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Dam breach analysis of Kibimba Dam in Uganda using HEC-RAS and HEC-GeoRAS

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Abstract

Dam failures have severe consequences on human life and property. In the case of an earth filled Kibimba Dam located in Eastern Uganda, the occurrence of a flood equal to or larger than the probable maximum food (PMF) could result in catastrophic economic losses including loss of human life. This study utilized the USACE Hydrologic Engineering Center's River Analysis System (HEC-RAS) and Hydrologic Engineering Center's Geographic River Analysis System (HEC-GeoRAS) to analyze the potential dam break of Kibimba Dam, considering overtopping and piping failure scenarios. The results of the analysis revealed that the spillway of Kibimba Dam possesses sufficient capacity to safely discharge a flood resulting from a probable maximum flood peak of 400 m^3/s. Therefore, the dam is not susceptible to breach under the overtopping failure mode. However, the dam failed under the piping failure mode. To assess the downstream impact of the dam break, the breach hydrographs resulting from piping failure were examined. Consequently, the study investigated the effects of flood propagation downstream of the dam. This resulted in varying inundation depths of up to 6 m and velocities ranging from 1.2 to 10 m/s. These findings highlight the devastating consequences of Kibimba Dam's failure, particularly affecting rice field plantations, infrastructure, and other economic activities in the downstream area. Therefore, the outcomes of this study are crucial for the development of Emergency Action Plans that incorporate dam breach and flood routing analyses specific to the affected downstream regions.

Keywords Dam breach, HEC-RAS, HEC-GeoRAS, Kibimba

Introduction

Dams are hydraulic structures built across the water course creating a reservoir in which water is stored to serve multiple purposes such as; flood risk management, navigation, hydropower generation, water supply for municipal and industrial, irrigation, fish and wildlife, low flow augmentation, and recreation (USACE 2016). Despite their positive impacts, when dams fail, they jeopardize the environment and public safety. During the past years, numerous dam failures have caused property damage and loss of human lives. For example; Banqiao Dam and the Shi-mantan Dam failure in 1975 claimed the lives of around 85,000 people in China (Sachin 2014), Patel Dam burst claimed the lives of 41 people leaving 2000 others homeless in Kenya (Soy 2018), Merriespruit tailings dam in South Africa killed 17 people and demolished several houses (Tail Pro Consulting 2002). Other dams whose bursting disrupted the environment and public safety include; St. Francis Dam (Rogers 2006), Buffalo Creek Dam (Gee 1999), Canyon Lake Dam (National Weather 2015), Teton Dam (Graham 2008), Kelly Barnes Dam (Sowers 1978), and Lawn Lake Dam (Root 2018).

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Failure of dams may be due to earthquakes, overtopping (spillway capacity insufficient during large inflows), extreme storms, foundation failures, piping and seepage through the dam or along internal conduits. Of these, overtopping is the most common cause of earth-filled dam failure (Khosravi et al. 2019). According to Ackerman & Brunner (2005), knowledge of the subsequent flood wave attributes and the area inundated can help alleviate the probable loss of lives and property damage likely to occur during a disastrous dam failure. This could be through using the flood results to develop contingency response plans and future land use planning. Tail Pro Consulting (2002) suggested that the Merriespruit tailings dam failure could have been prevented if an appropriate operating manual and emergency plan for the dam was existing and been implemented effectively. These floods often times lead to loss of lives and destruction to properties such as destroy properties including houses (Kiwanuka et al. 2021). Kumar et al. (2017) proposed analyzing the behavior flood based on the observed floods before suggesting possible flood management measures. All these are premised on providing knowledge concerning flood-prone areas which aids in the development of warning systems and evacuation plans (Ríha et al. 2020).

Several researchers and organizations have put up their findings to deal with the subject of dam break analysis modelling. They have developed several models for example; BRDAM model (Brown & Rogers 1981) used to perform erosion simulation of an earth dam in the event of overtopping or internal erosion, BREACH and Dam Breach Forecasting model (DAMBRK), National Weather Service dam-break flood forecasting model (NWS DAMBRK), numerical model (Jonathan & Fread 1984), empirical formulae, analogy, and hydraulic modeling (Ríha et al. 2020), and HEC-RAS model (Brunner 2014). Recently, HEC-GeoRAS and HEC-RAS have become prevalent in model building and analysis of the flooded area using geographic information systems (GIS), and modeling dam failure scenarios respectively. This could be attributed to the availability of terrain data and the ease in developing hydraulic models which can simulate a dam breach scenario and assess the consequential flood wave (Ackerman et al. 2005; W. S. Mohammed-Ali & Khairallah 2022). Leoul & Kassahun (2019) applied HEC-RAS and HEC-GeoRAS in analyzing the dam breach of Kesem Kebena dam. The study found out that the spillway has sufficient capacity for the flood resulting from the probable maximum flood (PMF). Using the HEC-RAS model, Mohammed-Ali et al. (2021) investigated the riverbank uncertainty consequential to the discharge difference of hydropower plants. HEC-RAS was similarly applied by Mohammed-Ali et al. (2021) to analyze the effects of outflow features upsetting the stability of lower Osage riverbank. Mehta & Yadav (2017) used HEC-RAS model to evaluate the flood conveyance performance of River Tapi. Within Uganda, Eyiiga (2019), applied HEC-RAS to model dam breach and flood inundation mapping of Bujagali Dam in Uganda. Other studies where HEC-RAS was applied in Dam Breach analysis include; Belay, (2017); Raman & Liu, (2019); and Xiong, (2011).

Kibimba dam was constructed with a government's initiative of increasing food production and improve people's livelihood within the country. This dam could break and cause huge economic and human life losses if a flood equal to or larger than the probable maximum flood occurred. Prior to this study, no study was conducted to analyze the dam breach analysis for the Kibimba dam. To provide necessary information to dam operators and policy makers, this study aimed at estimating the dam breach outflow hydrograph, routing the dam break hydrograph through the downstream river reach and floodplain and computing the inundation water depth and time of Kibimba dam. The findings of a dam break analysis are vital in preparation of inundation maps which foster the planning and implementation of precautionary measures, monitoring systems and Emergency Action/ evacuation Plans during a flood crisis.

Study area

Kibimba dam (Fig. 1) is an earth filled dam located on River Kibimba in the Victoria basin in Uganda. It has an open water surface area of 4.5 km^2, constructed to provide irrigation water to 450.23 Km^2 of Kibimba rice scheme. The area receives and experiences small variation in temperature, humidity, and wind throughout the year. It lies at an average elevation of 1176 m above sea level receiving a moderately high annual rainfall of 900–1400 mm distributed between two rainy seasons, late February-June and August-November, with a peak in April (BirdLife 2021).

Data

The study is based on existing Meteorological, hydrologic, and topographic data collected from different organizations. Hydrologic data of Kibimba River including Probable Maximum Flood (PMF), inflow hydrograph, outflows of spillway and base flow, and physical dam data (Table 1 and Fig. 2) that is; reservoir capacity and reservoir storage versus elevation curve were obtained from Tilda Uganda limited- a company operating the dam on behalf of the ministry of water and environment.

Methodology

Dam breach parameter estimation

Estimation of the breach characteristics is so vital as they impact the accuracy of the outflow hydrograph and

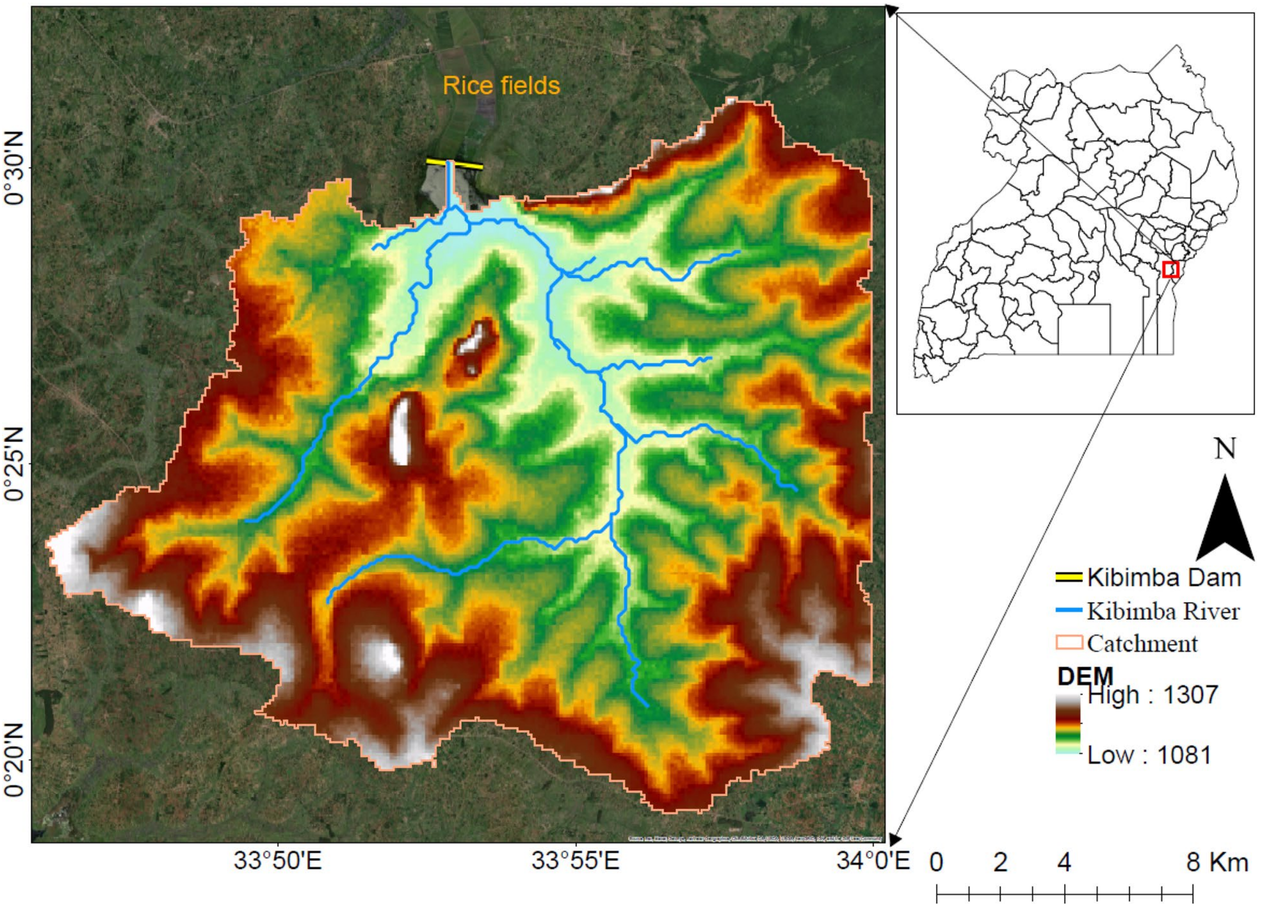

Fig. 1 Location of Kibimba dam

Table 1 Physical data of Kibimba Dam (Source: Tilda Uganda limited)

Dam properties	Description
Length of the dam crest (m)	1200
Width of the dam crest (m)	5
Spillway length (m)	80
Maximum height of the dam (m)	4.5
Spillway discharge capacity (cum/sec)	80
Reservoir capacity (Mm^3)	15.1
Sluice gate opening (m)	2.2 × 0.6

downstream inundation (Leoul 2015). These estimation techniques are; Comparative analysis (compares the dam with historical dam failures), Regression-based methods (based on data collected from historical dam failures), and Physically-based simulation models, Regression-based methods (MacDonald & Langridge-Monopolis, (1984) and Froehlich, (2008 & 1995) equations, Von Thun & Gillette, (1990), Singh & Scarlatos, (1988) and Xu & Zang, (2009) equations) and utilization of velocity versus erosion rates (Brunner 2014).

Physically-based numerical models for example; BREACH program (Fread 1988), require more comprehensive information of the soil properties which was scanty for the case of Kibimba dam. Additionally, these models rely on bed-load type erosion formulas, making them suitable for some stages of the breach process (Wahl 1998). This study therefore, employed the MacDonald & Langridge-Monopolis, (1984) (Eqs. 3 and 4) and Froehlich, (2008 & 1995) empirical formulas (Eqs. 1 and 2) to estimate the dam breach parameters of Kibimba Dam. These regression equations have performed better in several researches (Duressa & Jubir 2018; Leoul & Kassahun 2019; Mehta et al. 2021).

Froehlich, (1995) regression equations for the average breach width and time

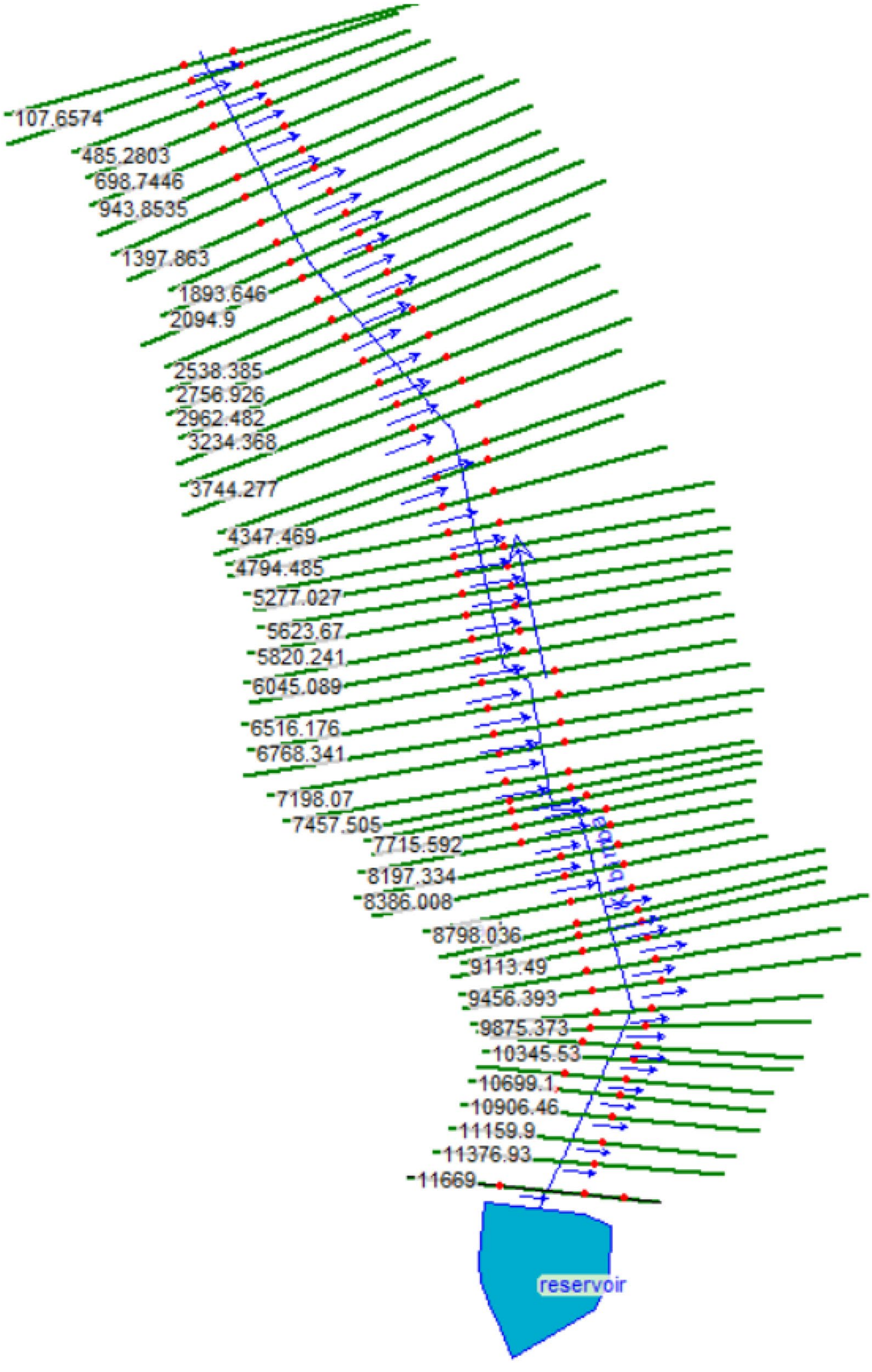

Fig. 2 HEC-RAS simulation of Kibimba dam break

$$\begin{aligned} B_{ave} &= 0.1803\ \mathrm{K_o}\ \mathrm{V_w^{0.32}}\ h_b^{0.19} \\ tf &= 0.00254\ \mathrm{V_w^{0.53}}\ h_b^{-0.90} \end{aligned} \tag{1}$$

where;

B_{ave} = average breath width (m).

$\mathrm{K_o}$ = constant (1.4 for overtopping, 1.0 for piping).

$\mathrm{V_w}$ = reservoir volume at times of failure ($\mathrm{m^3}$).

h_b = height of final breach (m).

tf = breach formation time (hrs.)

Froehlich, (2008) regression equations for the average breach width and time

$$\begin{aligned} B_{ave} &= 0.27K_0\ V_w^{0.32}\ h_b^{0.04} \\ tf &= 63.2\sqrt{\frac{V_w}{gh_b^2}} \end{aligned} \tag{2}$$

B_{ave} = average breach width (m).

K_0 = constant (1.3 for overtopping, 1.0 for piping).

g = gravitational acceleration ($\mathrm{m/s^2}$).

MacDonald & Langridge-Monopolis, (1984) equations used for breach parameter estimation.

For earth fill dams:

$$\begin{aligned} \mathrm{V_{eroded}} &= 0.0261\ (\mathrm{V_{out}}^*\mathrm{h_w})^{0.769} \\ tf &= 0.0179\ (V_{eroded})^{0.364} \end{aligned} \tag{3}$$

$\mathrm{V_{eroded}}$ = volume of eroded material from the dam embarkment ($\mathrm{m^3}$).

$\mathrm{V_{out}}$ = volume of water that passes through the breach ($\mathrm{m^3}$).

$\mathrm{h_w}$ = depth of water above the breach (m)

$$W_b = \frac{V_{eroded} - h_b^2(CZ_b + h_bZ_bZ_3/3)}{h_b(C + h_bZ_3/2)} \tag{4}$$

where;

W_b = bottom width of the breach (m).

h_b = height from the top of the dam to bottom of breach (m)

$$\mathrm{Z_3} = \mathrm{Z_1} + \mathrm{Z_2}$$

$\mathrm{Z_1}$ = average slope of the upstream face of the dam.

$\mathrm{Z_2}$ = average slope of the downstream face of the dam.

River hydraulics model building and simulation

Detailed Digital Elevation Model of resolution 12.5 × 12.5 m (DEM) bearing the data for the main channel and overbank floodplain areas was used to create a river hydraulics model in ArcGIS. A triangulated irregular network (TIN) in vector format was preferred as it allows accurate description of the land surface with minimum data and its ease in addition of data for linear features that direct the water flow (such as roads, levees, or ridges lines) (Ackerman et al. 2005). HEC-GeoRAS was used in the creation of datasets (collectively referred to as RAS Layers). HEC-GeoRAS processes geospatial data to support hydraulic model building and analysis of water surface profile results (HEC 2005). Land use data was used in estimating Manning's roughness coefficients. Due to the absence of observed water surface elevation information such as gaged data and high-water marks, Manning's n values were not calibrated. A value of 0.03 was adopted based on the vegetation type of the area (USACE 2016). Mannings n value are dependent on surface roughness, vegetation, channel irregularities, scour and deposition, and suspended material (USACE 2016). The completed datasets were exported to HEC-RAS for hydraulic modelling.

HEC-RAS as a one-dimensional river hydraulics model executes both steady-flow and unsteady-flow water surface profile calculations through a network of open channels (HEC 2002). It performs computations of flood wave propagation following a dam failure scenario by solving the full Saint–Venant equations (Ackerman et al. 2005). It also computes water surface profiles for steady, unsteady flow and flow regimes (subcritical, super critical, and mixed flow) (Mehta & Yadav 2017). The model uses the weir equation to calculate discharge for an overtopping breach and the orifice equation for a piping breach. The mean discharge is used in the estimation of volume of water released, equivalent pool elevation drop and discharge for the successive time-step to build the breach hydrograph (NRC 2012).

The model requires geometric data (Fig. 3), steady and unsteady flow data for computations. The geometric data establishes the connectivity of the river system as cross sections placed at intervals along streams characterizes the conveyance of the stream and its adjacent flood plain (Duressa & Jubir 2018).

The HEC-RAS model was used to process the built datasets. Prior to simulation, additional information on cross sections, data for hydraulic structures, flow data, and boundary conditions were added to the river hydraulics model. The probable maximum flood hydrograph (Fig. 3) for the reservoir and normal depth were used as the upstream and downstream boundary conditions respectively. A dam in HEC-RAS is modelled as an inline structure (Fig. 4) characterized by a weir profile (includes a spillway) and gates for normal low-flow operation.

Modelling the water storage behind the dam using HEC-RAS, can be calculated from either the cross sections taken from bathymetric survey data of the reservoir or using the storage area with an elevation-volume relationship which represents the storage volume behind

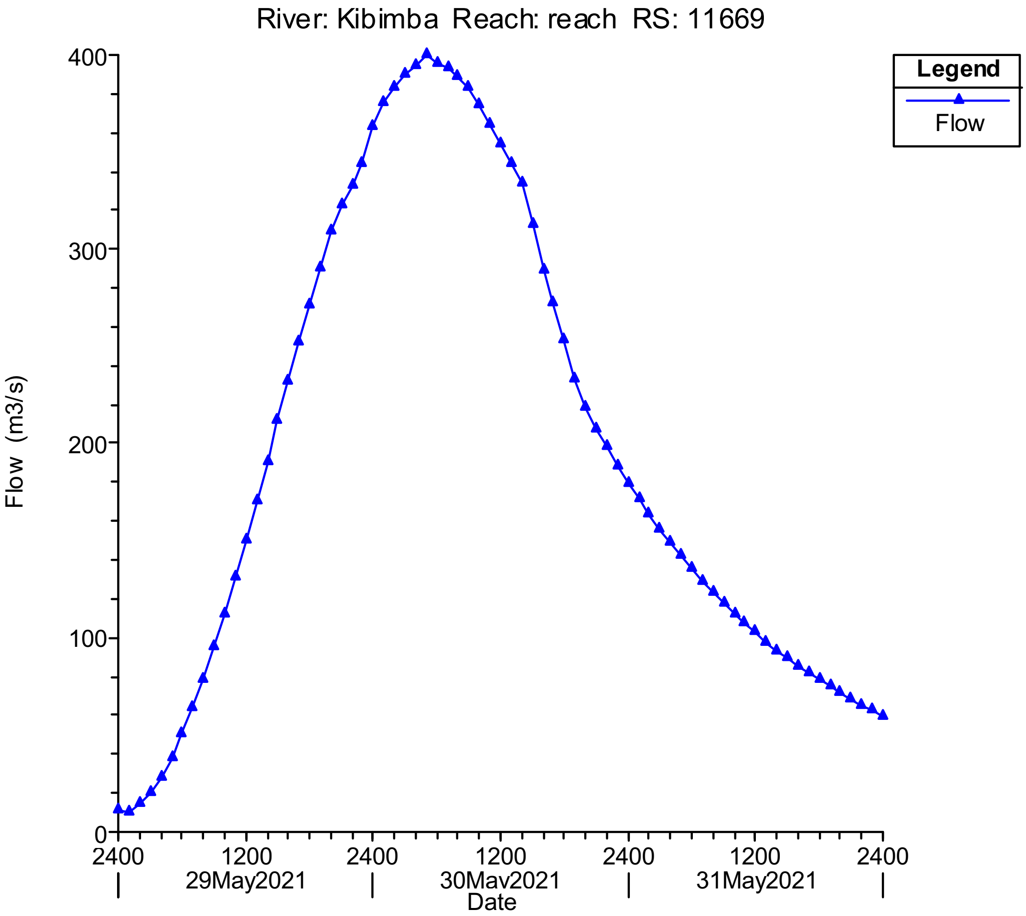

Fig. 3 PMF Inflow Hydrograph of Kibimba River

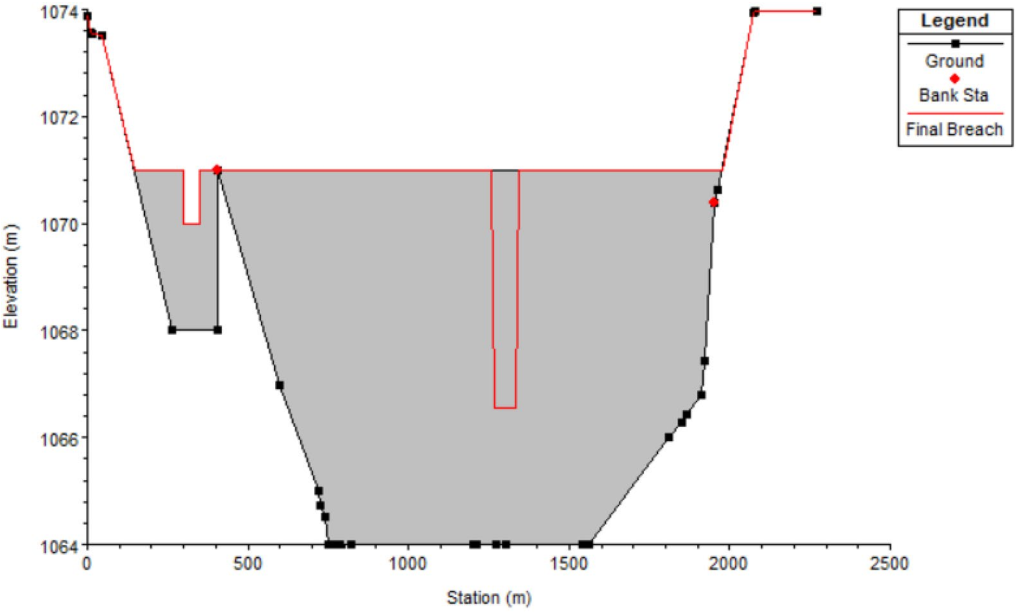

Fig. 4 Dam breach plot

the dam (Ackerman et al. 2005). Due to the absence of bathymetric survey data, this study considered the use of elevation-volume relationship to model the volume of water stored behind Kibimba dam.

This study basically considered overtopping and piping failure modes in Kibimba dam given that these failure modes are independent and occur at different parts in the dam (Ríha et al. 2020). The peak flows of breach outflow hydrographs from HEC-RAS model simulations were compared with those calculated from emprical Eqs. 5, 6 and 7.

$$\mathit{USBR}\ (1982)\text{: } \mathrm{Q} = 19.1\ (\mathrm{h_w})^{1.85} \tag{5}$$

MacDonald and Langridge-Monopolis

$$Q = 1.154(V_w h_w)^{0.412} \tag{6}$$

Froehlich (1995b).

$$Q = 0.607 V_w^{0.295} h_w^{1.24} \tag{7}$$

The outflow hydrographs were routed downstream to assess the maximum water surface (depth and velocity) and the inundation on the rice fields and other property that could be affected by the failure of the dam. This water surface profile maps give a preliminary assessment of the flood risk and prior knowledge for emergency preparedness (Ackerman et al. 2005).

Results and discussions

Regression equations were used to determine breach parameters (Table 2). MacDonald & Langridge-Monopolis, (1984) has a short breach formation time as compared to Froelich. This implies that the breach outflow hydrograph will take a short time to peak. It is observed that under both overtopping and piping failure, a total collapse of Kibimba Dam is possible as the computed breach width exceeds the dam's crest width of 5 m. Duressa & Jubir, (2018) in their study reported a linear relationship between the breach width and the peak discharge.

From the peak flow discharges (Table 2), it can be noted that the maximum breach flow obtained from HEC-RAS model simulation (Figs. 5 and 6) is found to be close compared to the calculated peak discharge by Froehlich, (2008 & 1995) and MacDonald & Langridge-Monopolis, (1984). Leoul & Kassahun, (2019) in a similar study reported similar findings.

The shape of the hydrographs (Figs. 5, 6) with a short rising limb and a long falling limb shows that the flood arrived rapidly and discharged progressively. Both failure modes had similar time to peak. The arrival time for flood wave determined by velocity and water surface elevation in the HEC-RAS model is vital for emergency action plans (Duressa & Jubir 2018). Comparing the modeled breach outflow hydrographs (Figs. 5, 6) shows that on average, the peak discharge resulting from overtopping failure is less than that triggered by piping. This shows that the risks caused by piping failure could be more than those caused by overtopping (Duressa & Jubir 2018).

For a dam to fail by overtopping, discharge has to flow over the dam crest (Amini et al. 2017). Since this scenario did not happen for Kibimba dam, it implies that the spillway has enough capacity to safely discharge the flood resulting from the probable maximum flood of 400 m^3/s. Similar results were reported by Leoul & Kassahun, (2019) in their study.

A scenario was developed where the inflow hydrograph was augmented to 2 times the designed probable maximum flood. This was intended to ascertain the level of peak discharge at which the dam would fail by overtopping. It was found that the spillway could not safely pass this discharge and thus resulting in dam failure by overtopping.

Results from the piping failure analysis show that Kibimba dam experienced piping failure. The reservoir water level was greater than the assumed center-line elevation for the breach. The resulting hydrographs from this failure were used to analyze the flood propagation downstream of the dam. Investigating the flow of water during a flood event, gives a feasible insight of locations that are at high risk of experiencing the potential negative effects of flooding (Kumar et al. 2023). Mitigation

Table 2 Breach parameters

Breach parameter	Overtopping failure			Piping failure		
	Froehlich 1995	Froehlich 2008	MLM 1984	Froehlich 1995	Froehlich 2008	MLM 1984
Breach bottom width (m)	60.20	69.40	209.00	43.44	53.68	438.74
Breach side Slope (H: V)	1.40	1.00	0.50	0.90	0.70	0.50
Breach formation time (hrs.)	4.23	4.89	0.56	4.22	4.89	0.56
Peak discharge (m^3/s)	506.69	-	1935.41	506.69	-	1935.41

MLM MacDonald and Langridge-Monopolis

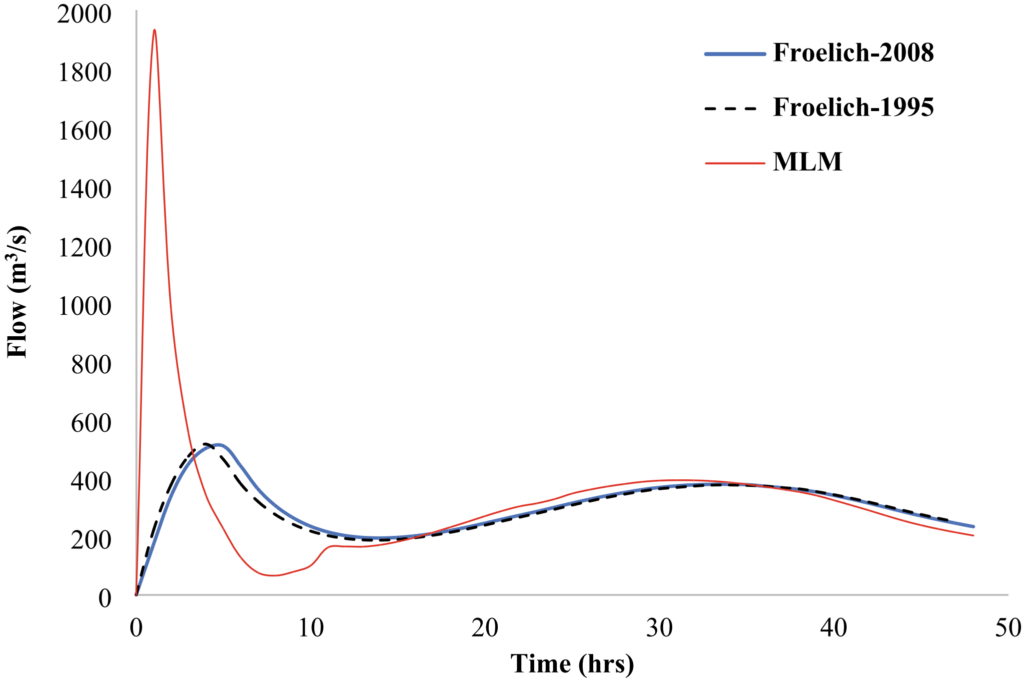

Fig. 5 Breach outflow hydrographs under overtopping failure

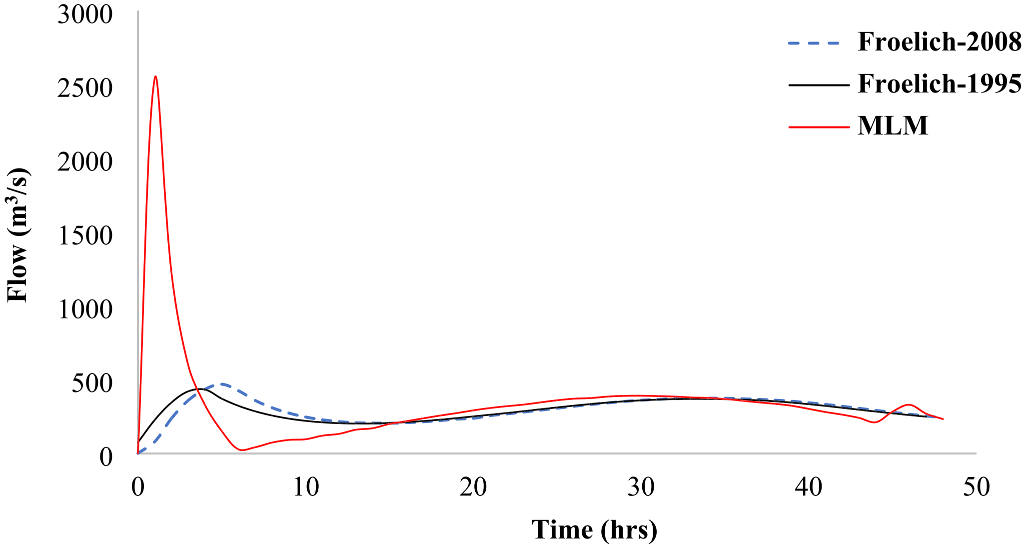

Fig. 6 Breach outflow hydrographs under piping failure

strategies could be employed in these locations to reduce flood impacts (Mehta et al. 2022a, b).

The flood inundation maps (Fig. 7) were created in the Ras mapper directly in the HEC-RAS given that it has an integrated geo-spatial capability (D. J. Mehta et al. 2022a, b). Inundation depths varied to a maximum of 6 m, with velocities ranging from 1.2 to 10 m/s. The variation in the velocity is attributed to the change in the topography of the area in which the flood traverses. With this high velocities and inundation depths,

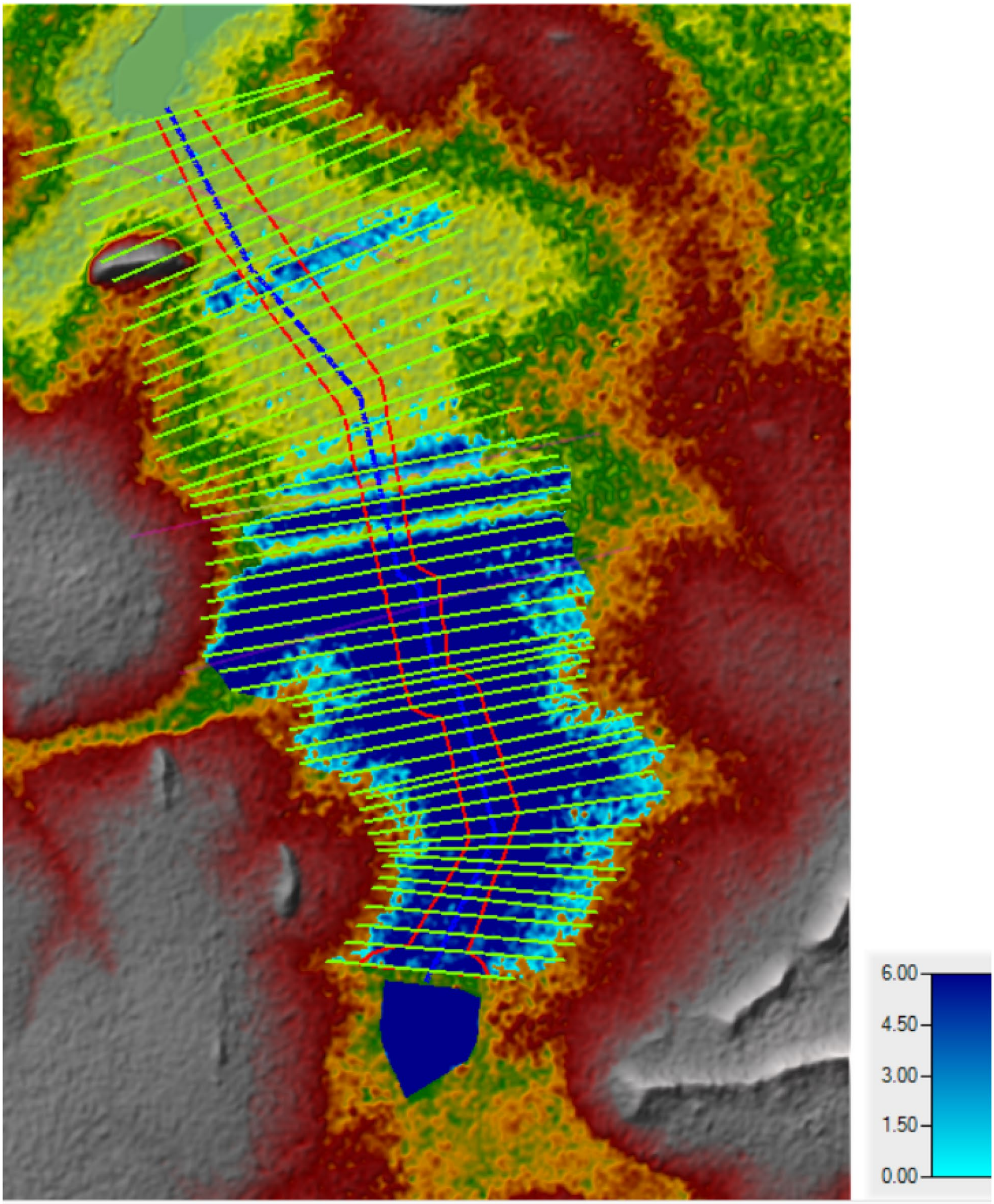

Fig. 7 Inundation depth of Kibimba rice field

it is evident that the rice fields would be destroyed. The flooding could also affect the aquatic ecosystem in the river (Mehta & Kumar 2022). This calls for a detailed risk analysis to prepare land use plans to safe guard the community from human and property loss. Mehta, et al., (2022a, b) recommended the use of hydraulic parameters from the model simulation to design flood protection measures.

Conclusion and recommendations

Failure of dams cause socio-economic and environmental catastrophes that calls for risk management and development of management plans. Simulation of dam break informs decisionmakers, managers, and authorities to develop plans to manage a crisis and avoid the disastrous impacts of a dam failure.

This study analyzed Kibimba dam failure under both overtopping and piping failure modes with probable maximum flood as an input to the reservoir. The breach parameters and the peak flow discharges were calculated using the Froehlich, (1995) and Froehlich, (2008) regression equations and the results compared to the model outputs. It was observed that the peak flow discharges were close to the model output discharges.

The breaching of the embankment due to overtopping was not possible as the spillway showed adequacy to safely discharge the flood equal to the probable maximum flood. The peak flow from piping failure was higher than from overtopping. Therefore, a further analysis of inundation at the downstream of the dam to obtain the water surface profile was carried out. The inundation depths and velocities indicated that failure of Kibimba dam affects the rice fields, infrastructure, and other economic activities in the downstream of the dam. The results of dam break analysis would enable the operators understand and design mitigation measures for the likely flooding impacts.

This study's findings are vital in land use planning and in generating emergency response plans to aid in alleviating disastrous property and human life loss encompassing dam break and flood routing analyzes for the affected downstream areas. Additionally, it will boost the community's resilience towards catastrophes, emphasizing the ability to lessen the probable impacts of a disaster as well as to effective recovery response after a dam break disaster.

The breach formation model does not provide a more detailed description of the physical process of erosion that takes place when an embankment dam does fail. However, future research could explore the use of more advanced models to obtain more accurate results. Some of the proposed open questions for future research may include; how to incorporate more detailed information about soil characteristics and composition into dam breach models, vegetation, channel morphology and sediment transport and how to develop more sophisticated risk assessment frameworks that take into account the uncertainties and complexities of dam breach scenarios. The authors recommend the use of high-resolution topographic data for future studies to improve the accuracy of the model.

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Author contributions

The authors were engaged in the conception, review, and approval of this manuscript for submission.

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Availability of data and materials

Data used in this research can be accessed through contacting the corresponding author.

Code availability

Not applicable.

Declarations

Ethics approval and consent to participate

This article does not contain any studies with human participants or animals performed by any of the authors.

Competing interests

The authors declare no competing interests.

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