Dam Break Analysis of the Hirakud Dam using MIKE 11 model

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Abstract– *Hypothetical dam break analysis of Hirakud dam, Odisha, India, is carried out in the present study. Dam break analysis is an important method to predict possible hypothetical dam failure modes and their consequences to prepare an emergency action plan (EAP), if it would happen. The possible dam breach failure parameters such as breach width, breach failure time, breach side slope and outflow characteristics such as maximum water level and its travel time are predicted using NWS DAMBRK equation and MIKE 11hydrodynamic mode, respectively in the downstream area up to the head of delta, Mundali. Estimated probable maximum flood (PMF) is used as reservoir inflow for probable dam breach failure along with different combinations of dam breach parameters. Outflow characteristics in the downstream river channel are generated using river cross-sections extended in the floodplain extracted from Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM). Moreover, flood inundation maps are prepared in Arc-GIS tool for downstream areas using maximum water levels generated by the dam break model for flood management plan.*

Keywords: *Dam Break, Flood, Inundation maps, NWS DAMBRK Equation, MIKE 11*

1. INTRODUCTION

Dam plays important role in the flood management, but its failure due to natural or manmade activities may cause flood havoc in the downstream river reaches. Moreover, dam failure would add high risk to the human life and property due to ever growing population and its establishment in the floodplains. Therefore, hypothetical dam break analysis is generally carried out to predict potential flood damage and to prepare emergency action plan (EAP) in advance. It is necessary to carry out such type of analysis not only for newly planned dam projects but also for the existing ones [1, 2].

Dam break flood (DBF) analysis aims at the prediction of the reservoir outflow hydrograph, which consists of the prediction of the breach outflow characteristics and reservoir routing, and routing of that hydrograph through the downstream river reach. Different breach outflow characteristics such as maximum water elevation, time to reach maximum water elevation and maximum discharge are generally considered for issuing flood warnings and estimating flood risks in the downstream river reaches. Prediction of these breach outflow characteristics is influenced by breach formation phenomenon which depends on the dam morphological characteristics and its ability to pass flood waves, different hydrologic conditions (e.g. PMF inflow to the dam), breach failure modes (due to overtopping or piping) and its process (instantaneous or gradual). For last four decades, many dam failures have been occurred across the world, which has led the hydrologists to understand possible types of breach formation phenomenon. Breach parameters are generally selected based on modellers' experience, judgement and historic dam failure cases. Furthermore, application of geographic information system (GIS) technique for mapping the flood inundated areas using breach outflow characteristic such as maximum water elevation can play a momentous role in minimizing the risk and damages in the downstream area of the dam [3, 4].

Many experimental, analytical, and numerical models have been developed to carry out dam break analysis. Computer-aided numerical models such as DAMBRK [5], SMPDBK [6], CADAMBRK [7], NWS FLDWAV [8], HEC RAS [9], BOSS DAMBRK [10], and MIKE 11 [11] have been widely used successfully across the world due to their high computational speed and efficiency. Majority of dam break analysis studies have been carried out using 1D model. The NWS DAMBRK model has been used for dam break analysis of Barna dam, Madhya Pradesh, India [12], Ghodahoda project Odisha India [13], and the proposed dam on Yamuna river, India [4]. BOSS DAMBRK model was used to study the dam break analysis of proposed dam on the Gerugu river Malaysia [10]. HEC RAS model has been used for dam break analysis of Oros Dam Brazil [14], Danjiangkou and Yahekou dam failures in the Han river China [15], and Foster Joseph Sayers Dam in Center Coutry PA, USA [16]. SMPDBK model has been used for dam break analysis of Foster Joseph Sayers Dam in Center Coutry PA, USA [17]. MIKE 11 model has been used for dam break analysis of Bichom and Tenga dam [18], Buffalo Creek Dam, North Carolina, USA [19], Indra Sagar and Omkareshwar project, India [20]. Furthermore, comparison of different 1D models with respect to their flexibly, complexity, robustness and user friendliness have also been reported in the literature [21, 22, 23, 24].

In the present study dam break flood analysis of the Hirakud dam in Odisha state, India using MIKE 11 one dimensional (1D) model has been carried out. For last one decade, contribution of runoff in the Hirakud dam from the upper reaches of Mahanadi River Basin during monsoon season has been increased. Moreover, increased inflow to the reservoir has been found critical during mid to end of the monsoon period, which is the condition where reservoir is reaching at its maximum reservoir level. Therefore, for the purpose of the dam safety maximum outflow is being released from the reservoir. This situation is creating high flood risks in the delta region, which is the low lying area in the Mahanadi River Basin. The flood situation occurred in 2011 is an example for such type situation. Therefore, hypothetical dam failure of the Hirakud dam due to PMF inflow to the reservoir has been considered in the present study to prepare the flood inundation maps of maximum water elevation which can be used for integrated flood management plan in the affected area.

2. STUDY AREA AND DATA USED

Hirakud dam (Lat/Long: 21°31'N, 83°52'E) is located in the Odisha state, India. It is the major longest earthen dam in the Asia, having catchment area of 85,171 km^2, which is mainly constructed to control floods in the delta region of the Mahanadi river. The middle reaches of the Mahanadi River Basin (Fig. 1) *i.e.* Hirakud dam and its downstream reach of the main Mahanadi river up to the Mundali delta head (Lat/Long: 21°31'N, 83°52'E) with an approximate length of 315 km is considered as the study area.

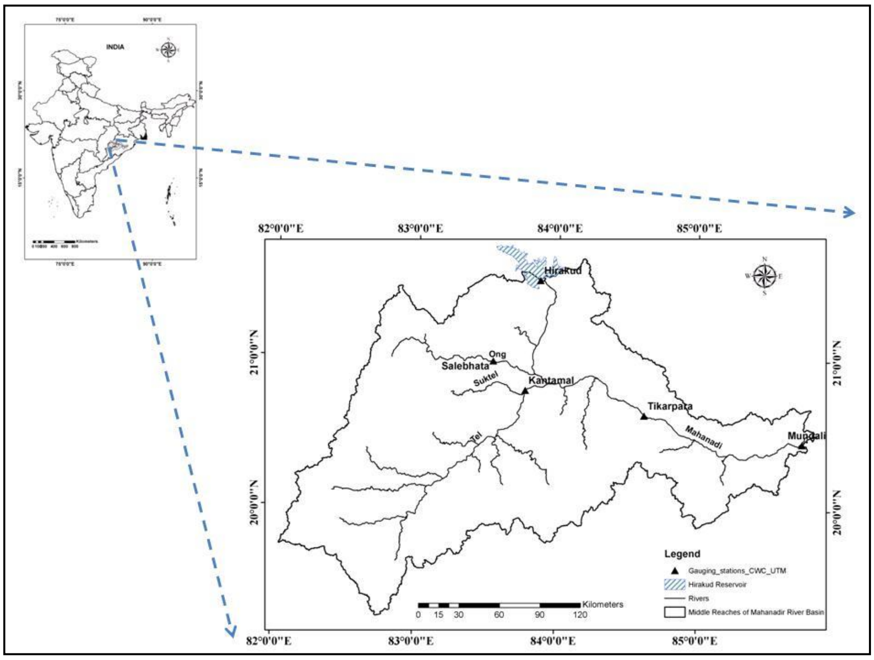
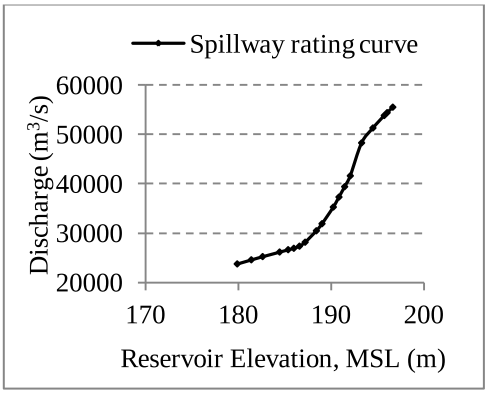


Fig. 1: Index Map of Middle reaches of the Mahanadi River Basin

This river reach consists of three major tributaries of Ong, Sukhtel, and Tel joining the Mahanadi river in the middle reaches. The main soil types found in the study area are red and yellow soils. The normal annual rainfall is about 1458 mm and the temperature in this region varies from 14 °C to 40 °C. The average monthly pan evaporation of the area varies from 2.4 cm to 14.6 cm.

Dam breach failure of Hirakud dam is analysed using the probable maximum inflow flow (PMF) to the Hirakud reservoir. Different dam characteristic curves, such as, a spillway rating curve (Fig. 2), reservoir area-elevation curve (Fig. 3), PMF curve (Fig. 4) are used as the input to the dam breach analysis. These data were procured from Hirakud Dam Circle (HDC), Burla, Odisha, India. The breach parameters resembling to the present dam morphological characteristics are selected from the literature [14].



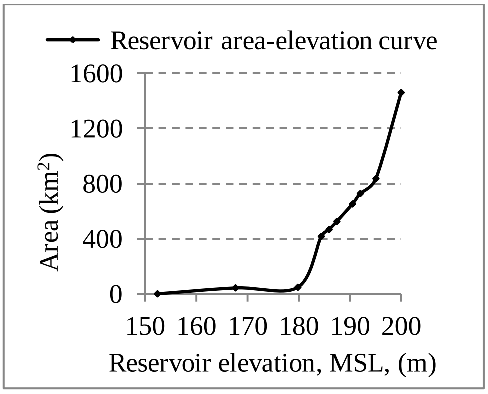


Fig. 2: Spillway Rating Curve **Fig. 3: Reservoir Area-Elevation Curve**

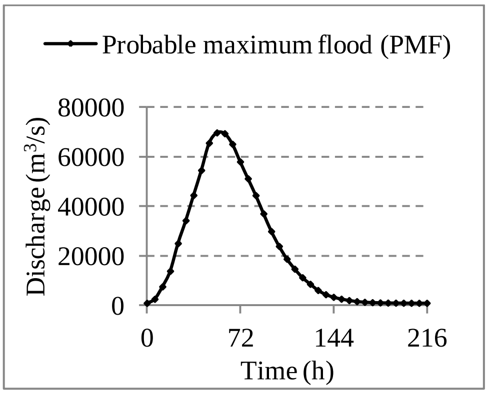


Fig. 4: Reservoir Area-Elevation Curve

The river cross-sections extracted from the shuttle radar topography mission (SRTM) digital elevation model (DEM) are used as the input for the flood routing model. Manning's roughness coefficients for the channel routing are chosen based on the topographical condition of the river channel [25].

3. METHODOLOGY

In this study, the dam breach analysis using MIKE 11 model is carried out using the parametric method which uses NWS DAMBRK equation for calculating dam breach outflow with linear mode of failure [26]. Breach parameters are selected based on historical dam failures reported in the literature [14].

It is assumed that dam failure due to overtopping caused by PMF inflow to the dam occurred when PMF enters in the reservoir, all spillway gates are open. Moreover, rise in the reservoir water level due to PMF impingement is computed keeping initially the reservoir is at its full reservoir level (FRL).

The hydrodynamic (HD) flood routing involves modifications of the basic Saint-Venant equations representing conservation of mass and momentum expressed as

$$\frac{\partial Q}{\partial X}+\frac{\partial(A+A_0)}{\partial t}=q \tag{1}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial\left(\frac{Q^2}{A}\right)}{\partial X}+gA\frac{\partial h}{\partial X}+S_f+S_c=0 \tag{2}$$

where, Q = discharge; A = active flow area; A_0 = inactive storage area; h = water surface elevation; q= lateral outflow; X = distance along waterway; t = time; S_f = friction slope; S_c = expansion contraction slope and g = gravitational acceleration.

Dam break model setup in the MIKE 11 has been carried out as described below [26]. Cross-sections are extracted for the extended flood plain such that the simulated maximum water level is within the given cross-section. Manning's roughness coefficient, n is the HD model parameter. Calibration (year 2003) and validation (year 2008) of HD model is carried out for the estimation of channel roughness coefficient using monsoon flood

flow data. Statistical indices such as Nash Sutcliffe efficiency (NSE) [27], Coefficient of determination (R^2), root mean square error (RMSE) and mean absolute error (MAE) [28] are used to check performance of the model. For the dam break flood scenario, Manning's roughness coefficient for the flood plain sections are varied from 0.020 to 0.090 at the interval of 0.005 for different simulations of flood routing keeping fixed (estimated from calibration and validation using only channel routing) *n* value for the channel section.
Different breach parameters selected are given in Table 1. Flood inundation maps for the downstream river reaches are prepared for the maximum water elevations using Arc GIS 9.3 tool [4].

Table 1: Breach Parameters Selected for Dambreak Analysis

Scenario	Breach Parameters		
	Breach Width (m)	Breach Failure Time (h)	Breach Side Slope (fraction)
Base Value	200	1	0.75

4. RESULTS AND DISCUSSIONS

4.1 Calibration and Validation of MIKE 11 Hydrodynamic (HD) Model

Calibration and validation of the Manning's roughness coefficient parameter for only routing the flow in the river channel (without floodplain) is carried out using MIKE 11 HD model for the monsoon period of the years 2003 and 2008, respectively. The performance indices (Table 2) of this analysis show that there is good agreement between the observed and simulated discharge (Fig. 5a and 5b) for which the optimal Manning's roughness coefficient value for the river channel is obtained as 0.020 for channel routing only.

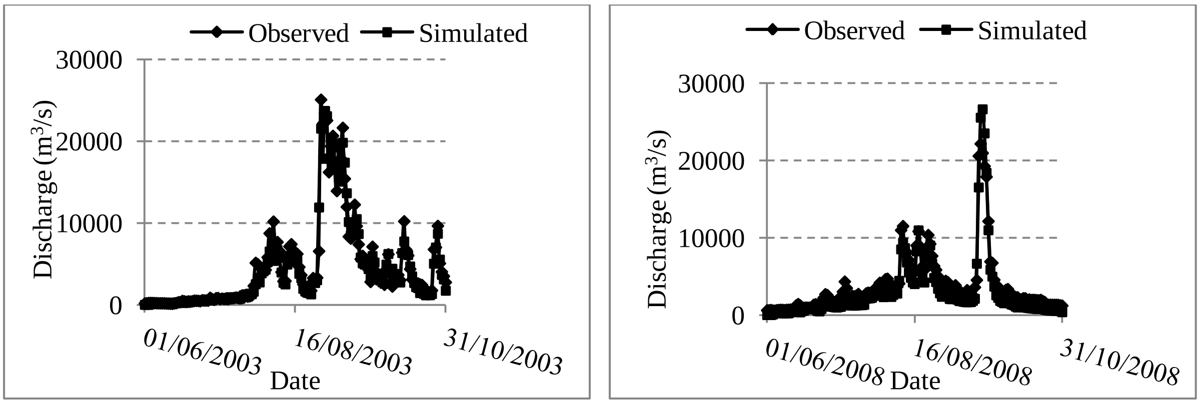


Fig. 5: (a) Calibration and (b) Validation of MIKE 11 HD Model

Table 2: Performance Indices of Calibration and Validation of MIKE 11 HD Model

Performance Indices	Results	
	Calibration	Validation
NSE	0.956	0.8801
R^2	0.979	0.9748
RMSE (m^3/s)	1129.25	1334
MAE (m^3/s)	646.85	1110

NSE = Nash-Sutcliffe efficiency; R^2 = Coefficient of determination
RMSE = Root Mean Square Error; MAE = Mean Absolute Error

4.2 Breach Outflow Characteristics

In the present study, dam breach failure due to overtopping of reservoir water level is analysed using NWS DAMBRK equation. Dam breach outflow characteristics such as maximum water elevation, time to reach of maximum water elevation and dam breach outflow for the downstream river reaches are described in the following sections.

As already described section 3, dam breach outflow characteristics in the downstream river reaches are analysed keeping fixed river channel roughness coefficient (n = 0.020) as estimated in section 4.1 and varying floodplain roughness coefficients (0.020 to 0.090 at the interval of 0.005). For the present study, extreme case of maximum water elevation (Fig. 6) in the downstream river reaches with the in-channel and floodplain roughness coefficients of 0.020 and 0.090, respectively, is used for the preparation of flood inundation maps (Fig. 7).

Overall, 50 cm difference in the maximum water elevation for different roughness coefficients is obtained which would be helpful for assessing flood damages in the flood prone area.

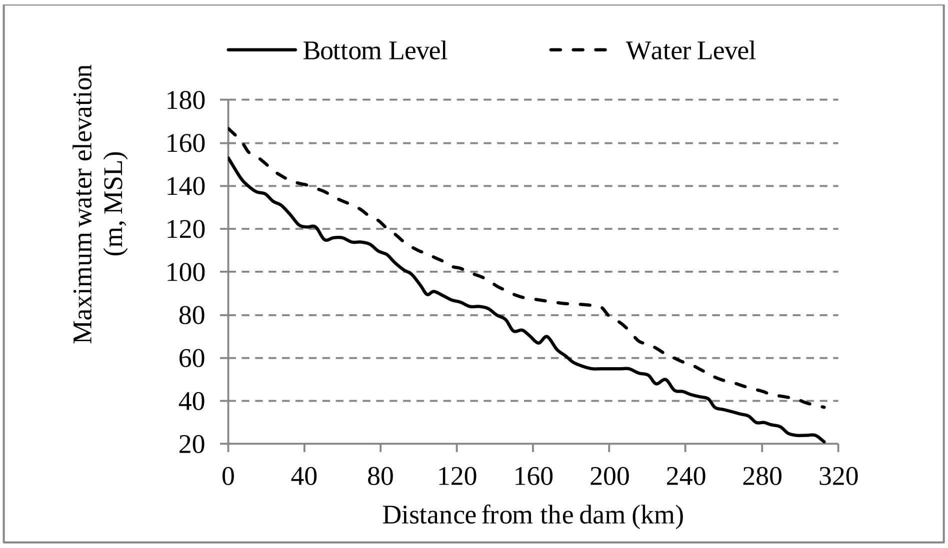
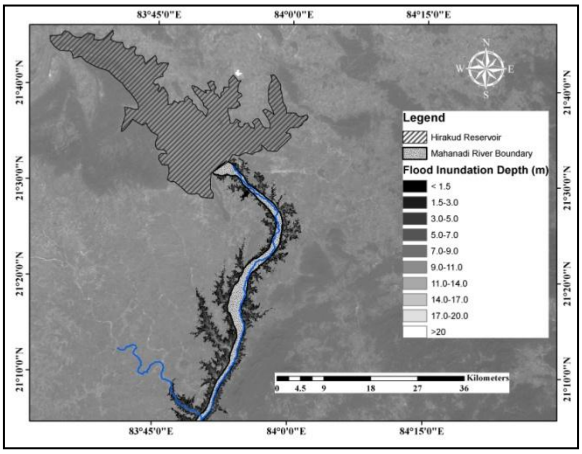
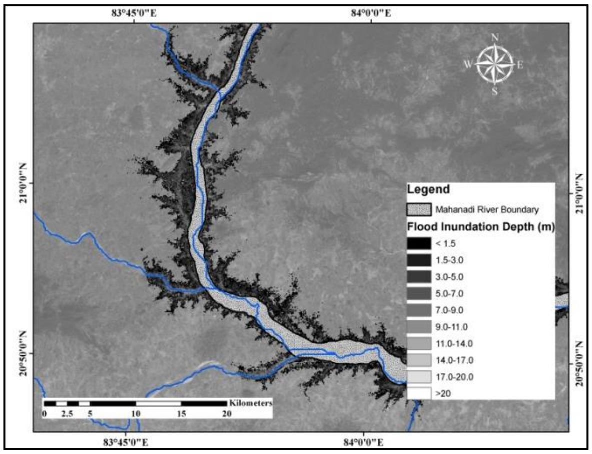


Fig. 6: Maximum Water Elevation Profile at Downstream River Sections



(a)



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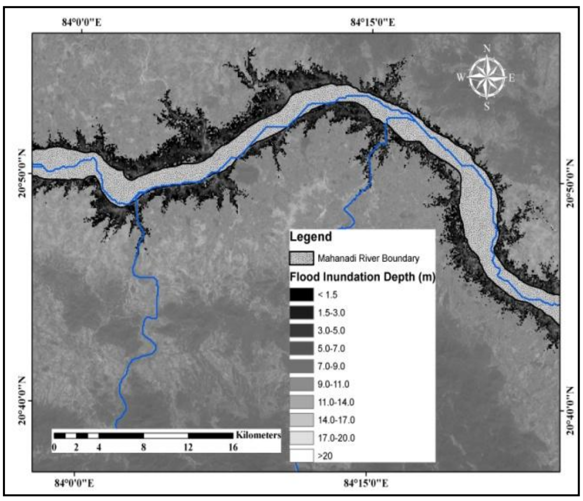

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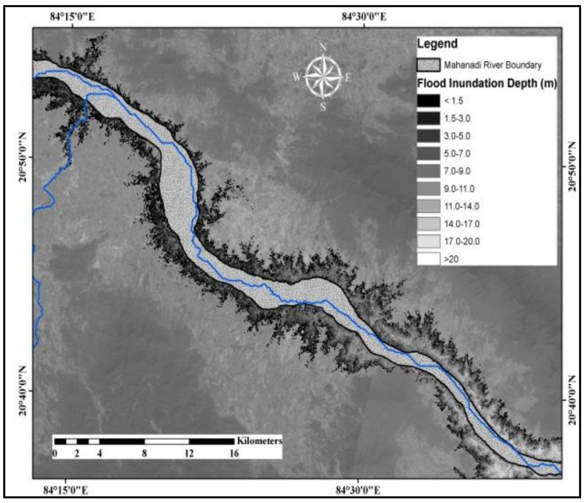
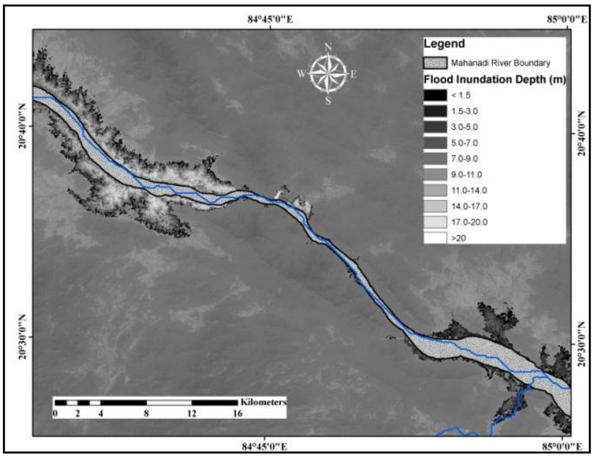
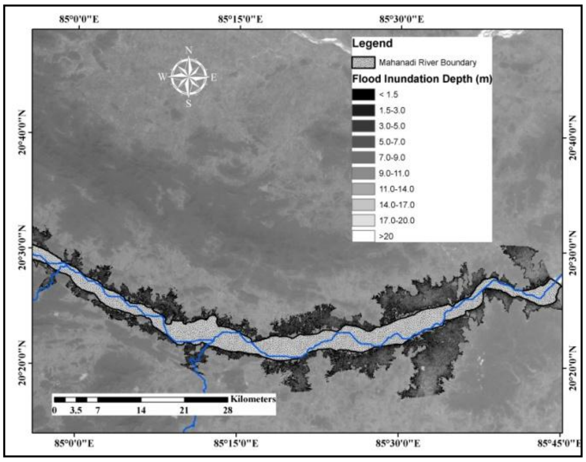


(d)



(e)



(f)

Fig. 7: Flood inundation map for Mahanadi river at (a) 0 to 50 km (b) 50 to 100 km (c) 100 to 150 km (d) 150 to 200 km (e) 200 to 250 km and (d) 250 to 315 km river reach from downstream of dam

It is envisaged from Fig. 7 that the maximum flood prone area due to the dam break condition considered herein for the Mahanadi river reach of 0- 315 km is approximately 97725.69 ha. Moreover, time to reach of maximum water level (Fig. 8) in the downstream river reaches is also represented.

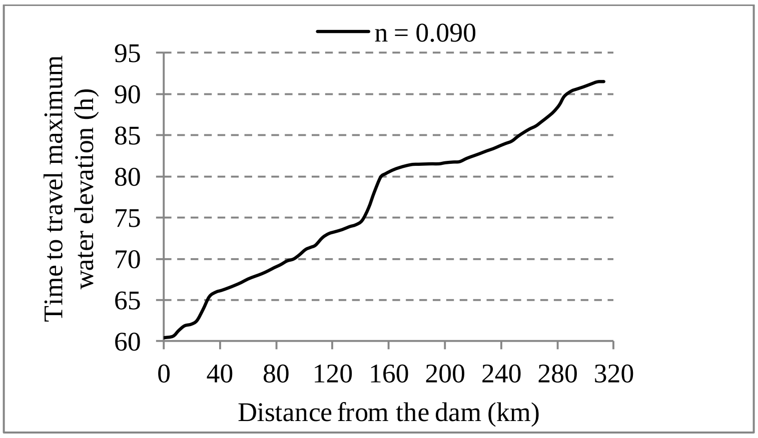


Fig. 8: Time to Travel Maximum Water Elevation at Downstream River Sections

The attenuation of dam breach flood hydrographs at different river cross-sections is shown in Fig. 9**.**

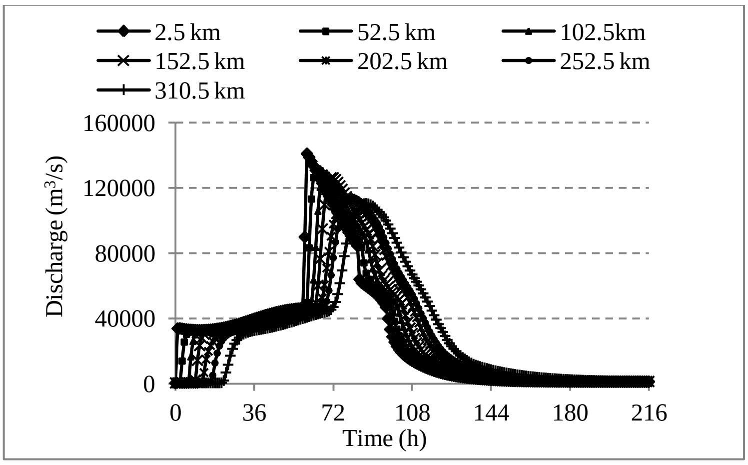


Fig. 9: Flood Attenuation Hydrographs of Dam Break Outflow at Different River Cross-sections

Figure 9 reveals that the amount of flood volume that have been stored at different reaches of 2.5 km, 52 km, 102.5 km, 152.5 km, 202.5 km, 252.5 km and 310.5 km from the dam site due to the current dam failure under study are approximately 1.198 Mha-m, 1.193 Mha-m, 1.194 Mha-m, 1.190 Mha-m, 1.176 Mha-m, 1.174 Mha-m, 1.16 Mha-m, respectively.

5. CONCLUSIONS

The dam break simulation of the Hirakud dam has been carried out using MIKE 11 model. Dam breach outflow characteristics such as maximum water elevation, time to travel maximum water elevation and flood attenuation volume are computed for downstream river reaches from the dam up to the Mundali delta head. Moreover, flood inundation maps are prepared using maximum water elevation, which may be used for flood management plan.

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