Downstream Flood Inundation Assessment due to Dam Breach of Dudh Koshi Storage Hydroelectric Project using HEC-RAS 2D

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Key Points:

- Dam breach is catastrophic event in which peak breach discharge and flood arrival time is influenced by dam height.
- Overtopping failure mode is critical than piping mode of failure.
- Dam breach width is most sensitive parameter for overtopping and piping failure modes under local and global sensitivity analysis.

Abstract

Dam breach is rare event in which dam fails releasing impounded water to downstream regions. Dam breach has low probability of occurrence but carries high risk of destruction. Dudhkoshi Storage Hydroelectric Project concrete faced rock fill dam (CFRD) was studied for dam breach under overtopping and piping failure modes. Dam breach simulation and flood propagation study is vital for identifying and minimizing the risks associated with breach flood. Two scenarios namely base-case scenario with average value of dam breach parameters and worst-case scenario with value of dam breach parameters resulting in maximum output. Local and global sensitivity analysis are performed for four dam breach parameters (dam breach width, breach formation time, weir coefficient, trigger failure elevation). Sensitivity analysis is performed for two river profile. Sensitivity on peak discharge, peak velocity, arrival time and water surface elevation were evaluated. ArcGIS, HEC-RAS and OriginPro 2022b are used for dam breach analysis. Overtopping failure was found to be critical as compared to piping mode.

Plain Language Summary

The collapse of Dudh Koshi Hydroelectirc Project dam will generate flood waves immediately destroying settlements near and beyond the dam site.The flood will travel along the river stream and sideways across river banks.The change in value of geometry and time associated with dam collapse changes the intensity of flood and arrival time of flood downstream.The depth of flood , arrival time of flood are mapped in terms of buildings, roads and local level affected downstream of dam.

1 Introduction

Dam breach is catastrophic failure which releases impounded water to immediate downstream resulting in loss of life and property. The causes of dam failure are earthquake, land slide, extreme precipitation, piping, equipment malfunctioning, structure damage, foundation failure and sabotage (Xiong, 2011; Brunner 2014). Vajont dam failed due to landslide (Barla & Paronuzzi, 2013), Kakhovka dam failed during Russia–Ukraine War (Vyshnevskyi et al., 2023) and Shibuya dam failed due of underestimation of geotechnical parameter (Chrzanowski et al., 2008). Banqiao Dam and the Shi-mantan Dam failure claimed the lives of around 85,000 (Sachin., 2014). Concrete faced rock fill dam (CFRD) has been subjected to failure due to overtopping and seepage erosion (Wahl, 1998; Xu & Zhang, 2009; Zhang et al., 2016). Various dam failures are documented in literature. Gouhou (Zhang & Cheng, 2006), Zipingpu (Zou et al., 2013), Campos Novos (Nieto, 2021), Aguamilpa (Ma & Cao, 2007), Tianshengqiao-1 (Ma & Chi, 2016) details about mode and mechanisms of CFRD dam failure. CFRD failure occurs due to crack formation which develops percolation channel along dam section (Zhang et al., 2016; Ma & Chi, 2016). The impacts of dam failure can be controlled by using accurate flood hazard maps (Balaji & Kumar, 2018). (Mudashiru et al., 2021) reviewed flood hazard mapping for physical-based, empirical and physical modelling. HEC-RAS is used for physical-based modelling.

(Eldeeb et al 2023) performed unsteady flow 2D dynamic routing and breach parameter sensitivity analysis for Grand Ethiopian renaissance dam (GERD). (Kiwanuka et al.,2023) performed dam breach analysis of Kibimba dam under overtopping and piping mode of failure with probable maximum flood as input. The breach parameters and the peak flow discharges were calculated using the Froehlich, (1995) and Froehlich, (2008) regression equations. (Beza et al., 2023; Khosravi et al., 2019; Sharma et al., 2017) used HEC-RAS for flood routing, flood plain delineation and hazard mapping. (Karki et al., 2022, Gaagai et al., 2022) conducted sensitivity analysis on dam breach parameters. Dam breach width, breach formation time, weir coefficient piping coefficient, breach bottom elevation, side slope are considered for the dam breach study (Brunner, 2014). (Ramola et al., 2021) modelled catchment area as storage area, flood hazard area as 2D flow area and dam as SA/2D connection in HEC-RAS for Baur Dam in which overtopping failure was found to be more critical than piping failure. (Albu et al., 2020) stated that dam breach simulation can be validated through literature review. Dam breach model could perform without manning's n calibration. (Bharath et al., 2021; Hicks & Peacock, 2005). (Psomiadis et al.,2021; Phyou et al., 2023) compared overtopping and piping failure modes for dam breach analysis. (Delenne et al., 2012) stated that sensitivity analysis can be used for shallow water equation analysis in place of global sensitivity analysis with short computation time. Global sensitivity analysis is critical for non-linear distribution (Iooss et al., 2015; Bellos et al., 2020).

Dudh Koshi Storage project lies on moderate seismic risk zone along active fault line between Okhaldhunga and Khotang district of Nepal (Japan International Cooperation Agency (JICA), 2014). Dudh Koshi basin has total glacierized area of approximately 410 km2 of which 110 km2 is debris covered (Shea et al., 2015). There is possibility of GLOF induced dam breach. High intensity rainfall on 5-13 July, 2004 had activated landslides and debris flow in the watershed of the Dudh Koshi River (Dhital, 2006). Storage project provides power system flexibility. Dudhkoshi, Adhikhola, Sunkoshi 3, Upper Mustang, Bharbhung storage projects are under different stages of study and development (NEA Annual Report, 2023). Storage HPP impound large volume of water in steep topography and fragile geology with potential seismic risk. Dam breach analysis should be performed for risk management. The objectives of this paper are:

(1) To determine dam breach outflow hydrograph for overtopping and piping failure at dam site and river sections downstream of dam.

(2) To delineate dam breach flood hazard map for overtopping and piping failure.

(3) To perform sensitivity analysis of dam breach parameters to breach discharge, water surface elevation, velocity and arrival time.

2 Study Area and Data

2.1 Study Area

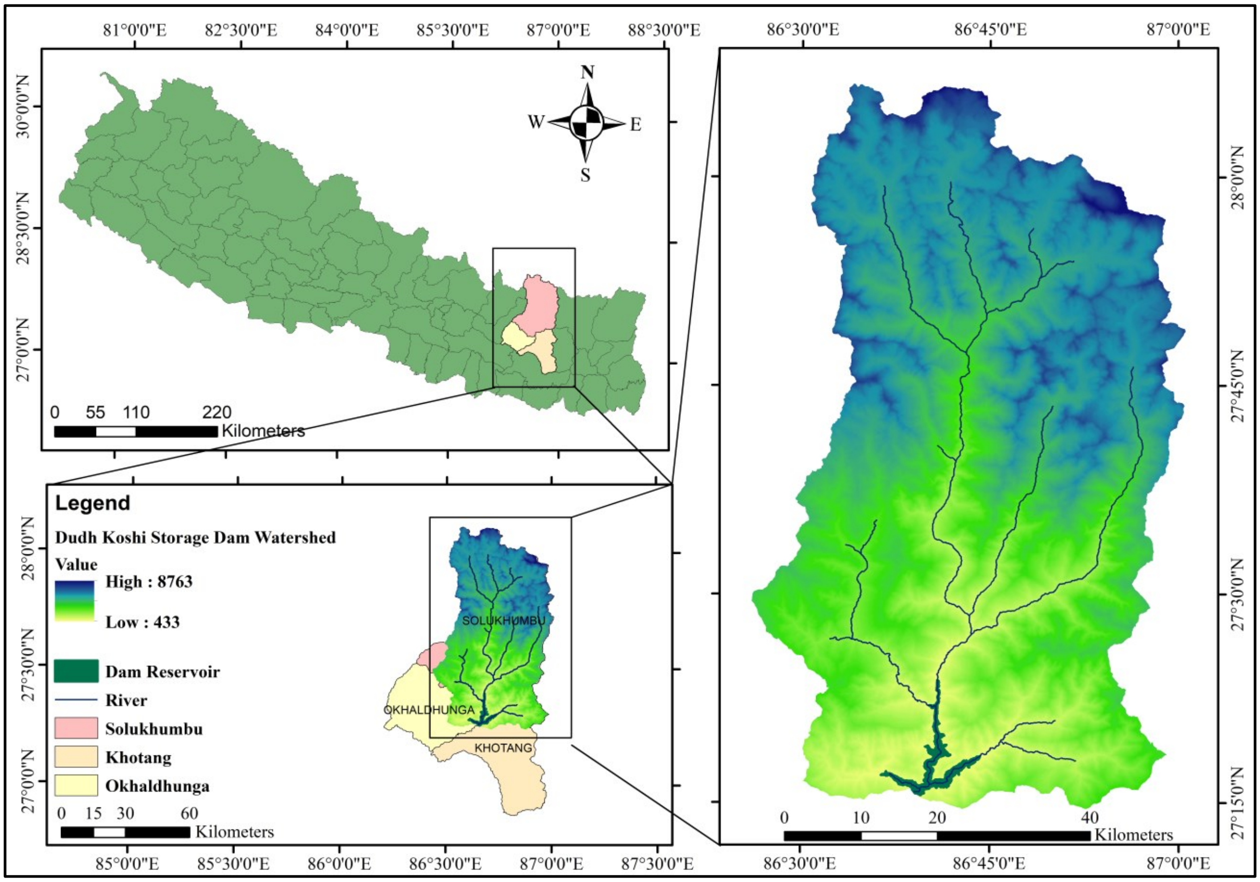

Figure 1: *Study Area Map*

The proposed Dudh Koshi storage hydroelectric project (DKSHEP) is a storage type project. The study area of DKSHEP is shown in Figure 1. The dam is located in the Dudh Koshi river approximately in the latitude of 27° 15’47” and longitude of 86°38’ 17” which is about 2km downstream from the confluence of Thotne river and Dudh Koshi. DKSHEP dam is of concrete faced rockfill dam (CFRD) with crest length of 620m, crest width of 16m and height of 210m. The full supply level (FSL) is at 636 masl while the dam crest is at 640 masl. The catchment area of dam is 3851.89 km2 while the capacity of reservoir is 1491.92 Mm3.Gated spillway and labyrinth spillway are present on left embankment of dam (Updated Feasibility Report of Dudh Koshi Storage Hydroelectric Project,2019).

2.2 Data Acquistion

The reliability of dam breach modelling results depends upon DEM data. ALOS PALSAR, ASTER GDEM, Sentinel and AW3D30 DEM data were evaluated (Okolie and Smith, 2022). AW3D30 showed most accurate representation of river profile and adjusted to dam geometrical characteristic among DEM’s considered. Rainfall data were analyzed using Thiessen polygon method to find mean annual rainfall. Shakya method (Shakya, 2002) was used to distribute the 10000-year rainfall into 24-hour time domain which was multiplied with unit hydrograph ordinate obtained from Taylor’s and Schwartz method (Taylor and Schwarz ,1952) to define the inflow hydrograph for HEC-RAS analysis. 10,000-year flood hydrograph with peak discharge of 12638 m3/s was used as inflow for HEC-RAS dam breach unsteady flow analysis. The shapefile for buildings and roads in study area is extracted from Geofabrik Open street map while population data is obtained from National Statistics Office, Nepal Census 2021. The source of data used for the research work is listed in Table 1.

Table 1

Data Collection

Data	Source
Digital Elevation Model (DEM)	30m DEM from Japan Aerospace Exploration Agency (JAXA) Advanced Land Observing Satellite World 3D (AW3D30) https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30
Dam geometry	Dudh Koshi Storage Hydroelectric Project: Final upgraded feasibility study rev. 01 executive summary, 2019
Precipitation	Department of Hydrology and Meteorology (DHM), Nepal: 1202, 1203, 1204, 1206, 1207, 1219, 1222, 1224, 1324 EVK2CNR: Everest Pyramid, Pheriche and Namche http://geonetwork.evk2cnr.org/
Dam location	Contour of dam crest level, length of dam and dam geographic coordinates
Catchment area	Arc GIS
Buildings, Roads Shapefile	Geofabrik Open Street Map data
Land use	Sentinel 2
Population	National Statistics Office, Population Census 2021

3 Materials and Methods

3.1 Methodology

The methododlogy used for dam breach analysis of Dudh Koshi Hydroelectric Project (DKSHEP) dam is shown in Figure 2.The result of dam breach analysis is fully dependent upon selection of breach parameter. Federal agency guidelines from USACE 1980; USACE 2007; FERC; NWS (Brunner, 2014), regression equation based on dam failure dataset (Froehlich, 1995a; Froehlich, 2008; MacDonald and Langdridge-Monopolis 1984; Von Thun and Gillete,1990; Xu and Zhang, 2009), simplified breach model, physically based breached model are used for estimation of dam breach parameters. The dam breach parameters are selected on the basis of USACE,2007 federal guidelines as Froehlich equation and other empirical equation are derived for dam of height upto 92m (Brunner ,2014).

The catchment area of Dudh Koshi Storage hydroelectric project (DKSHEP) dam was delineated in ArcGIS and modelled as storage area in HEC-RAS. The flood hazard area was modelled as 2D flow area. Dam geometry was modelled as SA/2D connection in HEC- RAS RAS mapper (Brunner, 2014). Downstream outlet was fixed at Koshi barrage while backwater effect was observed upto Likhu - Sunkoshi confluence. Labyrinth spillway was modelled for overtopping failure while gated spillway is assumed to be closed. The piping failure case was modelled without spillway for model simplicity and stability. Cell size of 40 m* 40m with break line of 40 m spacing to align cells along river profile was used for simulation.

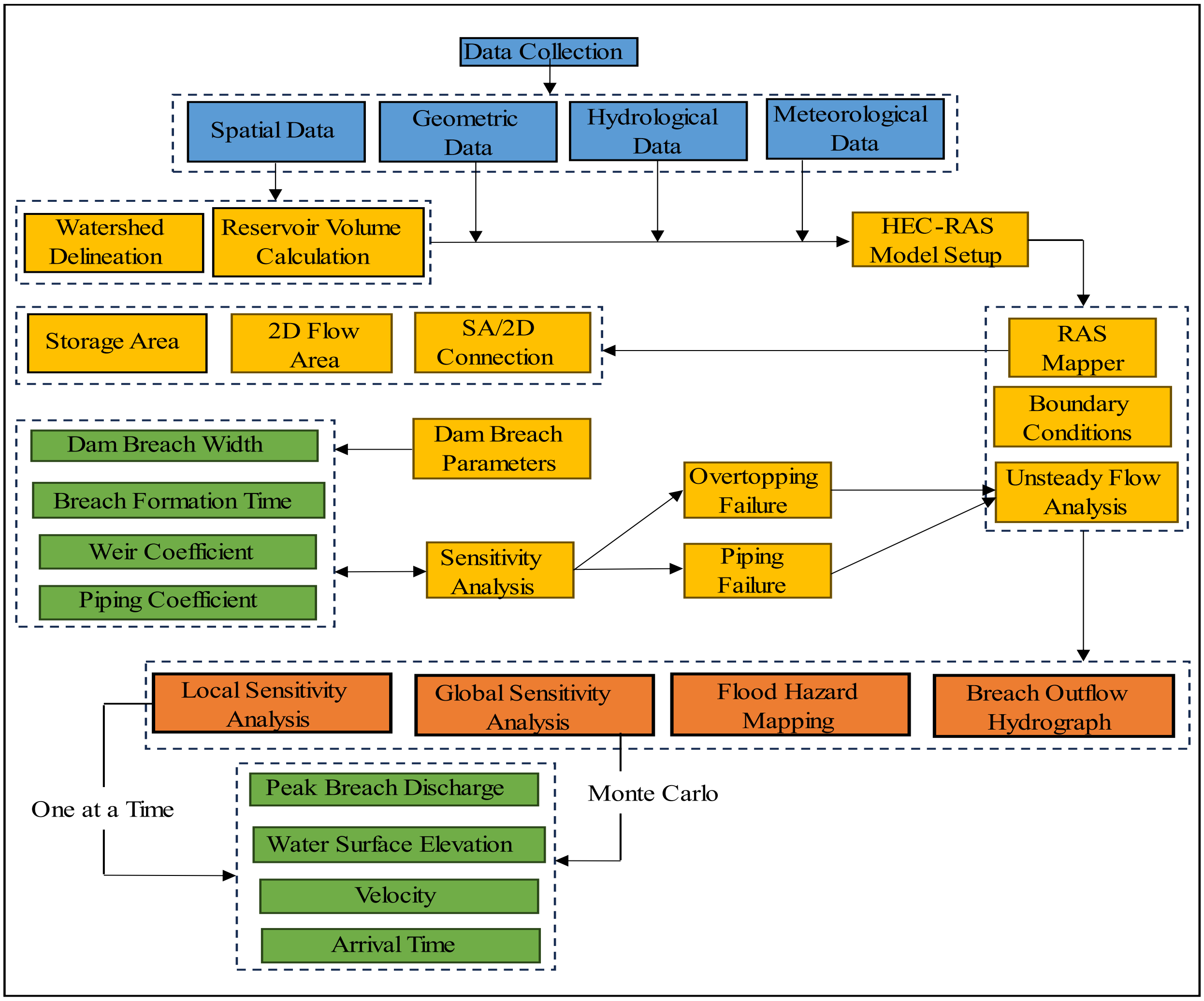

Figure 2: *Flowchart of methodology used for dam breach analysis*

Overtopping failure mode was simulated with fixed time step of 3 seconds while courant condition was used for piping failure. Shallow Water Equation (SWE) was used for accurate representation of velocity as compared to diffusion wave equation (Brunner, 2014). Pilot model run showed diffusion peak velocity three times of velocity obtained from SWE for overtopping failure. Five dam breach parameters were considered for sensitivity analysis. Dam breach width, breach formation time, weir coefficient, trigger failure elevation was used for overtopping failure while piping coefficient was used instead of trigger failure elevation for piping failure.The shallow water equation used for dam breach analysis is shown in Equation 1), Equation 2) and Equation 3). The full supply level is considered as initial water level during HEC-RAS analysis. Overtopping failure only occurs when the water level rises above dam crest whereas piping failure occurs through pipe channel formation in dam section (Chen et al., 2019).

Continuity Equation

$$\left(\frac{\partial H}{\partial t}\right)+\frac{\partial (hu)}{\partial x}+\frac{\partial (hv)}{\partial y}=0 \qquad \text{Equation 1}$$

Momentum Equation in X - Direction

$$\left(\frac{\partial u}{\partial t}\right)+u\left(\frac{\partial u}{\partial x}\right)+v\left(\frac{\partial u}{\partial y}\right)+g\left(\frac{\partial H}{\partial x}\right)+u\left(\frac{gn^2|u|}{R^{4/3}}\right)=0 \qquad \text{Equation 2}$$

Momentum Equation in Y - Direction

$$\left(\frac{\partial v}{\partial t}\right)+u\left(\frac{\partial v}{\partial x}\right)+v\left(\frac{\partial v}{\partial y}\right)+g\left(\frac{\partial H}{\partial y}\right)+v\left(\frac{gn^2|v|}{R^{4/3}}\right)=0 \qquad \text{Equation 3}$$

Where, H is water surface elevation (m), h is water depth, u and v are depth averaged velocities in x and y direction (m/s), g is acceleration due to gravity (m/s2), n is manning's coefficient and R is wetted perimeter (m).

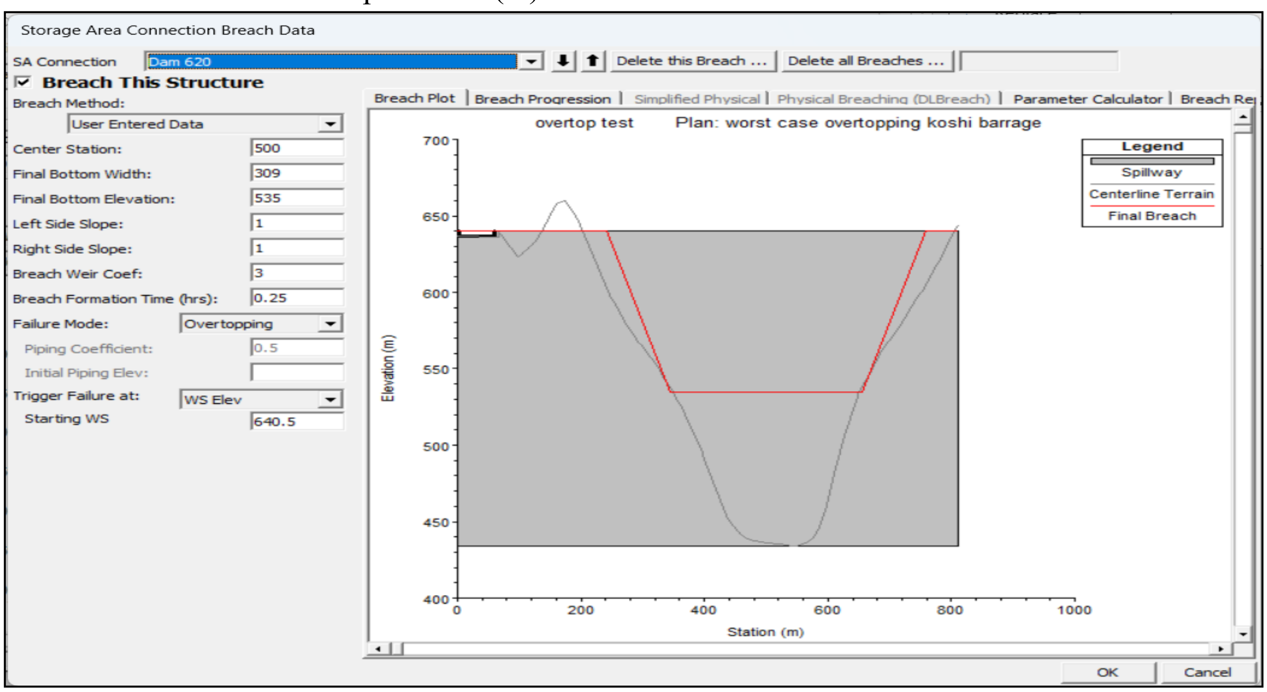

Figure 3: *Worst Case Dam Breach Cross Section for Overtopping Failure*

The worst-case scenario with worst combination of dam breach parameter was provided for dam breach analysis flood hazard mapping. The HEC-RAS dam breach data interface, dam cross section and labyrinth spillway geometry is shown in Figure 3 with input value for overtopping failure worst case scenario.Sensitivity Analysis (SA) is a method for studying model reliability and robustness. It is used to identify the influential parameters and quantify their impact on model outcomes (Saltelli et al.,2004). Monte Carlo filtering is used for local calibration of data set in sensitivity analysis (Saltelli, 2002). Different types, methods and procedures for sensitivity analysis are found in the literature (Saltelli et al.,2021; Ghanem et al.,2017; Iooss et al., 2015; D.G. Cacuci & Ionescu-Bujor, 2005; Frey & Patil, 2002). Local sensitivity analysis (LSA) determines the local influence of input factor variation on the model response (Zhou & Lin, 2008). OAT methods are adequate for linearly varying models while non-linear models with high parameter uncertainty must be analyzed using GSA (Saltelli et al.,2019). (Iooss et al., 2015) presents different methods for global sensitivity analysis. Pseudo global sensitivity with standard deviation-based Monte Carlo simulation was used for the research work (Karki et al., 2022). 3*3*3*3 matrix of four dam breach parameter with three cases will be used to create 81 permutation plans.

4 Results

4.1. Breach Flood Hydrograph

The dam breach analysis was conducted for both overtopping and piping failure modes. Headwater stage hydrograph and tailwater stage hydrograph for overtopping failure are shown in Figure *4* and Figure *5* while breach discharge hydrograph and velocity hydrograph for overtopping failure at dam location are shown in Figure 6 and Figure 7 respectively.

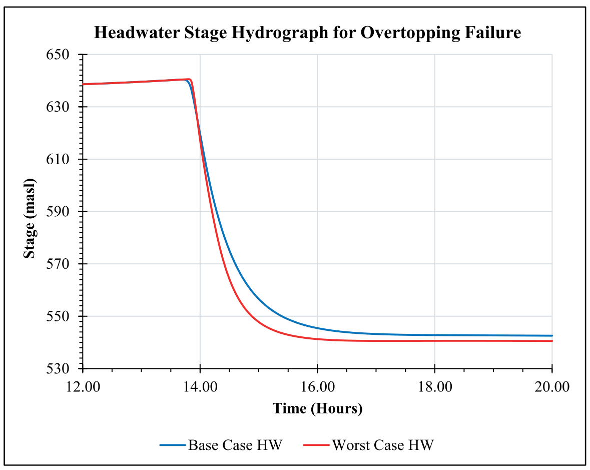

Figure 4: *Headwater Stage Hydrograph for overtopping failure*

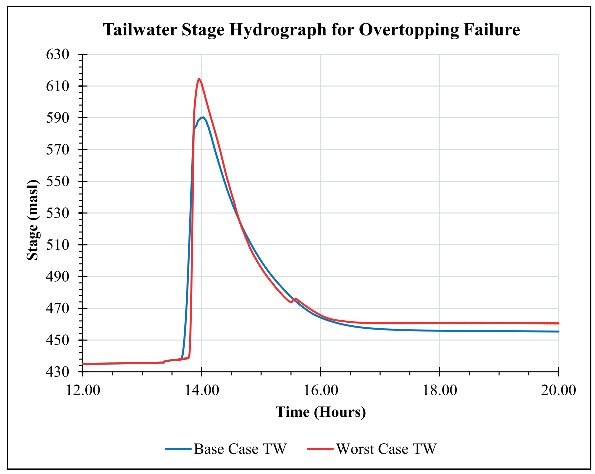

Figure 5: *Tailwater Stage Hydrograph for overtopping failure*

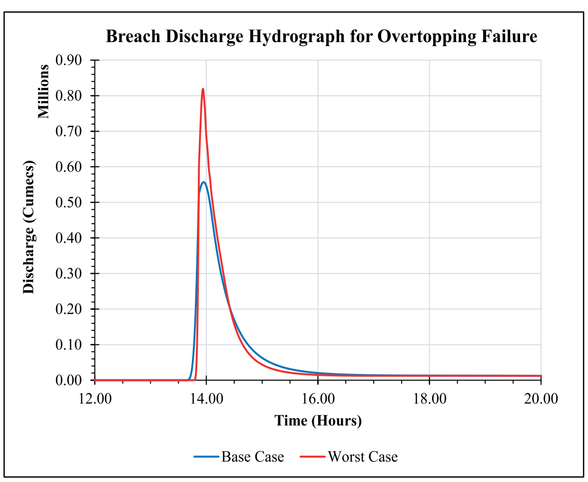

Figure 6: *Breach discharge Hydrograph for overtopping failure*

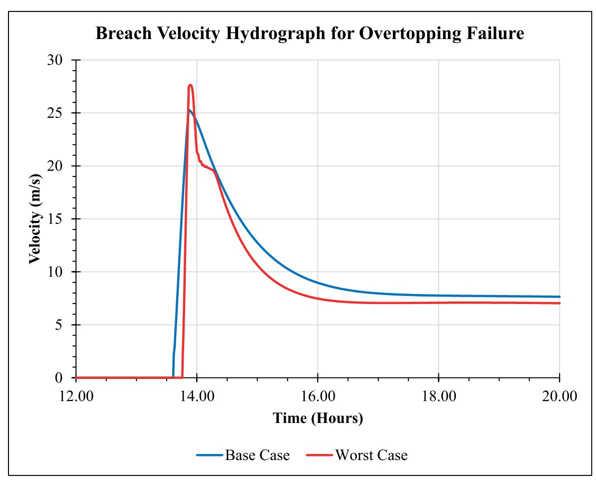

Figure 7: *Breach velocity Hydrograph for overtopping failure*

The flooded area from overtopping failure is only slightly greater than that of piping failure while discharge and velocity for worst case is greater than that for base case scenario as seen in Table 2.

Table 2

Dam Breach flood Hydrograph

Description	Overtopping Failure		Piping Failure	
	Base Case	Worst Case	Base Case	Worst Case
Flooding Area	72.27 km^2	72.31 km^2	67.94 km^2	69.62 km^2
Peak Discharge	556710.69 m^3/s	817456.80 m^3/s	491115.50 m^3/s	753351.60 m^3/s
Time of Peak Discharge	13:57:30 PM	13:56:30 PM	00:24:30 AM	00:11:30 AM
Peak Velocity	25.29 m/s	27.63 m/s	27.63 m/s	29.90 m/s
Time of Peak Velocity	13:52:00 PM	13:53:30 PM	00:15:00 AM	00:06:00 AM

Note. Base case represents average values of breach parametrs while worst case represented worst combination of breach parameters.Time of Peak discharge and velocity is represented from start of simulation at 00:00:00 rather than start of breach.

4.2. Breach Flood Routing

The discharge was routed along R1 and R2 profile for base case and worst-case scenario under overtopping and piping failure case. R1 profile represents river profile from dam location to Sunkoshi bridge outlet located 85km downstream of dam while R2 profile represents river profile from Dudhkoshi-Sunkoshi confluence to Likhu-Sunkoshi confluence.

Table 3

Flood Routing for Overtopping Failure

Scenario	River Profile	Overtopping Failure					
		Peak Discharge [m^3/s]			Arrival Time [hours]		
	R1 R2	0.25 km 1 km	30 km 10 km	Outlet	0.25 km 1 km	30 km 10 km	Outlet
Base Case	R1	554440.56	114739.37	76899.48	13:57:30	15:08:00	18:17:30
	R2	25539.50	12627.43	125.26	16:49:30	16:32:00	16:37:00
Worst Case	R1	810742.25	122779.41	78648.09	13:56:00	14:59:30	18:11:00
	R2	27790.88	13941.19	219.67	16:40:00	16:46:00	16:33:00

Table 4

Flood Routing for Piping Failure

Scenario	River Profile	Piping Failure					
		Peak Discharge [m^3/s]			Arrival Time [hours]		
	R1 R2	0.25 km 1 km	30 km 10 km	Outlet	0.25 km 1 km	30 km 10 km	Outlet
Base Case	R1	488484.22	104858.06	68847.26	0:24:30	1:34:30	4:43:00
	R2	23207.53	11508.02	887.76	3:10:00	3:01:00	3:00:30
Worst Case	R1	748480.56	113088.15	70680.77	0:12:00	1:17:00	4:26:00
	R2	25606.30	12910.41	11.25	2:47:30	2:42:00	2:47:30

Note: The flood routing for R1 profile is done from dam location to Sunkoshi bridge outlet while for R2 profile the routing is done from Dudhkoshi – Sunkoshi confluience upto Likhu – Sunkoshi confluence.The distance value represents river section for R1 and R2 profile respectively.The arrival time is calculated from start of simualtion.

The peak discharge for flood routing is shown in Table 3 for overtopping failure and Table 4 for piping failure.The breach occur immediately after simulation for piping failure as trigger elevation is set at initial water level. Overtopping failure only occurs when the water level rises from full supply level to crest level and finally to overtopping trigger elevation with labyrinth spillway operational. The overtopping occurs nearly 13.5 hours after start of simulation. There is sudden drop in peak at 30km downstream of dam this is due to dispersion of water in Dudhkoshi - Sunkoshi confluence and backwater flow towards Likhu-Sunkoshi confluence.The peak discharge flood routing showed that overtopping failure discharge have higher peak and longer arrival time as compared to piping failure. The worst and base case scenario for both failure modes showed varying behavior in terms of discharge at the start of breach while on downstream end the flood showed similar nature for both scenarios.

4.3. Flood Inundation and Hazard Mapping

Dam breach flood hazard mapping was performed in terms of depth, velocity, arrival time and water surface elevation with Koshi barrage as outlet. (Mudashiru ,2021) reviewed the use of HEC-RAS for flood hazard mapping. The number of local levels affected, number of buildings and length of road network for overtopping and piping failure modes are shown in Table 5.Population at risk (PAR) due to overtopping dam breach failure is 1,34,211 while PAR due to piping failure of Dudh Koshi Storage Hydroelectric Project dam is at 1,21,437.

Table 5
Dam breach flood Hydrograph

Parameters	Overtopping Failure	Piping Failure
Local Level	12 municipality 20 rural municipality Koshi Tappu Wildlife Reserve in 3 districts	12 municipality 21 rural municipality Koshi Tappu Wildlife Reserve in 3 districts
Buildings	28,032	25,343
Roads	812.35 km	776.87 km
PAR	1,34,211	1,21,437

The locality near dam site will be completely destroyed by dam breach in matter of seconds as peak discharge associated with breach is in the range of 0.75 to 0.87 million cubic meter for piping and overtopping failures. The depth of flood reduces along downstream river profile. Water depth is high along narrow river reach while it reduces sideways about the floodplain.The sudden change in depth profile 30km downstream of dam location is due to dispersion of flow along Dudhkoshi - Sunkoshi confluence. The velocity is critical near dam location due to high head associated with overtopping failure.

The inundation mapping shows that Dudh Koshi storage hydroelectric project (DKSHEP) dam breach flood will travel along the river profile until the Dudh Kosh - Sunkoshi confluence, The breach flood will then disperse along Sunkoshi River. Part of flow will move downstream towards Sunkoshi powerhouse tailrace location while another part will backflow upstream towards Likhu – Sunkoshi confluence. The downstream flow will again dissipate along Arun and Tamor confluence at Tribeni before finally moving to Koshi barrage through Chatara. The flood inundation plain due to dam breach under worst case scenario of overtopping failure is shown in Figure 8 and Figure 9 for R1 and R2 profile respectively.

The flood hazard mapping of depth, velocity, arrival time and water surface elevation is shown in Table 6.

Table 6
Flood Inundation and Hazard Mapping

Description	Overtopping Failure	Piping Failure	River Profile
Peak Discharge	866229.40 m^3/s	753341.30 m^3/s	
Flooding Area	686.29 km^2	670.62 km^2	
Depth	0 m - 181 m	0 m - 177 m	R1
	0 m - 80 m	0 m - 78 m	R2
Velocity	0 m/s - 45 m/s	0 m/s - 41 m/s	R1
	0 m/s - 24 m/s	0 m/s - 22 m/s	R2
WSE	75 m - 640.5 m	74 m - 620 m	R1
	400 m - 431 m	400 m - 424 m	R2
Arrival Time	13 hrs - 32 hrs	0 hrs - 20 hrs	R1
	15 hrs – 17 hrs	1 hrs - 3 hrs	R2

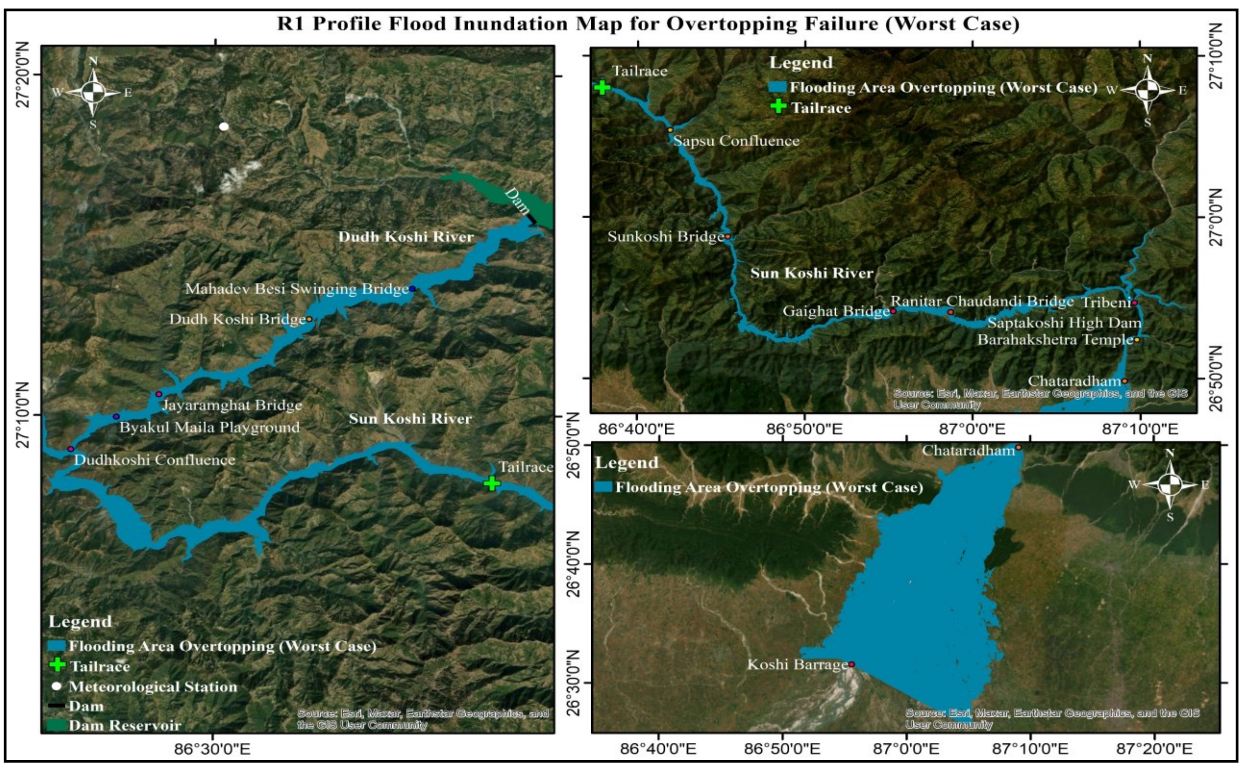

Figure 8: Overtopping Flood Inundation Mapping for R1 Profile

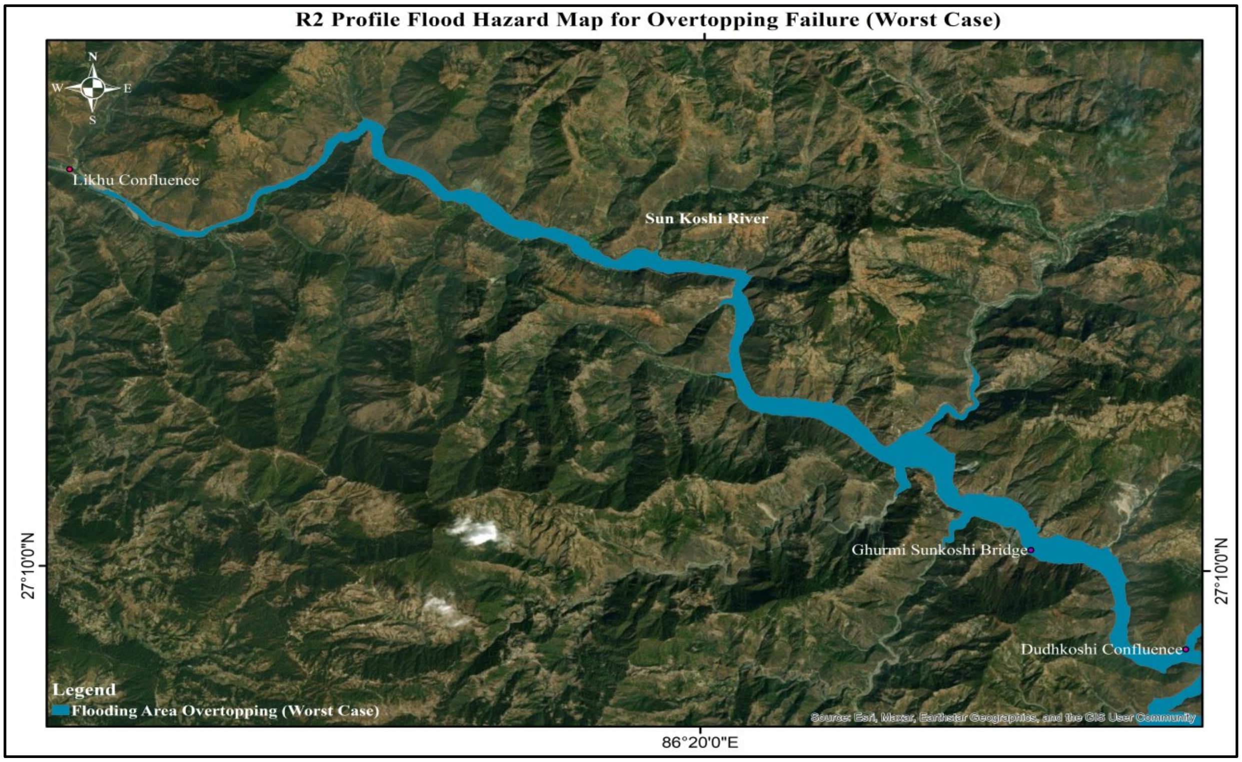

Figure 9*: Overtopping Flood Inundation Mapping for R2 Profile*

The overtopping failure depth mapping for R1 profile is shown in Figure 10 which represents maximum breach flood depth of 112m at Mahadev besi swinging bridge, 106m at Jayaramghat bridge, 75 m at Dudh Koshi - Sunkoshi confluence, 50 m near the tailrace, 47 m at Tribeni, 40 m at proposed Saptakoshi high dam and 2 m at Koshi barrage outlet.

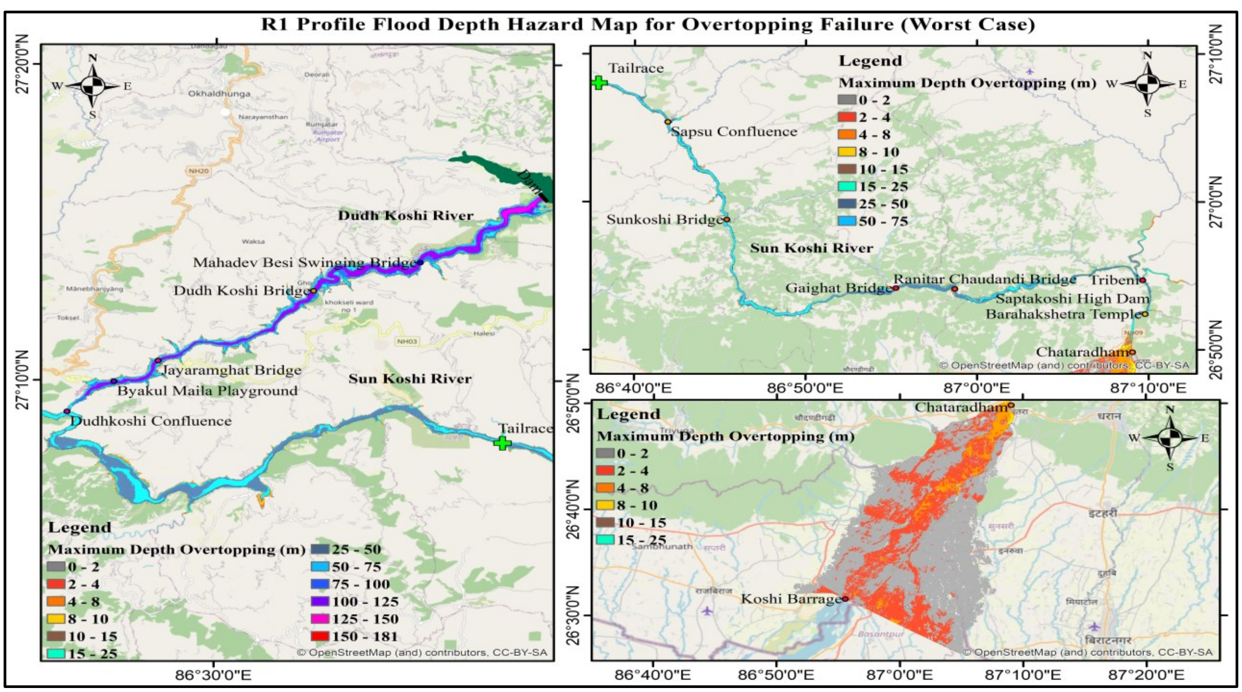

Figure 10: *Overtopping Flood Depth Mapping for R1 Profile*

The depth mapping for R2 profile is shown in Figure 11 which represents flood depth of 53 m at Ghurmi Sunkoshi bridge and 0.02m near Likhu - Sunkoshi confluence.

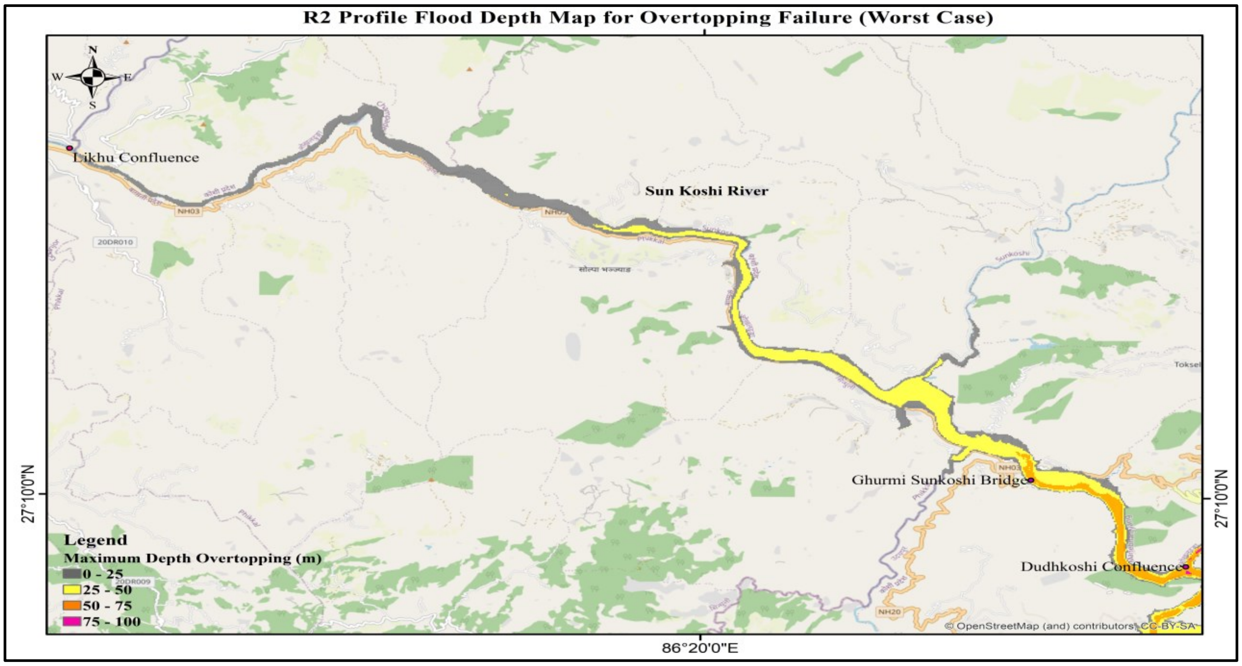

Figure 11: *Overtopping Flood Depth Mapping for R2 Profile*

The maximum velocity at Mahadev besi swinging bridge, Jayaramghat bridge, Dudh Koshi - Sunkoshi confluence, tailrace is 25m/s, 14m/s, 23m/s, 10m/s respectively while maximum velocity is 5 m/s at Tribeni, 11 m/s at proposed Saptakoshi high dam and 4 m/s Koshi barrage outlet for R1 profile as shown in Figure 12.

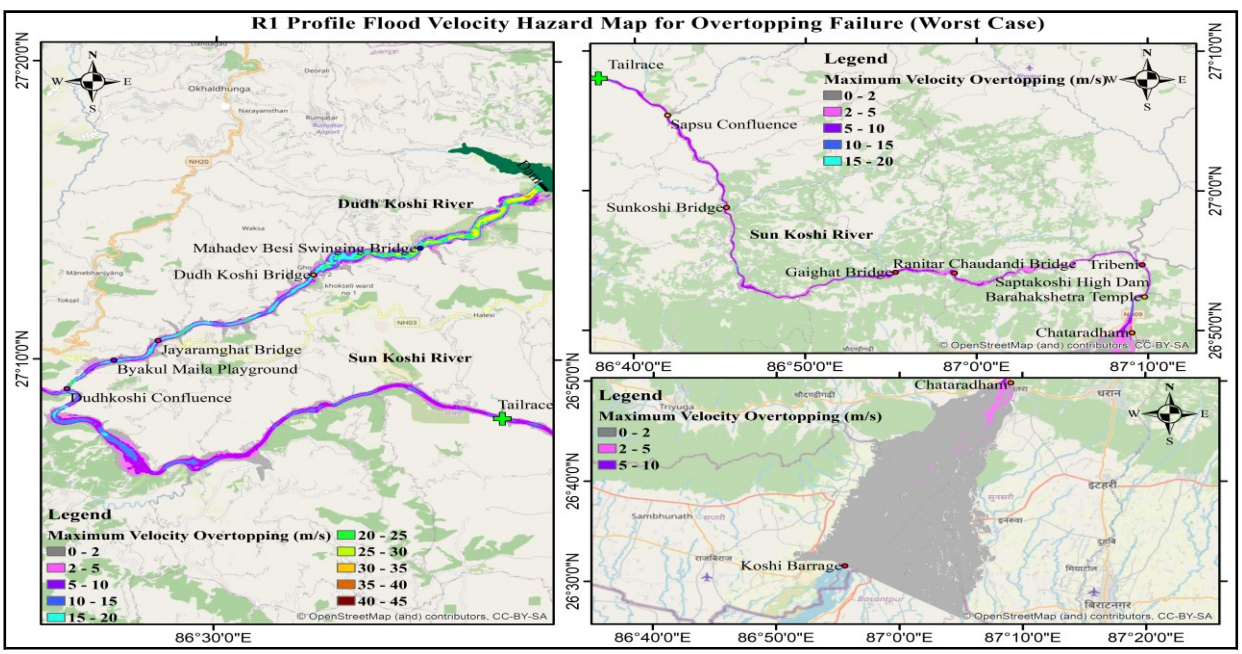

Figure 12: *Overtopping Flood Velocity Mapping for R1 Profile*

The velocity mapping for R2 profile depicts 10m/s at Ghurmi Sunkoshi bridge and 0.2 near Likhu - Sunkoshi confluence as shown in Figure 13.

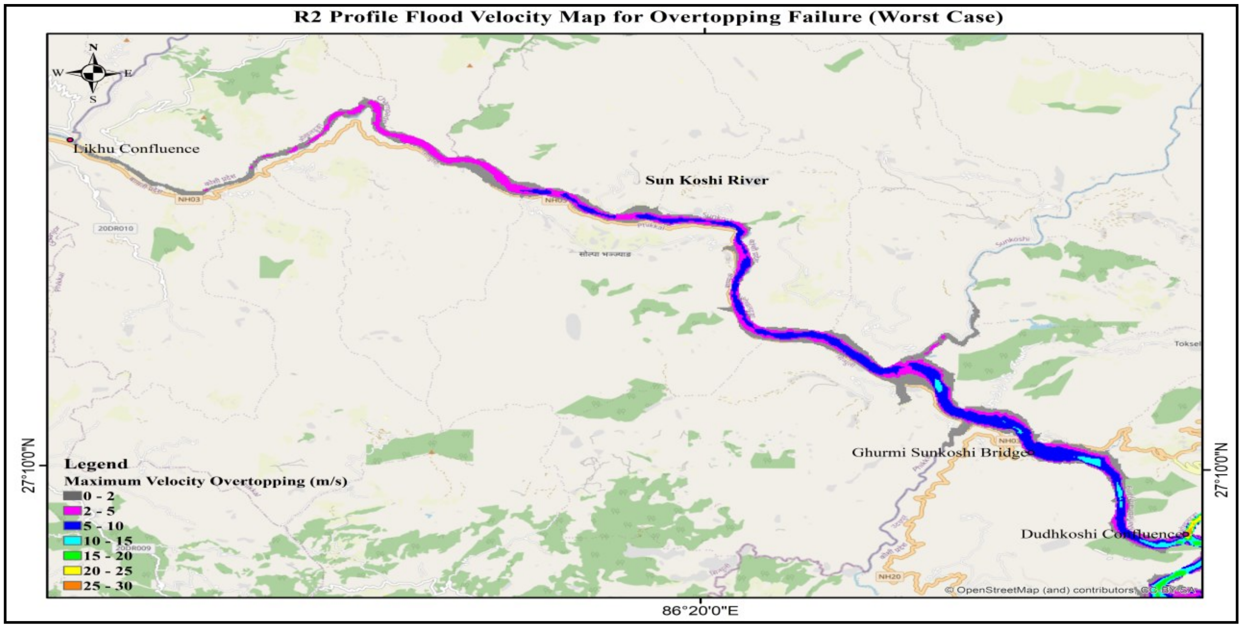

Figure 13: *Overtopping Flood Velocity Mapping for R2 Profile*

The maximum arrival time for breach flood is 14.3 hours at Mahadev besi swinging bridge, 14.8 hours at Jayaramghat bridge, 15.5 hours at Dudh Koshi – Sunkoshi confluence, 17.4 hours at tailrace, 23.4 hours at Tribeni, 23.5 hours at proposed Saptakoshi high dam and 32 hours at Koshi barrage location for R1 profile as shown in Figure 14.

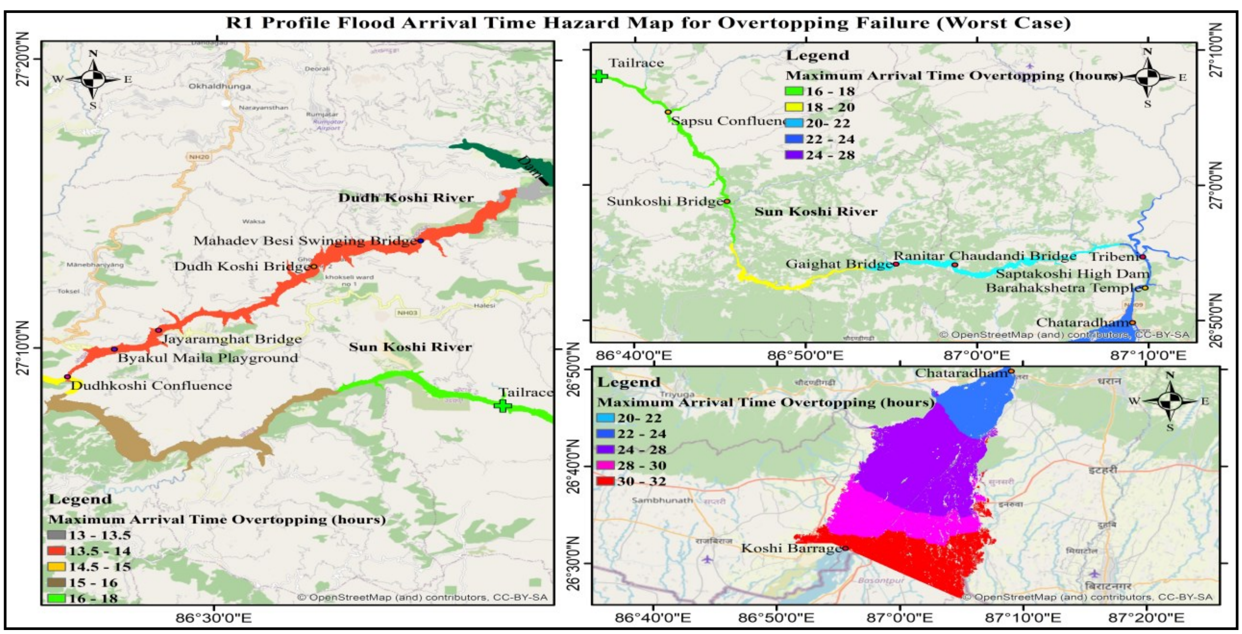

Figure 14: *Overtopping Flood Arrival Time Mapping for R1 Profile*

The maximum arrival time for R2 profile the maximum arrival time is 15.5 hours for Ghurmi Sunkoshi bridge and 16.5 hours near Likhu - Sunkoshi confluence as shown in Figure *14* and Figure 15 respectively.

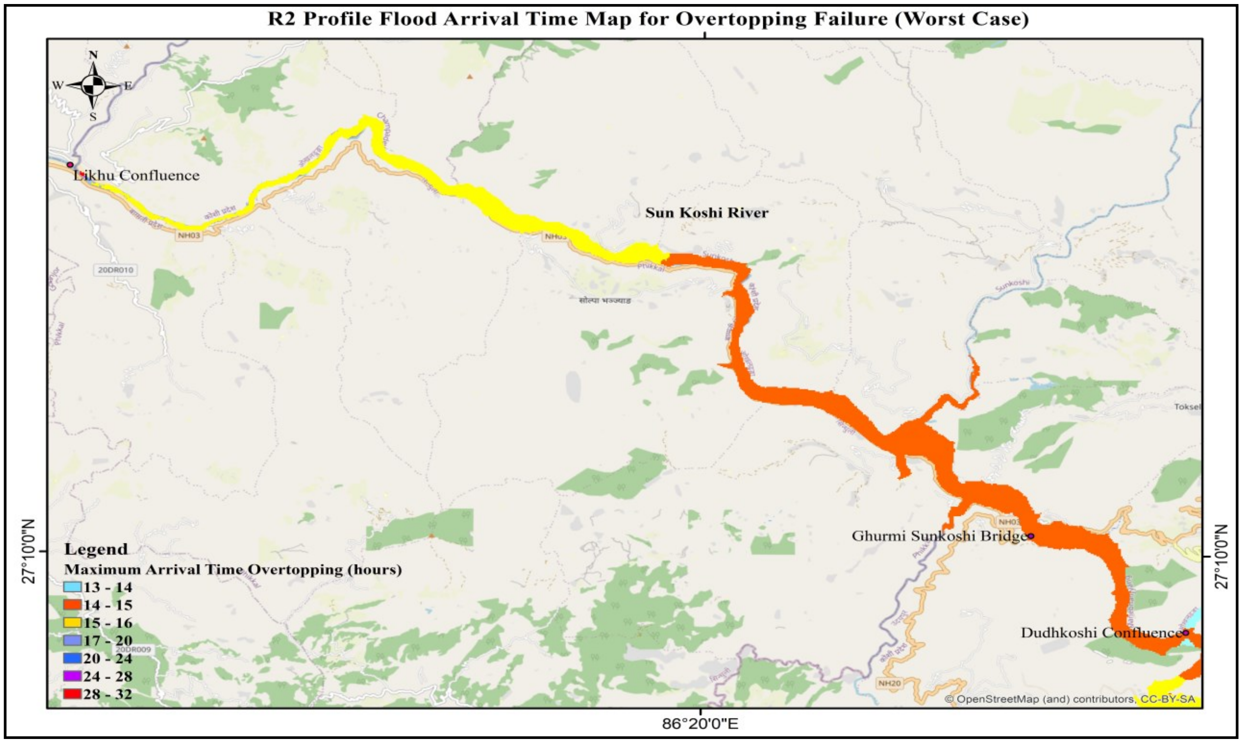

Figure 15: Overtopping Flood Arrival Time Mapping for R2 Profile

4.4. Sensitivity Analysis

4.4.1. Local Sensitivity Analysis

Local sensitivity analysis was performed using one at a time (OAT) approach. Dam breach parameters were ranked on the basis of ratio of percentage change in output per unit percentage change in input. Trigger failure elevation is most sensitive and breach formation time is least sensitive for local sensitivity analysis of peak discharge for overtopping failure while for piping failure weir coefficient is most sensitive parameters and piping coefficient is least sensitive as shown in Table 7 and Table 8.The research results shows that trigger elevation defines the peak discharge , water surface elevation , velocity and arrival time downstream of dam after breach for overtopping failure while weir coefficient is driving factor for piping failure mode for downstream impacts under local sensitivity analysis.

Table 7
Local sensitivity analysis for overtopping failure

Sensitivity on	Overtopping Failure			
	Dam Breach Width	Breach Formation Time	Weir Coefficient	Trigger Elevation
Peak Discharge	0.3657	0.2784	0.7171	10.5255
WSE (R1)	0.0530	0.0182	0.0785	1.5329
WSE (R2)	0.0102	0.0004	0.0106	0.0059
Velocity (R1)	0.1085	0.0838	0.1636	0.2420
Velocity (R2)	0.1666	0.0016	0.1923	0.0469
Arrival Time (R1)	0.0262	0.0131	0.0275	0.1276
Arrival Time (R2)	0.0245	0.0148	0.0286	0.2158

Table 8
Local sensitivity analysis for piping failure

Sensitivity on	Piping Failure			
	Dam Breach Width	Breach Formation Time	Weir Coefficient	Piping Coefficient
Peak Discharge	0.4720	0.3186	0.7275	0.0284
WSE (R1)	0.0644	0.0185	0.0794	0.0365
WSE (R2)	0.0113	0.0003	0.0125	0.0027
Velocity (R1)	0.1068	0.1314	0.1928	0.1183
Velocity (R2)	0.2198	0.0373	0.2511	0.0429
Arrival Time (R1)	0.1179	0.0617	0.1228	0.0645
Arrival Time (R2)	0.1766	0.1115	0.1700	0.0170

4.4.2. Global Sensitivity Analysis

Five lakh sample data within permutation range was used for Monte Carlo simulation with Monte Carlo filtering for outputs results in Origin Pro. Global sensitivity analysis was examined on the basis of variation of standard deviation of outputs with respect to variation of standard deviation of inputs. Dam breach width is most sensitive parameter followed by breach formation time. weir coefficient and trigger failure elevation for global sensitivity analysis of peak discharge for overtopping failure while for piping failure dam breach width is most sensitive parameter followed by breach formation time. weir coefficient and piping coefficient as shown in **Error! Reference source not found.** and **Error! Reference source not found.**.The research result shows that dam breach width is most sensitive parameter for both

overtopping and piping failure hence the width of breach will mainly define the downstream impacts from the breach under global sensitivity analysis of dam breach parameters

Table 9
Global Sensitivity Analysis for Overtopping Failure

Sensitivity on	Overtopping Failure			
	Dam Breach Width	Breach Formation Time	Weir Coefficient	Trigger Elevation
Peak Discharge	46350.57	44264.01	5214.57	468.85
Peak Velocity	0.1186	0.0993	1.2735	0.0026
WSE	0.5993	0.0038	0.0153	0.0081
Arrival Time	0.1727	0.0388	0.0036	0.0590

Table 10
Global Sensitivity Analysis for Piping Failure

Sensitivity on	Piping Failure			
	Dam Breach Width	Breach Formation Time	Weir Coefficient	Piping Coefficient
Peak Discharge	96195.07	31808.50	4259.15	291.53
Peak Velocity	0.0188	0.0114	1.4303	0.0128
WSE	0.8137	0.0019	0.0126	0.0017
Arrival Time	0.1933	0.0541	0.0025	0.0005

6 Discussions

The dam breach analysis of Dudh Koshi storage hydroelectric project (DKSHEP) was performed for overtopping and piping modes of failure under worst case and base case scenario. The results obtained from analysis are summarized as follows:

(1) Overtopping failure was found to be critical mode of dam breach failure for peak discharge and flood plain area while piping failure mode was critical for arrival time. The outflow hydrograph for worst case scenario showed greater discharge, larger flood plain, higher velocity profile and faster arrival time as compared to base case scenario for both overtopping and piping failure modes.

(2) The peak discharge flood routing showed that overtopping failure discharge have higher peak and longer arrival time as compared to piping failure. The worst and base case scenario for both failure modes showed varying behavior in terms of discharge at the start of breach while on downstream end the flood showed similar nature for both scenarios.

(3) The flood routing for proposed Saptakoshi High dam located 143 km downstream of DKSHEP dam location showed peak depth at 40.87 m, peak discharge of 48163.65 m3/s with arrival time at 23.44 hours from start of simulation and 9.67 hours after start of breach. The maximum velocity of dam breach flood is 11 m/s with WSE of 158.86 m for overtopping failure under worst case scenario.

(4) Flood hazard mapping for worst case scenario was performed for Koshi barrage outlet. Peak discharge and flood plain area of overtopping failure was critical. The variation of depth, velocity, arrival time and water surface elevation were studied.

(5) 12 municipality, 20 rural municipality and Koshi Tappu Wildlife Reserve in 3 districts would be affected with 28,032 buildings and 812.35 km of road under dam breach flood risk for overtopping failure. The population at risk is 1,34,211.

(6) 12 municipality, 21 rural municipality and Koshi Tappu Wildlife Reserve in 3 districts will be affected with 25,343 buildings and 776.87 km of road under dam breach flood risk for piping failure. The population at risk is 1,21,437.

7 Conclusions

(1) The breach outflow hydrograph for overtopping and piping failure was determined for base case and worst-case scenario while flood routing was performed up to Sunkoshi bridge outlet.

(2) Flood hazard mapping was performed with respect to depth, velocity, arrival time and water surface elevation at Koshi barrage outlet for worst case scenario under overtopping and piping failure modes. The local levels affected, population at risk of hazard, buildings and roads flooded due to dam breach hazard was determined.

(3) Trigger failure elevation was most sensitive parameter for overtopping scenario and weir coefficient was most sensitive parameter for piping scenario under local sensitivity analysis while for global sensitivity analysis dam breach width was most sensitive for both overtopping and piping failure scenario.

8 Validation

(1) Dam breach parameters were selected as per USACE (2007) guidelines.

(2) Dam breach bottom elevation was selected within dam cross section as per State of Colorado Guidelines for Dam breach analysis (2020).

(3) (Mudashiru et al., 2021) reviewed flood hazard mapping methods which presented use of HEC-RAS 2D model for dam breach flood hazard mapping.

(4) (Psomiadis et al., 2021; Phyou, 2023) concluded that flooded area for overtopping scenario is slightly larger than piping scenario in case of DEM data which aligns with research work.

(5) (Abdulrazzaq et al., 2021) sensitivity analysis for Hamrin Dam showed that increase in DBW increased the peak discharge while increase in BFT decreased the peak discharge.

(6) (Karki et al., 2022) dam breach analysis on Nalgad Hydroelectric Project depicted WC parameter as more sensitive than DBW and BFT for Peak Discharge and WSE while for arrival time, TFE was most sensitive parameter which aligned with result obtained for R1 profile in LSA while for GSA on peak discharge and WSE, DBW was found most sensitive parameter.

9 Limitations

(1) Dam breach flood hazard mapping was done for Koshi barrage outlet while local sensitivity analysis, global sensitivity analysis and downstream flood routing was done for Sunkoshi bridge outlet lying 85 km downstream of dam location.

(2) Dam breach bottom elevation was fixed to 535masl due to cross sectional constraint for both overtopping and piping failure analysis. Gated spillway is assumed to be closed for overtopping failure analysis.

(3) Only four dam breach parameters were considered for sensitivity analysis.

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Open Research

Rainfall data processing was done in excel (Mohanty et al.,2014). Buildings and road shapefile was obtained from geofabric open street map (Singla et al., 2021). Dam breach analysis was performed in HEC RAS 6.4 (Brunner,2014). Flood hazard mapping was performed in ArcGIS 10.8.3 (Negesse et al., 2022). Origin Pro 2022 was used for global sensitivity analysis of dam breach parameters (Karki et al., 2022).

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