
FLOOD INUNDATION RISK ASSESSMENT OF AN EARTHEN DAM UNDER PIPING FAILURE USING HEC-RAS AND QGIS:

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ABSTRACT

This study presents the flood inundation risk evaluation of the dam formerly called Kubanni, an earthen dam with a water catchment area of 57 km², situated in Zaria area, Kaduna State, Nigeria. The research aims to explain the pattern of dam breach by modeling it in three different return periods, (30, 50, and 100 years) and the hazard posed by the dam. HEC-RAS with QGIS software was used to run unsteady flow simulation of the dam break for piping failure. The breach parameters like the width of the bottom, the slope on the sides, and the time to formation were all obtained using empirical regression equations of Froehlich (2008), and as a result, the downstream hazard was mapped in several risk zones. The discharges during breach were 1,426.56m³/s, 1,697.71 m³/s, and 1,758.04 m³/s respectively for the three events. The flood events lasted for approximately 1 hour (30 and 50 year return periods) and 3 hours (100-year return period). The floodwater covered a distance of more than 10 km with Zango, Hanwa, Yan Karfe, and parts of Northeast Tudun Wada showing high flood vulnerability. Approximately 2,705 residences and several croplands located along the floodplain are in great danger from floods. The flood water took the minimum time of 10 sec reaching the nearest zone against the farthest zone where the water reached after 20min at the fastest depth level of 16.3m. These findings can assist dam safety management, land use regulation, and even the establishment of an early warning system at community level in other regions with similar challenge not monitored well.

Keywords: dam break analysis; piping failure; flood inundation mapping; ABU Dam

1 INTRODUCTION

Dams are probably the most strategically important of all hydraulic structures. By controlling the river flow, they provide irrigation, domestic water supply, industrial water use and downstream flood attenuation services, which together form the basis of livelihoods for the million people around the world. (Alhassan et al., 2019) stated the benefits of dams in the provision of these water services. However, it is the very energy that the reservoir releases that the structural failure would have devastated effect. There is dam failure recorded on all inhabited continents, and some have had only crop losses, while others have resulted in total destruction of communities in the downstream areas (Aureli et al., 2021). More exactly, in Nigeria, the majority (>81%) (Umaru et al., 2010), the dam types vulnerable to two dominant failure mechanisms: overtopping and internal erosion (piping). Piping is very dangerous because the failure might even pass unnoticed until a catastrophic collapse happens. (Foster et al., 2000) From the study and analysis of dam failure databases on a worldwide scale, the percentage of internal erosion in embankment dam failures is around 40% (Jandora & Riha, 2009). This amplifies more the impacts in cases of dam failures in the West Africa due to factors like: downstream urban settlements being more dense; agricultural plots close to floodplains; and unavailability of an early warning system and associated infrastructure(Okeola et al., 2025).

Kubanni Dam was originally known as ABU Dam before being incorporated into the water supply system of Ahmadu Bello University (ABU). The dam is a simple earthwork built along the Kubanni River in Zaria, Kaduna State, Nigeria (Latitude: 11°08'03.18" N Longitude: 7°39'15.67" E). Given that the dam has a catchment area of 57 km², average water depth of 6 m, and a reservoir volume

of more than 2.6 million m³ of water at normal water level, it gives the main water resource for the university campus and various nearby communities. Even though this dam is very essential for the people who are getting settled in the city at a fast pace, prior research on the topic of dam breaks and quantitative risk of downstream floods was not published about the structure until this study. As a result, emergency planners, Dam safety engineers, and community heads are unable to develop reliable response strategies without the relevant information.

This study addresses the identified research gap by developing an integrated dam-break assessment framework for Zaria Dam using HEC-RAS unsteady-flow hydraulic modelling and QGIS-based spatial analysis. The study simulates a piping-induced dam failure under 30-, 50-, and 100-year return-period inflow conditions to evaluate potential downstream flood hazards. Unlike previous studies, this research provides the first comprehensive dam-break assessment for Zaria Dam by integrating HEC-RAS hydraulic modelling with GIS-based inundation mapping and google satellite basemap imagery to improve the delineation, visualization, and interpretation of flood-prone areas. Furthermore, the study incorporates community-level risk characterization to support dam safety assessment, emergency planning, and informed decision-making for downstream communities. It further evaluates multiple hydrological return periods to capture the influence of increasing flood magnitude on downstream hazard, thereby offering a more comprehensive assessment than studies based on a single design event. The adopted framework is consistent with recent applications of HEC-RAS and GIS for dam-break assessment in data-scarce environments (Beza et al., 2023; Mo et al., 2023), while extending their application through a site-specific multi-scenario risk assessment for eleven downstream communities. Consequently, the study provides a practical decision-support framework for dam safety management, land-use planning, and emergency preparedness in the Zaria region.

1.1 Historical Context of Earthen Dam Failures

Today in Africa, most earthen dams that were poorly maintained, have been built in the 1960s to 1980s through post-independence development programs, pose a growing safety threat as they confront changing rainfall patterns through their deteriorating infrastructure (Moreno-Rodenas et al., 2025).

In the country, a failed Cham Dam incident at Gombe State is a notable example: an inadequate spillway capacity coupled with seepage-induced internal erosion caused a sudden major breach, which resulted in the large death toll downstream and damage of property (Umaru et al., 2010). Generally, a major problem with many dams in the sub-Saharan area is lack of maintenance or safety checking of dams and only slow adoption of quantitative methods for predicting breaches so that local residents living near old embankment dams rarely know how much danger they face (Okeola et al., 2025).

1.2 Mechanisms of Embankment Dam Failure

Two failure mechanisms dominate embankment dam loss: overtopping and internal erosion. Overtopping occurs when reservoir levels surpass the dam crest, typically during inflow floods that exceed spillway design capacity or when debris blocks the spillway. The uncontrolled flow of water over and down the downstream face rapidly initiates erosion of the embankment material, a process that accelerates non-linearly until breach formation is complete (Jandora & Riha, 2009). For small catchment dams such as ABU Dam, a single extreme precipitation event can generate inflows that exceed the design discharge standard, making overtopping a credible scenario even at moderate return periods.

The second type of failure mechanism -internal erosion- occurs through a form of internal "piping". It typically starts in those parts where the permeability of materials is higher or in case the dam is built on an impermeable layer (Jandora & Riha, 2009) (e.g. in case of leakage). It is the so called "piping." The fine soils particles get washed from the source location and are taken further downstream until a bigger and bigger channel is created. At a certain point the velocity of the flow of the particles is so high that the particles themselves help in forming the channel, making the process almost endless until the failure of the dam structure (Foster et al., 2000).

In reality, this piping failure mode has a reinforcing loop to the dam can go from a perfectly good working condition to complete failure in a matter of seconds. As (Zhang, et al., 2007) researched,

if the reservoir level is raised then there is an enhancement in the hydraulic gradient resulting in an increase in the likelihood of the pipe starting. This is mainly important for ABU Dam, where the reservoir capacity is always near full during the rainy season. Piping was the primary failure mechanism considered for this dam because the spillway has adequate capacity for the design flood, based on (Bharath et al., 2021); as a result, spillway overtopping due to flood was not considered a likely failure mode. That means internal erosion like piping is much more likely scenario for triggering the failure in this dam than the external ones like overtopping.

1.3 Dam Break Analysis

One of the most popular platforms for performing both steady and unsteady flows in one-dimensional (1D) and two-dimensional (2D) cases is HEC-RAS developed by and under the control of US Army Corps of the Engineers Hydrologic & Hydraulic Engineering Center. The breach modeling capacity of this tool has been found applicable to various dam types and locations including earthen dams in Africa (Beza et al., 2023; HEC, 2023). Newer research shows that for rivers having clearly defined cross-sectional geometry, it is still valid to rely on 1D HEC-RAS model to simulate flows and that the results it generates are detailed enough to help with EAP creation even when further GIS processing is done on them (Mo et al., 2023)

GIS-based spatial analysis Mostly through QGIS is being increasingly used for creating risk maps that can be used for risk reduction and management efforts. HEC-RAS outputs together with satellite images and digital elevation maps can be used as reference inputs for inundation areas classification and quantification in the GIS environment, about land use types and settlement density (Aureli et al., 2021)

2 MATERIALS AND METHODS

ABU Dam (Kubanni Dam), a gravity earth dam, was built in 1970s in the Kubanni River Zaria Kaduna State, Nigeria of Ahmadu Bello University (Yusuf, 2013). The dam is located in a watershed which is covered mainly in savannah vegetation, rolling hills, and seasonally changing water flow regime. (Yusuf, 2013) After the dam, the Kubanni valley becomes a narrow flood plain and then extends to a peri-urban area with a high population density, residential houses shops market places gardens small farms and schools. This study did not include overtopping failure as a consideration. The Kubanni (ABU) Dam has a central spillway that is sufficient to carry design flood inflows so overtopping would be practically impossible failure pathway for the scenarios presented. Piping failure was, because of this, considered as the main failure mechanism that matches the dam's physical condition and that is in line with practice for embankment dams whereby internal erosion is the more likely failure mode than crest overtopping. Table 1 describes the main structural and geometric features of the dam.

Table 1: Key structural and geometric parameters of ABU Dam (Kubanni Dam), Zaria

Parameter	Value
Location	Latitude: 11°08'03.18" N Longitude: 7°39'15.67" E, Zaria, Kaduna State, Nigeria
Dam Classification	Earthen embankment
Top of Dam Elevation	645.38 m a.s.l.
Breach Bottom Elevation	632.53 m a.s.l.
Dam Crest Width	5 m
Mean Water Depth	6 m
Crest Length	122 m
Catchment Area	57 km ²
Reservoir Capacity	~2.6 × 10 ⁶ m ³
Upstream Face Slope (Z1, H:V)	1:2.5
Downstream Face Slope (Z2, H:V)	1:2
Pool Volume at Failure	22,600 × 10 ³ m ³

2.1 Data Acquisition and Terrain Representation

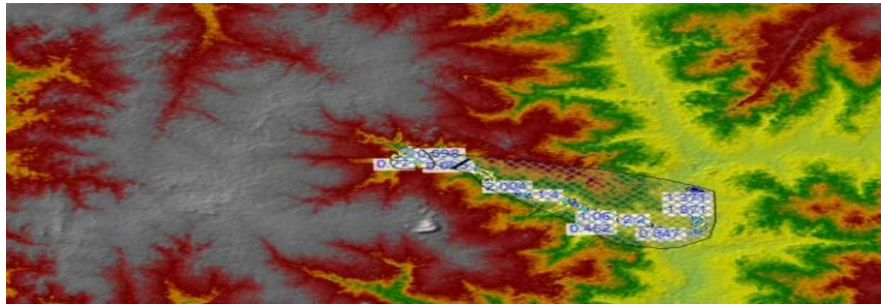


Figure 1: DEM of ABU Dam

The datasets and model inputs used in the hydraulic simulation are summarized in Table 2. A 30 m Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) was adopted to represent the terrain (Farr et al., 2007)). The DEM was georeferenced in ArcGIS 10.8 to match the HEC-RAS coordinate system following established georeferencing procedures. River cross-sections and overbank geometries were extracted from the processed DEM and incorporated into the HEC-RAS geometry file. Manning's roughness coefficients for the channel and floodplain were assigned based on field observations and published values for similar savanna environments (Salah Abd Elmoaty & T. A., 2020) The reservoir elevation–storage relationship required for level-pool routing was generated from DEM-derived contours and imported into HEC-RAS as a Storage Area Elevation–Volume table initialized at the normal operating level.

Table 2: Summary of inputs

Input	Purpose in the Study	Source	Reference
Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (30 m)	Extraction of terrain elevation, watershed topography, channel geometry, and reservoir characteristics	NASA Shuttle Radar Topography Mission (SRTM)	Farr et al. (2007)
River cross-sections and overbank geometry	Development of HEC-RAS geometric model	Extracted from the georeferenced SRTM DEM using ArcGIS 10.8	Derived from SRTM DEM (Farr et al., 2007)
Manning's roughness coefficient	Hydraulic resistance assignment for channel and floodplain	Field observations and published values for comparable savanna environments	Salah Abd Elmoaty & T.A. (2020)
Elevation–Storage (Elevation–Volume) relationship	Level-pool routing and reservoir storage definition	Derived from DEM contours and entered into HEC-RAS as a Storage Area Elevation–Volume table	Derived from SRTM DEM (Farr et al., 2007)

2.2 Breach Parameter Estimation

The HEC-RAS parameter calculator is used for comparing five empirical formulas for predicting breach of pipe failure by failure modes: MacDonald and Langridge-Monopolis (1984), Froehlich (1995), Froehlich (2008), Von Thun and Gillette, and Xu and Zhang. The dam geometry and reservoir features were put up in the connection data editor. HEC-RAS calculated internally the reservoir volume and the breach height needed for each regression method; the estimated breach parameters are displayed in Table 2. The Xu and Zhang method resulted in unrealistic numbers of a

breach width of 6080 m, and a negative side slope for a rather small reservoir size that was discarded from further consideration.

The equations by Froehlich (2008) have been accepted as the design-reference parameters mainly because they stem from the most substantial checked failure database that the methodological independence of these formulas has been proven through reliable operation for earthy dams having approximately the same geometry in recent papers (Beza et al., 2023; Bharath et al., 2021) the formulas are the only ones formally acknowledged by the US Army Corps of Engineers for standard dam safety assessments. The average breach width (B_{avg}) and the breach formation time is:

$$B_{avg} = 0.27 K_o V_w^{0.32} h_b^{0.04} \quad \text{equation I}$$

$$t_f = 63.2 \sqrt{\frac{V_w}{g h_b^2}} \quad \text{equation II}$$

Table 3: Breach parameters for ABU Dam estimated by five empirical methods (piping failure mode)

Method	Breach Bottom Width (m)	Side Slope (H:V)	Formation Time (hrs)
MacDonald & Langridge-Monopolis (1984)	2	0.5	0.26
Froehlich (1995)	126	0.9	6.83
Froehlich (2008) — Selected	132	0.7	2.99
Von Thun & Gillette	49	0.5	0.25
Xu & Zhang (excluded)	6,080*	—*	—*

* Xu & Zhang result is physically implausible for this dam geometry and was excluded from further analysis.

2.3 HEC-RAS Modelling Framework

The one-dimensional unsteady flow model of HEC-RAS version 6.3.1 follows recent practice for comparable earthen dam analyses (Beza et al., 2023; Mo et al., 2023) The simulation setup covered the whole system from the reservoir storing area going through the connecting structure of breach between storage areas, and ending at downstream channel outflow boundary. Cross-section spacings were 100 to 500 m varying with topographic complexity. The storage area for the reservoir was bridged by an inline breach structure to the downstream routing reach through which boundary conditions for the upstream inflow hydrograph and downstream normal depth were provided. Separate unsteady flow simulations were run for return periods of 30, 50, and 100 years, each started from a steady-state base flow condition. The model variables that were exported for post-processing were mainly the breaching width, breaching flow, time-series records of velocity and water surface elevations at headwater and tailwater reference points; while flood depth raster, velocity, and elevation outputs at water surface were produced through RAS Mapper tool.

2.4 QGIS Spatial Analysis and Inundation Mapping

Raster outputs from RAS Mapper were exported and imported into QGIS version 3.61 for spatial classification and risk mapping. Google Satellite Hybrid imagery, accessed via the QuickMapServices plugin, provided high-resolution visual context for identifying built-up areas and land use types. (QGIS.org, 2019) Flood-depth rasters were classified into risk bands and overlaid on satellite imagery to produce flood inundation maps for each return period. Eleven downstream risk zones Areas 1 through 11 were manually delineated by digitizing visible residential and agricultural extents, with boundaries validated against available administrative boundary data. For each zone, maximum flood depth, inundated area, estimated number of exposed residential structures, and flood arrival time were extracted from the QGIS attribute table and compiled into the risk assessment matrix presented in the results section. This spatial analytical approach is consistent with current best practice for inundation mapping in data-scarce African contexts (Ekeu-Wei & Blackburn, 2018).



Figure 2: Satellite view of the area

3 RESULTS AND DISCUSSION

3.1 Breach Hydrograph Characteristics

Unsteady flow simulation produced time-series outputs for each return period scenario capturing the complete breach sequence from initial piping to recession. In all three scenarios, the breach progression follows a consistent three-phase pattern: (i) an initial quiescent period during which the piping orifice is small and outflow is limited; (ii) a rapid intensification phase during which breach width and outflow accelerate to their respective peaks; and (iii) a recession phase in which the depleted reservoir is unable to sustain peak discharge and outflow gradually diminishes. This tripartite temporal structure is consistent with the theoretical piping failure process described by (Jandora and Riha 2009) and with empirical hydrograph patterns documented in recent HEC-RAS dam break studies (Mo et al., 2023; Beza, 2023).

For the 30-year return period, the breach peak occurred at 0:59:52 hours, at which point breach width measured 31.14 m, total flow reached 1,426.56 m³/s, and velocity through the breach was 4.51 m/s. By the recession phase at 02:59:45 hours, breach width had expanded to its maximum of 40 m as the breach stabilized, outflow had fallen to 454.00 m³/s, and velocity had declined to 2.77 m/s.

The 100-year scenario exhibited a qualitatively different character. While initial and recession conditions were broadly comparable to the shorter return periods, the peak discharge of 1,761.71 m³/s occurred much later, at 02:59:45 hours. This delayed peak reflects the substantially larger reservoir volume accumulated during the 100-year inflow event prior to failure initiation; notably, it is the timing of the peak that shifts markedly with return period, while its magnitude increases only modestly relative to the 50-year event. This is consistent with (Aureli et al. 2023), who documented that breach-outflow timing can be more sensitive to antecedent pool volume than peak magnitude at the upper end of the return period range. Table 4 summarizes the peak hydrograph values across all three scenarios.

Table 4: Summary of peak breach hydrograph characteristics by return period

Return Period	Peak Discharge (m ³ /s)	Peak Velocity (m/s)	Breach Width at Peak (m)	Time to Peak	Headwater Elevation (m)	Tailwater Elevation (m)
30-year	1,426.56	4.51	31.14	00:59:52	642.91	637.41
50-year	1,697.71	4.56	31.14	00:59:52	643.16	637.48
100-year	1,761.71	4.44	31.14	02:59:45	643.00	637.15

3.2 Flood Inundation Extent

Across all three return periods, the flood wave propagated approximately 10 km downstream from the dam face, inundating communities from Zango in the immediate downstream reach to Sabon Gari Zaria at the distal limit of the modelled domain. This spatial extent is consistent with the travel distances documented for comparable small-to-medium earthen dam failures in West Africa (Salimon et al., 2023) and with analytical wave-celerity estimates for the observed peak discharges and channel geometry.

As expected, higher return periods produced greater inundation depths and slightly broader flood extents. The velocity and water-surface elevation rasters from RAS Mapper show that energy dissipation over the lower-gradient sections of the downstream reach generates the deepest inundation in mid-to-distal zones, where the flood wave encounters the widening valley floor. This pattern is present across all three scenarios, with the modestly higher peak discharge and delayed timing of the

100-year event generating somewhat deeper inundation in several zones relative to the 30- and 50-year events. The inundation maps produced for the three return periods (30-year, 50-year, and 100-year) show distinct flood depth, velocity, and water-surface-elevation layers, each providing spatially explicit information for emergency planning purposes.



Figure 3: Flood Inundation extent.

3.3 Downstream Risk Assessment

Table 5 presents the comprehensive risk assessment results for the eleven delineated downstream zones. Two findings are particularly significant for emergency planning. First, flood arrival times are extremely short. Even in the most distant zone (Area 11), located approximately 10 km downstream of the dam, the flood wave arrives in under 20 minutes under the 30-year return period scenario, while the nearest communities (Areas 1–3) experience inundation within the first minute. These results indicate that downstream residents would have little or no opportunity for spontaneous evacuation following a dam breach, making real-time monitoring and automated warning systems essential. Arrival times in some zones (e.g., Areas 4 and 5) converge or remain nearly identical between the 50- and 100-year scenarios rather than continuing to decrease; this is consistent with the flood wave in these zones approaching the channel's hydraulic capacity, beyond which additional inflow increases depth and discharge more than it increases wave-front speed. This finding is consistent with previous Nigerian dam-break studies. Comparable Nigerian dam-break studies have applied HEC-RAS to downstream reaches of approximately 11–12 km, including the Oyan River and Asa Dam systems, highlighting the importance of short downstream reaches in assessing potential flood impacts and emergency preparedness (Balogun & Ganiyu, 2016; Olanipekun et al., 2026)

Table 5: Inundation risk metrics for eleven downstream zones under three return period scenarios (Arrival columns give incremental travel time between consecutive zones, not cumulative time from the dam)

Area	Inund. Area (km ²)	Houses at Risk	Max Depth 30yr (m)	Max Depth 50yr (m)	Max Depth 100yr (m)	Arrival 30yr	Arrival 50yr	Arrival 100yr
1	0.79	325	9.01	11.57	11.34	00:00:16	00:00:10	00:00:10
2	0.19	47	5.05	8.47	8.24	00:00:42	00:00:35	00:00:34
3	0.20	30	4.92	8.27	8.12	00:00:56	00:00:50	00:00:46
4	0.63	18	4.60	8.19	10.51	00:01:15	00:01:07	00:01:07
5	0.57	35	9.04	11.74	11.06	00:01:39	00:01:33	00:01:07
6	0.50	250	6.32	9.13	8.03	00:02:10	00:01:47	00:01:22
7	0.32	500	4.00	7.49	10.25	00:02:41	00:02:00	00:01:38
8	0.88	400	8.81	10.40	10.48	00:03:38	00:02:13	00:02:02
9	2.55	300	8.49	10.33	10.04	00:04:00	00:02:30	00:02:22
10	3.21	600	14.88	13.20	12.87	00:06:37	00:03:20	00:03:13
11	0.46	200	15.00	16.26	16.31	00:07:08	00:06:00	00:04:05

The second major finding is the severity of downstream inundation. Maximum flood depths exceed 9 m in Areas 1, 5, 8, 9, and 10 under the 30-year scenario and increase to over 15 m in Areas 10 and 11 under the 100-year scenario, indicating catastrophic flooding capable of causing extensive

shortcoming is that breach characteristics were taken from Froehlich's (2008) empirical regression equations, which although validated against the largest database of failures, the equations are subject to inherent uncertainty of the parameters. The third factor is that our hydraulic simulation was based on a relatively low-resolution DEM (30 m SRTM) which results in a decreased precision of capturing the smallest variations (microtopography) of a floodplain, so possibly changing how deep and far the floodwater is spreading at individual places. Because the 2,705-residence exposure estimate is derived directly from the extent of these depth rasters, it carries the same resolution-dependent uncertainty: at a 30 m cell size, individual structures and narrow drainage features smaller than one pixel cannot be resolved, so the true count of exposed residences in the actual floodplain likely deviates from this estimate, with the direction and magnitude of that deviation unverified without a finer-resolution DEM (e.g., LiDAR or sub-10 m satellite-derived terrain data) for comparison. Fourth, in our assessment of downstream people exposed (i.e. houses and farmlands) we only considered static land-use data which Yet, cannot record recent or informal residential or commercial development with Zaria floodplain.

5 RECOMMENDATIONS

Based on the findings, the recommendations to be considered are: (i) Installing automated, real-time, early-warning systems at the dam and downstream for the limited warning windows, Mostly in the nearest zones, which were extremely short; (ii) Drawing up and testing community-level Emergency Action Plans regularly, including holding evacuation drills for each of the eleven identified risk zones; (iii) Enforcement of land-use zoning to disallow more residential and agricultural development in the high-risk floodplain area determined; (iv) Regular safety inspection and equipping the dam (e.g. installation of piezometers, seepage monitoring) to detect signs of piping and structural problems in the building of the dam at an early stage; and (v) The future studies should combine overtopping failure scenarios, higher resolution terrain data, and updated land-use/population datasets to refine the risk estimates.

6 CONCLUSIONS

This research paper is the first to report a dam-break, breach-modelling-based flood inundation risk assessment of Kubanni (ABU), a Dam in Zaria, Nigeria. It uses a HEC-RAS, QGIS model under a scenario when water is escaping through a pipe or any small opening (piping failure mode) and considering return periods of 30, 50, and 100 years. Breach factors (width 132 m, side slope 0.7H:1V, formation time 2.99 hours) came from Froehlich's (2008) equations, chosen following a joint assessment with four other empirical models. Peak breach discharges of 1,426.56 m³/s, 1,697.71 m³/s, 1,761.71 m³/s were modelled for these scenarios giving rise to a flood that swelled so much that it reached settlements downstream from Zango to Sabon Gari, which were about 10.3 km large (through 11 risk zones), and where 2,705 houses as well as vast areas of cropland have been identified as being at risk of high flood. The shortest duration of flood arrival, as fast as 10 seconds, was in a zone very close to the dam while in the farthest zone it took about 20 minutes. These results demonstrate a very limited time margin in case of emergency evacuation of the population. So, such work should be useful not only for dam safety but also for regulation of land use besides community-level early-warning systems in Zaria and similar less-observed river basins in the area.

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