
8	URMD	Residential land with medium density	714.80	1.79
9	FODB	Deciduous Broadleaf Forest	84.09	0.21

Digital soil data for the study area were obtained from Harmonised Digital Soil Map of the world (HWSD v1.1) produced by the Food and Agriculture Organization (FAO) of the United Nations (Nachtergaele *et al*., 2008). Table 2 provides detailed information on the soil of the study area which shows that the area is dominated by loam soil. It presents the soil texture of the study area. Temporal (meteorological) data for this study were obtained from the Nigerian Meteorological Agency (NIMET). The meteorological data included daily precipitation, humidity, maximum and minimum temperatures, solar radiation, and wind speed between 1st January 2012 to 31st December 2020, then the meteorological data from January 2021 to December 2041 were forecasted using the Markov model. This approach is appropriate for forecasting streamflow, rainfall, temperature, and other variables whose values change with time (Loucks and Van Beek, 2005).

Table 2: Information on Soil Texture of the Study Area

N	SWAT Code	Description	Area (Ha)	Percentage (%)
1	Lf49-1475	Sandy-Clayey-Loam	11816.98	29.55
2	I-60	Loam	22957.00	57.41
3	Lf62-3a-1488	Sandy-Clayey	5217.23	13.05

Modelling processes

A Geographical Information System (GIS) coupled with HEC-GeoRAS, Soil and Water Assessment Tool (SWAT) Model, and HEC-RAS were used to model the study area. The HEC-RAS model requires two major types of model input data: geometric and steady flow. HEC-GeoRAS, an extension of ArcGIS, was used to generate the geometric properties (stream centerline, riverbanks, flow paths, cross sections, and bridges) along the river flow from the DEM of the study area, whereas the SWAT model was used to predict the steady flow of the river. Then, the geometric features predicted flow, Manning's value, and boundary conditions were simulated in the HEC-RAS model to generate the water surface profile of the study area and predict the flood stage of the bridges. Manning's values, n of 0.04, and 0.045 were assigned to the channel and overbank, respectively, for all cross sections except for the boundary cross sections of the bridges that have a Manning value, n, of 0.05. These values were based on the study area conditions compared with Chow's table (Sredojevic and Simonovic, 2009). In addition, an average slope of 1.2% was set as the normal depth for the boundary condition. Figure 3 shows the methodological framework for bridge modelling.

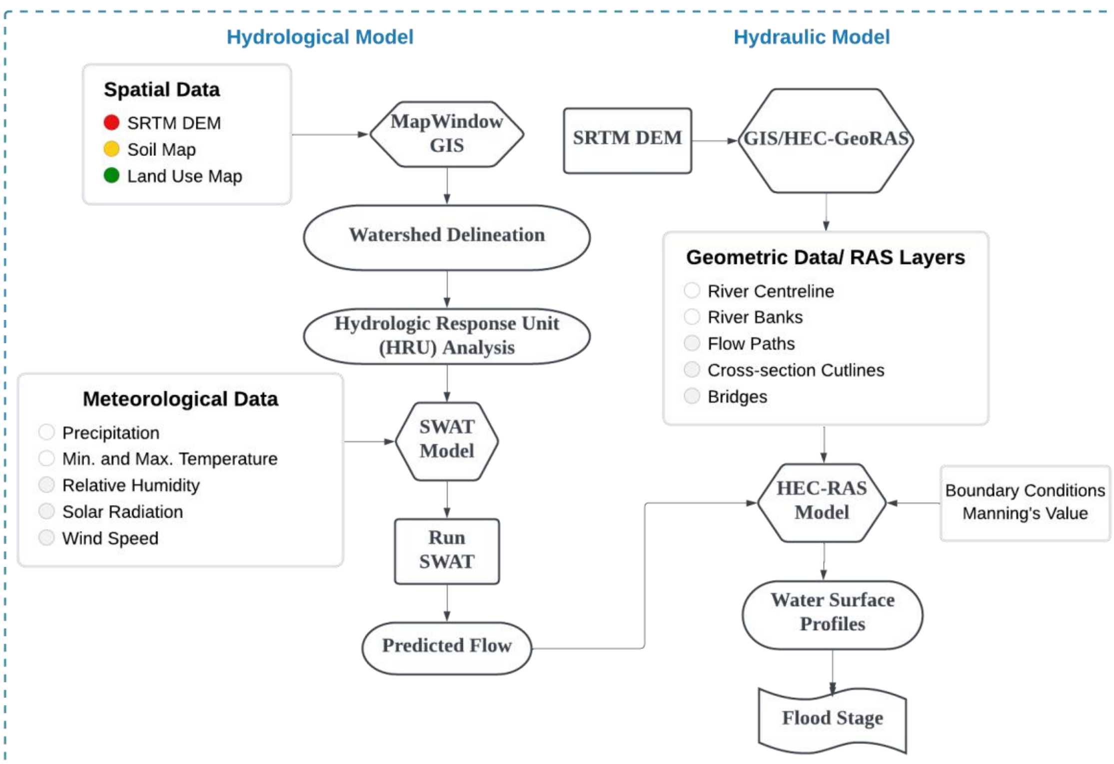

Figure 3: A Methodological Framework for Bridge Modelling

Results and Discussion

Geometric properties of the river

The geometric data required by the HEC-RAS model generated in the GIS coupled with HEC-GeoRAS are presented in Figure 4. The river reach length covered for this study was about 3.4 km, with the delineation of one hundred and fifty (150) cross-sections along the river.

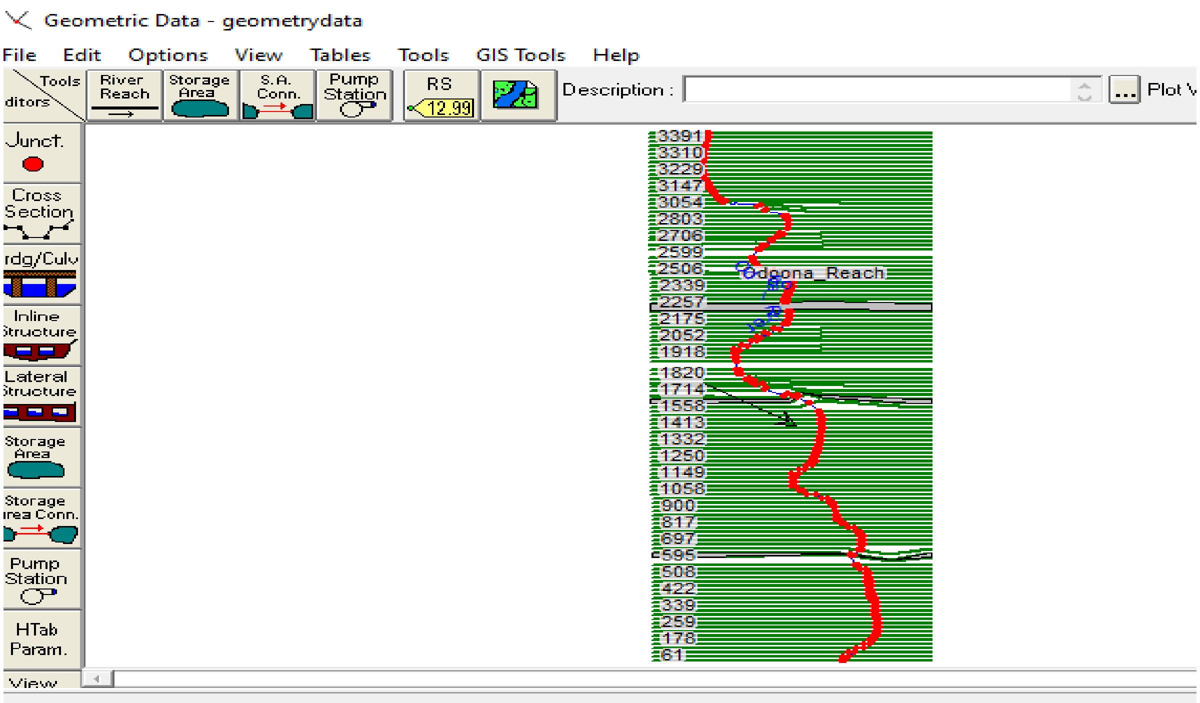

Figure 4: Graphical Interface of Ona River Geometric Properties

Prediction of flow

The predicted flow for all the sub-basins in the study area watershed is presented in Figure 5.

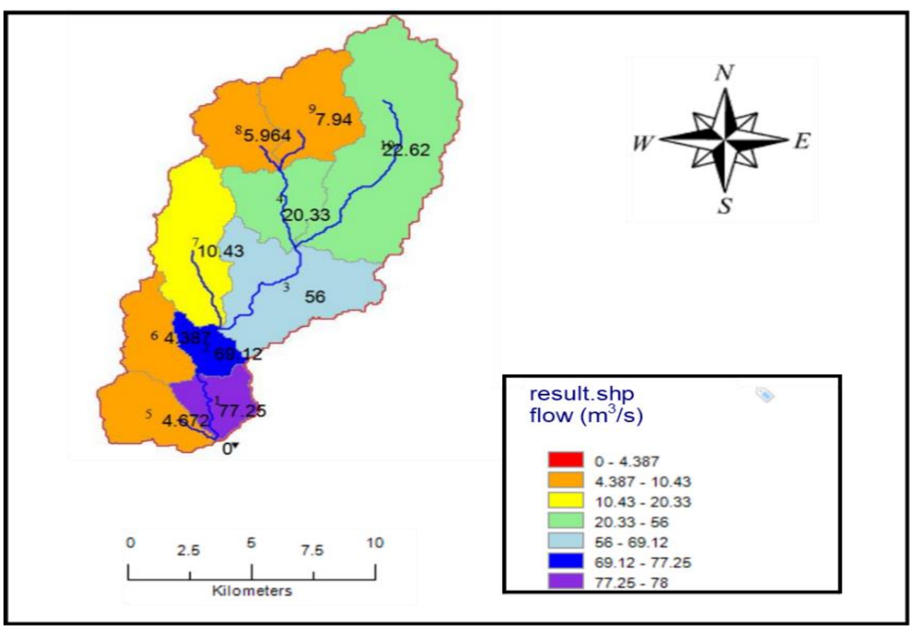

Figure 5: The Flow Spatial Map of the Study Area

The results revealed that sub-basins 1 and 6 had the highest and lowest predicted flow at 75.25 m^3/s and 4.39 m3/s respectively. The study area was in sub-basin 1 at a predicted value of 75.25 m^3/s. This flow was used as one of the input parameters in the HEC-RAS model to predict the water surface profile of the study area.

Prediction of flood stage of the modelled bridges along Ona River

The Alaafin Avenue, Seven-Up, and Oluyole bridges are the three bridges modelled along the Ona River. The freeboard minimum clearance-based flow rate recommended by ERA (2002) is presented in Table 3. Figures 6, 7, and 8 show the water surface levels of the Alaafin Avenue, Seven-Up, and Oluyole Bridge, respectively.

Table 3: Freeboard Minimum Clearance Recommendation (ERA, 2002)

Discharge, Q (m^3/s)	Free Board (m)
0-3	0.3
3-30	0.6
30-300	0.9

Source: Birhanu and Vijaykumar (2020)

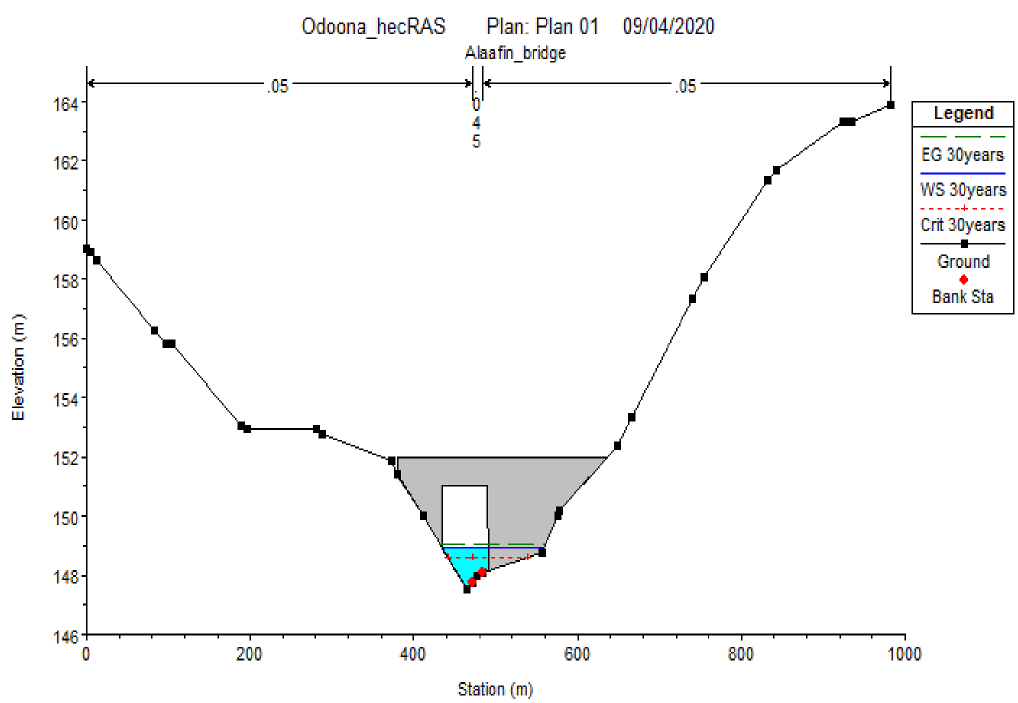

Figure 6: Cross-section of Alaafin Avenue Bridge showing the Water Surface Elevation

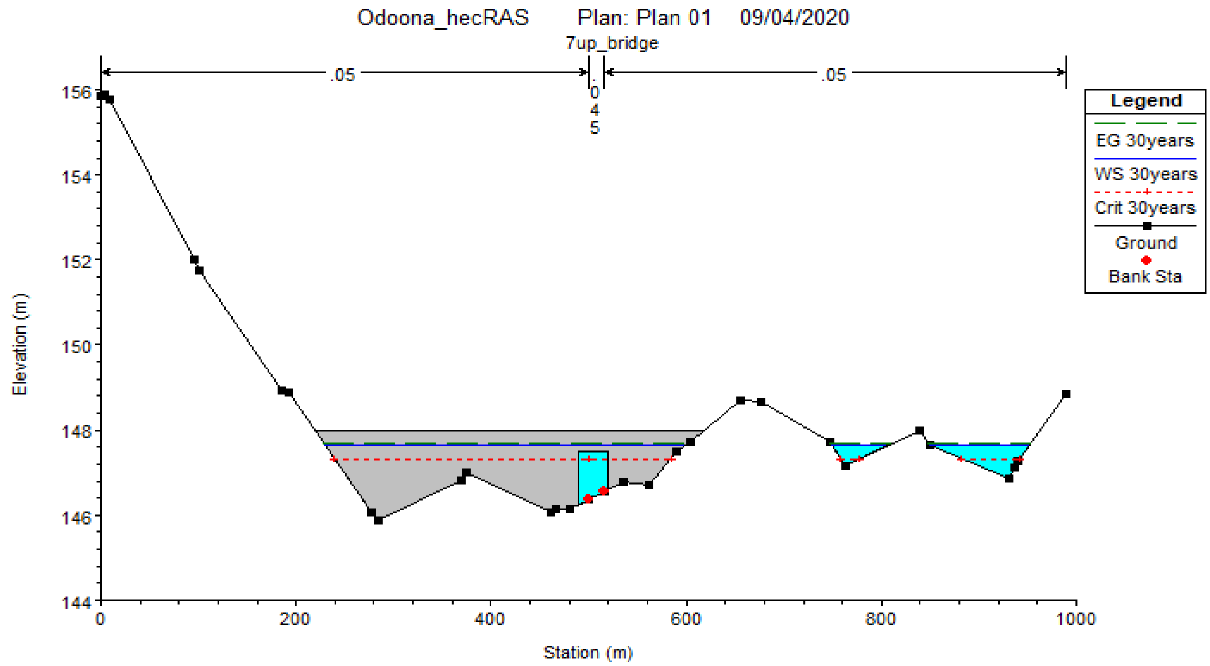

Figure 7: Cross-section of Seven-Up Bridge showing the Water Surface Elevation

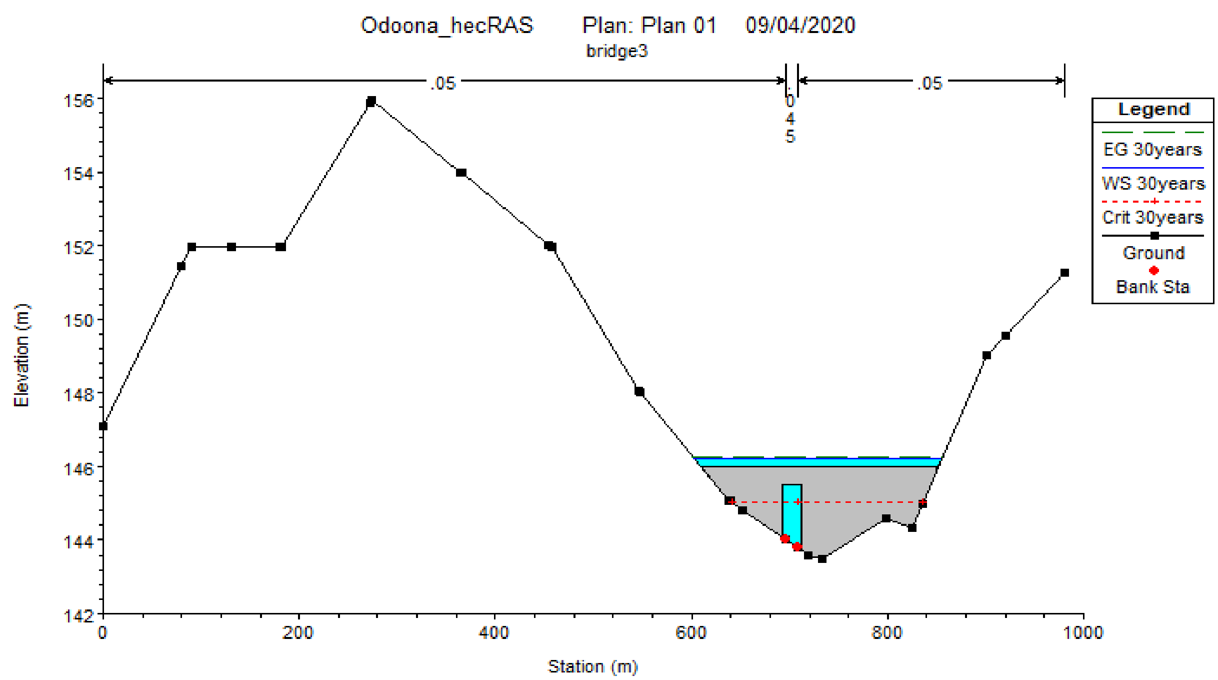

Figure 8: Cross-section of Oluyole Bridge showing the Water Surface Elevation

Based on the outcome of the study, it was observed that the predicted values of riverbed elevation, water surface profile elevation, and deck soffit elevation for the Alaafin Avenue Bridge were approximately 147.5 m, 149 m, and 151 m, respectively. The approximated values of flood stage and flood clearance were 1.5 m and 2 m, respectively. For Seven-Up Bridge, the riverbed elevation, water surface profile elevation, and bridge deck soffit elevation have approximated values of 146.2 m, 147.8 m, and 147.5 m respectively, and the flood stage was predicted at an approximated value of 1.6 m. Therefore, there was no clearance between the bridge deck and the flood stage. Whereas for Oluyole Bridge, the riverbed elevation, water surface elevation, and the bridge deck soffit elevation were predicted at approximated values of 143.5 m, 146.0 m, and 145.5 m respectively having a flood stage of an approximated value of 2.5 m. The bridge was inundated by approximately 0.3 m above the surface of the bridge deck. Similarly, a recent study by Ganiyu *et al*. (2022) showed that 33% of the flood-prone areas of the Ona River have a flood stage above 2 m.

Furthermore, the predicted flow (75.25 m^3/s) was compared with the corresponding flow value in ERA (2002) for a free board minimum clearance. It was revealed that Alaafin Avenue Bridge is safe with flood clearance of approximated value of 2 m while Seven-Up and Oluyole bridges are not safe, as they are prone to inundation by predicted flood clearance values of 0.3 m and 0.5 m respectively.

Conclusion

This study presents a systematic approach for modelling bridges along the Ona River in Ibadan using a one-dimensional HEC-RAS model. The geometric features of the study area were digitized from the Digital Elevation Model in HEC-GeoRAS, which is an extension of ArcGIS. Likewise, the SWAT model was used to predict steady flow with meteorological data. The geometric features, including the river centerline, bank lines, flow paths, and bridges, and the predicted steady flow of 75.25 m^3/s served as model input data in the HEC-RAS, which predicted the flood level of the modelled bridges. The results were examined in reference to ERA (2002), and it was concluded that only the Alaafin Avenue Bridge is safe, while the Seven-Up and Oluyole bridges are prone to inundation. Therefore, regular inspection and maintenance of the bridges are recommended to prevent inundation.

References

Adeogun, A. G., Ganiyu, H. O., Ladokun, L. L. and Ibitoye B. A., (2020) Evaluation of hydrokinetic energy potential of some selected rivers in Kwara State, Nigeria. *Environmental Engineering Research*, 25 (3): 267-273.

Amulya, T., Dhanashree, N. and Rajashri, M., (2018) Hydrological analysis for proposing new bridge at Vrishabhavathi River Valley, Laggere. *International Journal for Research in Applied Science & Engineering Technology*, 6(1): 743-749.

Birhanu H, G. and Vijaykumar, N., (2020) Hydrological analysis for the proposed bridge at South Wollo Ethiopia. *International Journal of Scientific & Technology Research*, 9(9): 66-71

Balasubramanian, A. (2017). Bridges and their types. Technical Report, Centre for Advanced Studies in Earth Science, University of Mysore, Mysore. Retrieved on September 12, 2022, from http://dx.doi.org/10.13140/RG.2.2.18109.46566.

Brandimarte, L., Woldeyes, M. K. (2013) Uncertainty in the estimation of backwater effects at bridge crossings. Hydrological Processes, 27: 1292-1300.

Chavel, B. W. and Yadlosky, M. J. (2011) Framework for improving the resilience of bridge design. *U.S. Dept. of Transportation, Federal Highway Administration, Washington, D.C.*

Choudhury, J. R. and Hasnat, A. (2015) Bridge collapse around the world: causes and mechanisms. Joint Conference on Advances in Bridge Engineering-III, August 21-22, 2015, Dhaka, Bangladesh.

Delatte, N. (2010) Failure literacy in structural engineering. *Eng. Struct.*, 32(7), 1952-1954.

Ede, A., Nwankwo, C. O., Oyebisi, S., Olofinnade, O., Okeke, A. and Busari, A. (2019) Failure trend of transport infrastructure in developing nations: Cases of Bridge Collapse in Nigeria. *IOP Conf. Ser.: Mater. Sci. Eng*. 640 012102. DOI 10.1088/1757-899X/640/1/012102.

Elufioye, A., (2016) Environmental and social impact assessment (ESIA) for emergency rehabilitation of Eleyele Dam, Ibadan, Oyo State. Retrieved on December 8, 2020, from https://documents.worldbank.org/.

Ganiyu, H.O., Adeogun, A.G. Bakare, S.B. and Aremu, A.S. (2022) Effectiveness of GIS-based approach for flood hazard assessment of Ona River, Ibadan, Nigeria. *Acta Technica Corviniensis – Bulletin of Engineering*, 15(2): 63-66.

GLCC. Global Land Cover Characterization. Retrieved on September 12, 2020, from http://edc2.usgs.gov/glcc/glcc.php.

Heilemariam, F. M., Brandimarte, L. and Dottori, F. (2013) Investigating the influence of minor hydraulic structures on modelling flood events in lowland areas. *Hydrological Processes*, 28: 1742-1755.

Isreal, A. O (2017) Nature, the built environment and perennial flooding in Lagos, Nigeria: The 2012 flood as a case study. *Urban Climate*, 21: 218-231.

Loucks, D. P. and Van Beek, E. (2005) Water resources systems planning and management: an introduction to methods, models, and applications. Retrieved on September 10, 2020, from https://link.springer.com/book/10.1007/978-3-319-44234-1.

Nachtergaele F, Velthuizen HV, Verelst L. (2008) Harmonized World Soil Database (HWSD). Food and Agriculture Organization of the United Nations. FAO, Rome, 2008. IIASA, Laxenburg, Harmonized World Soil Database (version 1.1).

Oliver, K., Yonnana, E., Philemon, W., Bobboi, I., Umar, A. and Matapa, J. (2021) Assessment of the hydraulic geometry of River Yedzeram at Lokuwa Bridge, Wuro-Gudeand Wuro-Mayo channel section, Adamawa State, Northeast Nigeria. *International Journal of Advances in Engineering and Management (IJAEM)*, 3(2): 634-643.

Patra, J. P., Kumar, R. and Mani, P. (2022) Hydrologic and hydraulic modelling of a bridge. *Hydrological Modelling*, 317–326.

Pochpande, S., Goswami, Y., Rajnor, V., Shirsath, S., Gangurde, M., Malik, K. and Boki, S. (2019) Innovative methodology for developing analytical hydraulic model of bridge. *Journal of Emerging Technologies and Innovative Research (JETIR)*, 6(3): 64-68.

Sina, A. (2009) River modelling for flood risk map prediction: a case study of Sungai Kayu Ara. Published thesis submitted to Universiti Sains Malaysia. Retrieved on November 18, 2020, from https://core.ac.uk/download/pdf/32599786.pdf.

Siregar, R. I. (2018) Hydraulic modelling of flow impact on bridge structures: a case study on Citarum bridge. IOP Conf. Series: Materials Science and Engineering 309 (2018) 012015

Sredojevic, D. and Simonovic, S. P. (2009) Hydraulic Modelling and Floodplain Mapping. Water Resources Report, Department of Civil and Environmental Engineering, University of Western Ontario, Canada.

Wang, Z., Patgett, J. E. and Osorio, L. D. (2014) Risk-consistent calibration of load factors for the design of reinforced concrete bridges under the combined effects of the earthquake and scour. Hazards Elsevier, 79: 86-95.