Dam Break Flood Hazard Mapping and Vulnerability Analysis in Kulekhani Dam, Nepal

Nabin Shrestha, Upendra Dev Bhatta, Bhola Nath Sharma Ghimire, and Akhilesh Kumar Karna

Abstract Construction of dam serves numerous purposes. Despite all the advantages, failure of dam structures could result in enormous losses in downstream areas due to unexpected floods. So, dam break study is important to reduce threats of flood in downstream areas during dam failure. The present study was conducted in the year 2021–2022 for Kulekhani Dam in Nepal and it helps to prepare dam break flood hazard map, to identify the vulnerability of downstream and to estimate the time for peak discharge to reach at different sections of the river from Kulekhani Dam to Bagmati River. The equations proposed by Froehlich in 2008 and 1995 were used to calculate dam breach parameters and peak outflow respectively. The maximum flood discharge was calculated as 15,303.61 m^3/s. HEC-RAS two-dimensional unsteady flow analysis was performed from which approximately 2.03 km^2 of the downstream area was found to be inundated with maximum flood depth of 31.60 m. The cultivable lands, vegetation, roads, bridges, buildings, electric poles and other infrastructures were found to be vulnerable during flood. The peak flood during the dam breach was estimated to reach different settlements in a time period between 60 and 100 min. The model was validated by comparing simulated flood depth and calculated flood depth using the coefficient of determination, Nash–Sutcliffe Simulation Efficiency, RMSE-observation for Standard Deviation Ratio and Percent BIAS which were found to be 1.00, 0.81, 0.44 and −7.81% respectively, all remaining within a prescribed range. Using flood hazard map and vulnerability of the downstream areas, the local government have to identify areas of risk and only then design and extension of market towns, infrastructures, buildings, etc. should be allowed. Concerned authority, local government and national government together have to perform dam break study and prepare flood hazard map, emergency action plan and standard operating procedure, proper evacuation route and open spaces during a disaster.

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1 Introduction

Natural hazards vary in magnitude and intensity in time and space [1]. Under certain conditions and influenced by triggering factors, they may cause loss of life, destroy infrastructures and properties, impede economic and social activities and cause destruction to the environment and other infrastructures [2]. Flood is defined as an overflow of water that can submerge the land that is usually dry [3]. Floods usually occur during heavy rainfall but there might be situations when dams or water-flowing-path-obstructing structures are suddenly broken down. Floods usually affect the downstream the most but in the context of water reservoirs, they will affect the people at upstream as well [4]. Dams are constructed to address the necessities in the fields of agriculture, water supply and hydropower. According to adverse incremental consequences of failure or misoperation of dams, they can be categorized into three hazard potential classifications as low, significant and high [5]. The structural damage of dam is limited to areas of immediate vicinity of the structure but the failure of dam and sudden release of impounded reservoir water cause destruction over large areas at downstream of the dam [6]. Planning for disasters, providing emergency assistance and issuing flood warnings are the benefits from systematic assessment of the risks presented by potential dam failure [7]. The catastrophic consequences of dam break events urge the need for dam break modeling analysis so as to provide inundation maps at a scale sufficient to determine the extent of flooding, timing of the arrival and peak of flood wave [8]. However, researches on risk management, warning mechanisms and loss assessment considering dam failures have not yet been properly established.

When compared to other types of flooding, floods by failure of dams are distinguished by their sudden occurrence, enormous volume of water flow and strong water forces. High flood, caused by dam failure, travels downstream of the dam and damages people's lives and properties along the flood wave's path [9]. Flood routing is the technique of determining flood hydrograph at a section of river by utilizing the data of flood flow at one or more upstream sections [10] to determine flood protection, flood forecasting, spillway design and reservoir design and estimate peak discharges and stage of discharge in river channel [11]. The hydrologic approach (Muskingum method) and hydrodynamic approach (Saint–Venant equations) are the two methods of flood routing [12]. Flood routing and flood level forecasting can be easily performed using HEC-RAS model as it saves time in calibration of model to determine flood level forecasts [13]. HEC-RAS river network model provides upgraded simulations with better computational routing and supports in importing and exporting GIS data to prepare flood hazard map [14]. Simulated flood depth and observed flood depth were used to validate the HEC-RAS unsteady flow model prepared for Lower Tapi river [15]. HEC-RAS in combination with ArcGIS can be used for flood plain mapping, which provides results that are more realistic and same can be used to prepare decision support system for possible disaster [16].

For effective land-use planning in flood-prone areas and for preparing communities at downstream areas, flood hazard mapping can play a vital role as it creates easily readable, rapidly accessible charts and maps, thus facilitating the identification of areas at risk of flooding and helping in prioritizing mitigation and response efforts during disaster events [17]. Flood hazard maps are prepared to increase awareness of the likelihood of flooding among public, local authorities and other organizations, which encourage people living and working in flood-prone areas to take appropriate actions [18]. The flood hazard map can be used to identify affected areas, flood depth and time of arrival of flood in order to determine flood risk and flood risk management activities [19].

United Nations International Strategy for Disaster Reduction (UNISDR) describes vulnerability as the characteristics and circumstances of a community, system or asset that make it susceptible to damaging effects of hazard [20]. Vulnerability to floods is determined by several factors such as levels of economic status, control over assets and controlling power of hazard or disaster, and livelihood opportunities [21].

Nepal is one of the high potential nation regarding water resources [22]. In Nepal, monsoon brings much of rainfall, which are the main source of water for the rivers [23]. Dams exceeding 15 m in height have been built for tapping the water resource potential. Young geology and active tectonic region with steep topography are contributing factors for disasters like landslides in mountainous terrain, which might trigger the overtopping of natural or artificial dams [24]. During the construction of Kulekhani hydropower power station, heavy rains in 1984 and 1986 triggered slope failures, collapses and landslides around the project area affecting roads, bridges and houses, causing casualties of people [25]. Nepal Electricity Authority initiated Kulekhani Disaster Prevention Project after diversion from dam in its project and has no proper interest in main stretch of Kulekhani River [26] so, the study of river channel and its vicinity is lacking in context of downstream of Kulekhani Dam. Department of Humanitarian Affairs (1994) has recommended for the study of possible dam break of Kulekhani Dam in future and for the assessment of vulnerability, evacuation plans and training for evacuation during possible dam breach condition.

The goal of this study is to develop flood modeling and to prepare flood hazard map in downstream of Kulekhani Dam due to its outbreak condition. The study also helps to identify areas of downstream vulnerable to dam break flood and to estimate probable travel time for peak discharge to reach at different parts downstream of Kulekhani dam located in Indrasarowar Rural Municipality, Nepal.

2 Study Area and Dataset

2.1 Study Area

Location and Physiography

The Kulekhani watershed covers the area of Thaha Municipality and Indrasarowar Rural Municipality in Makwanpur District of Nepal. The watershed is of national importance as it is the source for one and only reservoir type of hydel plant in the country. The hydel plant has rock filled earthen dam of length 406.00 m and height of 114.00 m with gross storage of 94.26 million cubic meters. The study area lies in Mahabharat range consisting of rugged terrain with sharp crests and steep slopes [27]. The study area covers the area from Kulekhani Dam to Bagmati River within Indrasarowar Rural Municipality. Indrasarowar rural municipality lies in north-eastern part of Makwanpur district of Bagmati province in Nepal (Fig. 1). Palung River feeds the watershed from west to east and Chitlang River from north to south. River tributaries like Tistung River, Chitlang River, Thado River, Chalku River and Bisingkhel River combine to form Kulekhani River. The study area can be divided into two zones as warm temperate humid zone and cool temperate humid zone. The average temperature of warm temperate humid zone ranges between 15 and 20 °C and for cool temperate humid zone, it ranges between 10 and 15 °C. The average annual precipitation over the watershed is about 1500 mm [28].

Kulekhani Dam

The Kulekhani dam is located at a latitude of 27°35′26″N and at a longitude of 85°09′20″E. Kulekhani dam is zoned rock-fill dam with inclined core zones, filter core zones, quarry rock zones and random rock zones. The dam is 114.00 m high with 10.00 m wide and 406.00 m long crest. The crest lies at an elevation of 1534.00 m. The foundation has been made impervious by excavating the bedrock and grouting in the foundation to eliminate seepage. In 2018, from bathymetric survey the sedimentation rate of Kulekhani reservoir was measured to be 5216 m^3/km^3/year with minimum bed level near the intake of Kulekhani I hydropower project of 1459.83 m [29].

2.2 Dataset

Data from governmental and non-governmental sources were acquired for the study (Table 1).

Meteorological Data

Flood and its behavior are dependent on the characteristics of catchment area, hydro-meteorological conditions, soil characteristics and terrain of the catchment area [30].

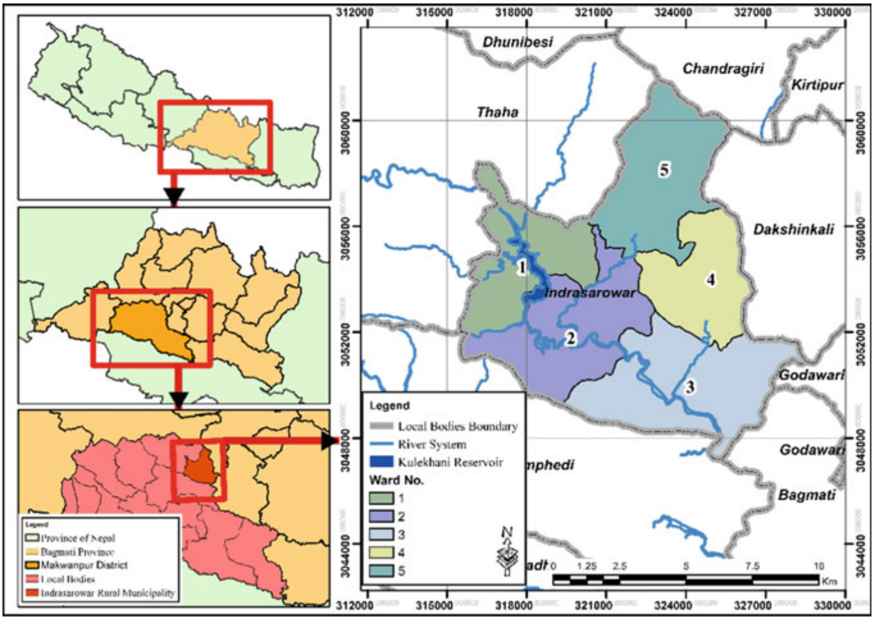

Fig. 1 Location map of indrasarowar rural municipality

Table 1 Dataset used for study

Dataset	Data type	Source
Digital elevation model (DEM)	Raster	Earthdata
Precipitation	Excel file	Department of hydrology and meteorology, Nepal
Landcover	Vector file	Department of survey, Nepal
Satellite image	Raster	Google earth

Rainfall intensity and duration of rainfall also play a vital role in the flood development in any watershed [31]. In case of dam break flood, hydro-meteorological conditions and soil and terrain characteristics are important [32]. There is one meteorological station within the catchment of study area at Markhugaun. Precipitation data of the station was obtained from Department of Hydrology and Meteorology, Nepal. The meteorological data were used to generate hydrograph at the dam site.

Digital Elevation Model (DEM)

Elevation data are important in each flood modeling technique [33]. DEM data of 12.5 × 12.5 m grid have been obtained from ALOS palsar (Fig. 2). The elevation data were used to create Triangular Irregular Network (TIN) for the preparation of geometric data.

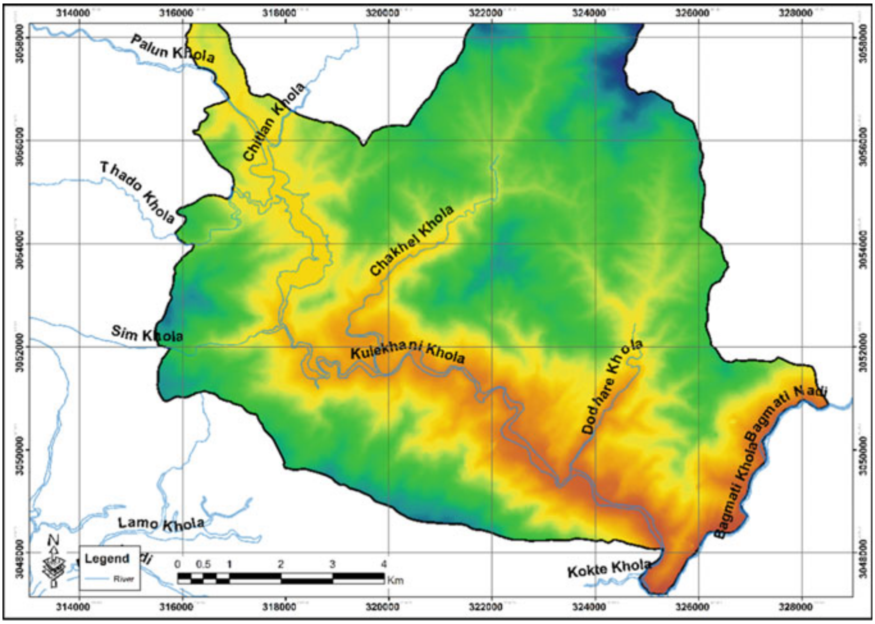

Fig. 2 DEM of study area

Landcover, Settlement Name

Landcover information is important in modeling of floods and assessing the vulnerability of the communities at downstream [34]. Landcover data and name of settlement were obtained from Department of Survey of year 2000, which was updated using satellite image captured on April 2021 (Fig. 3). Landcover data are important in determining Manning's coefficient of the study area.

3 Methodology

For the preparation of flood hazard mapping and vulnerability analysis in downstream of Kulekhani Dam due to dam break situation, the Kulekhani dam was initially classified according to dam hazard potential using FEMA Dam Safety guidelines. There are numerous causes of dam failure among which overtopping failure and piping or leakage failure are the most dominant type of failure than spillway erosion, sliding, faulty construction, gate failure, excessive deformation and earthquake instability. The Kulekhani Dam failure was analyzed for overtopping failing scenario. Dam breach parameters were estimated using available empirical equations for the final breach depth of the dam taken as 60 m. Using flow regression equation, the peak flow at different breach depths were computed at different intervals of time, which

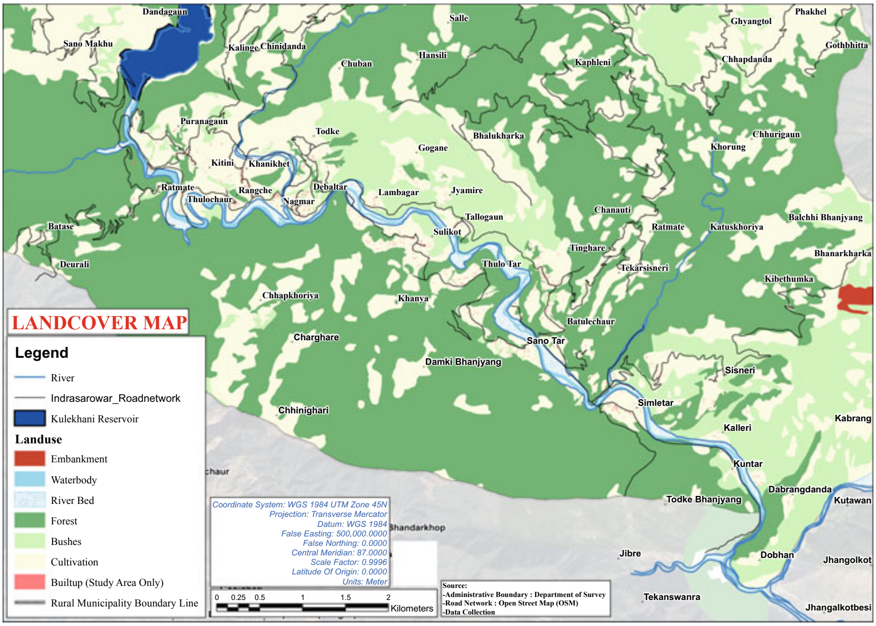

Fig. 3 Landcover map of study area

was used to prepare dam breach hydrograph. The dam breach outflow hydrograph was used for the modeling, which was routed for downstream areas to determine peak flood wave and time of travel of flood wave. With all available data which include DEM, Manning's roughness coefficient and dam breach hydrograph, HEC-RAS model was prepared and then analyzed for obtaining the flood hazard map. The flood hazard map was finalized after validation of the model and vulnerability analysis of the downstream was performed. The flowchart of the methodology is described in Fig. 4.

3.1 *Dam Hazard Potential Classification*

Flood has a great influence on its vicinity area and has effects on settlements, households and land-use. According to the probability of loss of human life and economic, environmental and lifeline losses, the dams can be classified into three hazard potentials i.e., low, moderate and high [3].

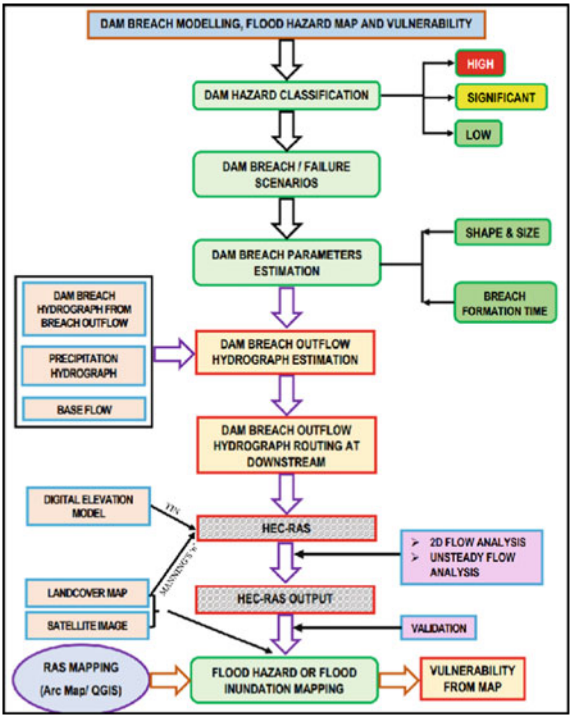

Fig. 4 Flowchart of methodology

3.2 *Dam Breach Parameters and Peak Outflow*

During dam break modeling, dam breach parameters have to be identified to predict breach width and breach development time. Formation of breach in dam and shape of breach govern the impact of flood wave at downstream. Numerous empirical formulae have been proposed for the determination of final breach width and breach formation time. Froehlich has studied numerous earth dams and proposed empirical formula to determine breach parameters. Equation provided by Froehlich (2008) was used to determine the final dam breach width and breach formation time. Among the proposed empirical formula, regression equation provided by Froehlich (1995) was used for estimating peak discharge. The variation of peak flow with respect to time was computed to prepare dam breach hydrograph. The superposition of dam breach hydrograph, precipitation hydrograph and base flow of the river were used to prepare final dam breach hydrograph. The final dam breach hydrograph was routed using Muskingum routing equation based on specification of the space and time intervals to determine the peak flow and travel time of flood wave at downstream areas.

Table 2 Manning's coefficient

Categories	Range	Adopted value
Buildings	0.050–0.120	0.050
Bushes and cultivation	0.025–0.050	0.030
Forest	0.045–0.150	0.045
Riverbed and waterbody	0.025–0.050	0.025

3.3 HEC-RAS Analysis

HEC-RAS 6.0 software was used for flood simulation. For the study area, Manning's roughness coefficient was adopted according to changes in landcover data (Table 2). Final flood hydrograph and frictional slope were used as upstream and downstream boundary conditions. With all data and information required for the model, two-dimensional unsteady analysis was performed.

3.4 Model Validation

Model validation was performed by comparison between simulated depth and calculated depth using statistical equations. Coefficient of determination (R^2), Nash–Sutcliffe Simulation Efficiency (NSE), RMSE-observations standard deviation ratio (RSR) and Percent Bias (PBIAS) were used to evaluate model prediction.

3.5 Flood Hazard Mapping and Flood Vulnerability

Flood hazard map was prepared after the validation of the model. The map was prepared to provide information about inundation areas, inundation extents and inundation depths [35]. Flood vulnerability due to outbreak of Kulekhani dam was analyzed with guidance from flood hazard map. For ease of the study and to prepare plans for future disaster risk reduction and management activities, the vulnerability levels were classified into five levels, namely, very low, low, moderate, high and very high with respect to flood depths (Table 3).

Table 3 Vulnerability level for classification

Hazard and vulnerability level	Flood depth (m)
Very low	<0.5
Low	0.5–1.5
Moderate	1.5–2.5
High	2.5–5.0
Very high	>5.0

4 Results and Discussion

4.1 Dam Breach Analysis

During overtopping failure of Kulekhani Dam, the final breach width of the dam was calculated as 140.32 m with breach formation time of 0.84 h. The maximum discharge of 15,303.61 m^3/s was attained at 50 min from the start of dam breach. The final hydrograph at dam was prepared which was used as input boundary condition. The probable time for peak discharge to reach at 1.00 km, 2.00 km, 5.00 km, 7.00 km, 10.00 km and 12.00 km downstream were estimated to be about 52 min, 55 min, 67 min, 75 min, 88 min and 96 min respectively (Fig. 5). The probable time for peak discharge to reach at 5.30 km, 6.70 km, 8.86 km, 9.51 km, 10.45 km and 11.06 km downstream were estimated to be about 68 min, 74 min, 83 min, 86 min, 90 min and 92 min respectively. HEC-RAS two-dimensional unsteady flow analysis was performed to measure simulation depth at different chainages. The flood depths at 5.30 km, 6.70 km, 8.86 km, 9.51 km, 10.45 km and 11.06 km were simulated to be 12.41 m, 11.19 m, 6.91 m, 6.90 m, 11.39 m and 12.66 m respectively (Table 4).

4.2 Model Validation

The simulated depths and calculated depths (Table 4) were compared for the validation of model. The computed result of $R^2 = 1$ (which is >0.5) depicts flood depths from model can be predicted at any chainage at downstream without error. NSE = 0.81 (which lies between 0.0 and 1.0) implies that model is superior and accurate representation of real system. The RSR = 0.44 (which lies between 0.0 and 0.5) indicates that model simulation performance is better. The PBIAS = −7.81% (which is negative and <10%) indicates that the model is overestimation bias but lies within acceptable range indicating very good performance rating. From the statistical calculation, all four values remain within the prescribed range indicating validation of the model.

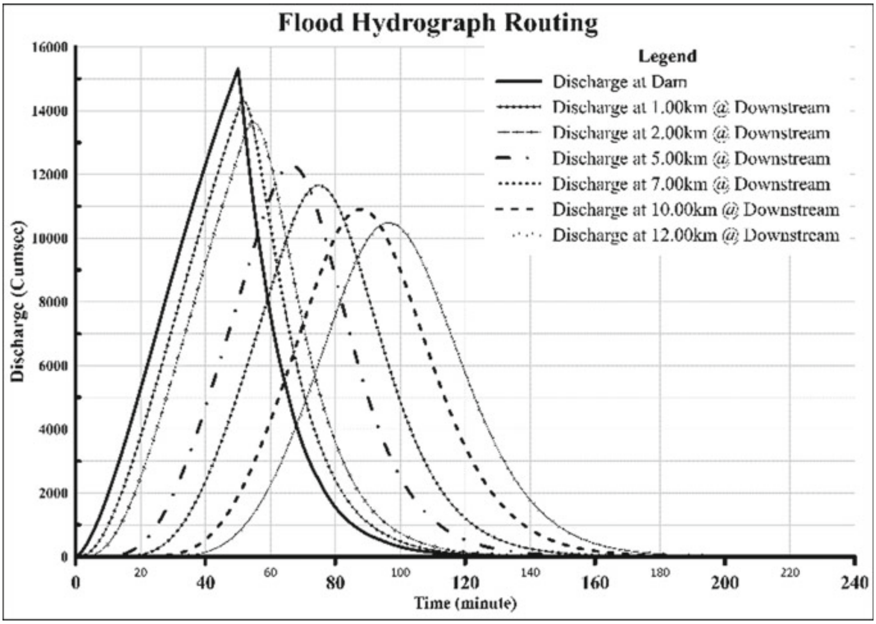

Fig. 5 Flood routing of Kulekhani dam outbreak flood

Table 4 HEC-RAS model flood depth and calculated flood depth at different sections

Chainage	HEC-RAS depth (m)	Calculated depth (m)
5 + 300	12.41	11.30
6 + 700	11.19	10.34
8 + 860	6.91	6.72
9 + 510	6.90	6.79
10 + 450	11.39	10.43
11 + 060	12.66	11.39

4.3 Flood Hazard Mapping and Flood Vulnerability

The flood hazard mapping was done after validation of model. The flood map shows approximately 2.03 km^2 of downstream land areas to be inundated with varied flood depths with maximum depth being 31.60 m. The major settlements at Thulochaur, Nagmar, Debaltar, Lambagar, Tallagoun, Sanotar, Simletar and Kuntar are inundated during flood events (Fig. 6). As shown in Fig. 6, the Pharping-Kulekhani road (at the vicinity of dam and at section 8.85–10.50 km downstream) and other feeder roads will be inundated during flood. There is a high possibility of failure of bridge at the base of dam, bridge over Chakhel River and circular pipe bridge at Simletar. The flood will also affect the electric poles installed at the banks of river. Approximately 292

Fig. 6 Flood hazard mapping of dam outbreak (*Source flood hazard analysis*)

buildings were found to be vulnerable (Fig. 7) during the flood which might displace approximately 1262 people. From the study, 35.95% of buildings lie in "very highly vulnerable" areas followed by 29.10% in "highly vulnerable" areas. Only 9.93% of buildings are located in "very low vulnerable" areas. About 364,055 m^2 of vegetation and 571,614 m^2 of cultivable areas were found to be inundated (Fig. 8). Among these calculated areas, maximum areas of vegetation and cultivable areas were found to lie in "very high vulnerable" region while least areas of vegetation and cultivable areas were found to lie in "very low vulnerable" regions.

5 Conclusion and Recommendations

From numerous available empirical equations, Froehlich equation provides the most satisfactory result for earthen dams. During overtopping failure of dam, the final breach width was calculated to be 140.32 m. The estimated peak discharge was computed to be 15,303.61 m^3/s which was attained after 50 min of starting of breach of dam. The simulation results in inundation of 2.030 km^2 downstream, which inundates settlements of Thulochaur, Nagmar, Debaltar, Lambagar, Tallagoun, Sanotar, Simletar and Kuntar. The roads, bridges, buildings, electric poles, etc. are the vulnerable infrastructures during disastrous flood events. The peak discharges after

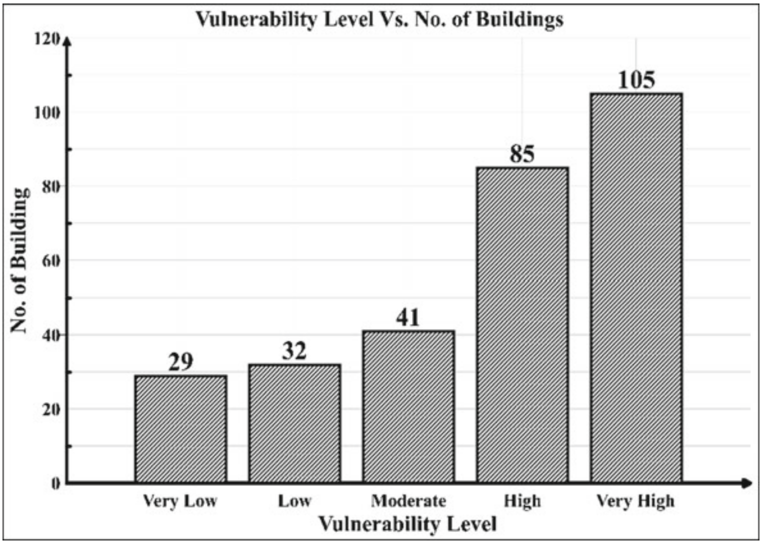

Fig. 7 Vulnerability level and building count

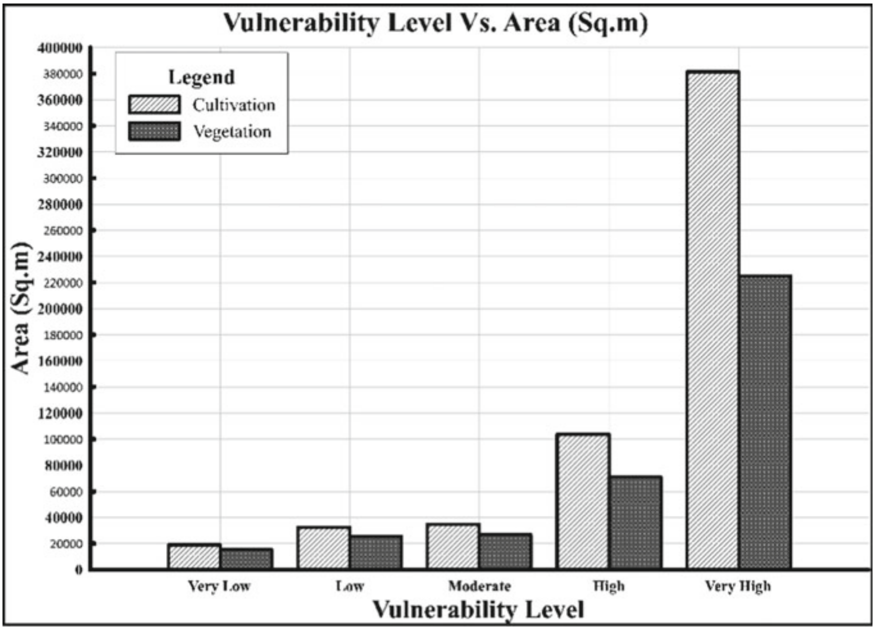

Fig. 8 Vulnerability level and vegetative and cultivable areas (*Source* Flood Hazard Map and Landuse Map)

breach of dam reaches different settlements between 60 and 100 min. Use of two-dimensional unsteady flow analysis in HEC-RAS is suitable to prepare flood hazard map during flood events. Concerned authorities, local governments and national government should perform dam break study for constructed dams or dams being constructed to identify risk areas for disastrous events then only extension of infrastructures and development activities should be allowed. Emergency action plans and standard operating procedures have to be prepared for possible disastrous events.

References

1. UNDRR (2022) Understanding disaster risk. Prevention Web. https://www.preventionweb.net/understanding-disaster-risk/component-risk/hazard
2. Dutta D, Teng J, Vaze J, Lerat J, Hughes J, Marvanek S (2013) Storage-based approaches to build floodplain inundation modelling capability in river system models for water resources planning and accounting. J Hydrol 504:12–28
3. WHO (2022) World Health Organization. https://www.who.int/health-topics/floods#tab=tab_1
4. Fread DL (1996) Dam-breach floods. In: Hydrology of disasters. Springer, Dordrecht, pp 85–126
5. FEMA (2004) Federal guidelines for dam safety: hazard potential classification system for dams. U.S department of homeland security federal emergency management agency
6. Charles JA (2011) Delivering benefits through evidence: lessons from historical dam incidents. Project
7. Michaud J, Johnson C, Iokepa J, Marohnic J (2005) Methods for estimating the impact of hypothetical dam break floods. In: Chemistry for the protection of the environment, vol 4. Springer, Boston, MA, pp 195–199
8. Zagonjolli M (2003) Dambreak modelling analysis
9. Katopodes ND, Strelkoff T (1978) Computing two-dimensional dam-break flood waves. J Hydraul Div 104(9):1269–1288
10. Hossain MM (2014) Analysis of flood routing. Dhaka Univ J Sci 62(2):69–73
11. Ogbonna D, Okoro BC, Osuagwu JC (2017) Application of flood routing model for flood mitigation in Orashi river, south-east Nigeria. J Geosci Environ Protect 5(03):31
12. Cunge JA (1969) On the subject of a flood propagation computation method (Musklngum method). J Hydraul Res 7(2):205–230
13. Hicks FE, Peacock T (2005) Suitability of HEC-RAS for flood forecasting. Can Water Resour J 30(2):159–174
14. Yang J, Townsend RD, Daneshfar B (2006) Applying the HEC-RAS model and GIS techniques in river network floodplain delineation. Can J Civ Eng 33(1):19–28
15. Timbadiya PV, Patel PL, Porey PD (2011) HEC-RAS based hydrodynamic model in prediction of stages of lower Tapi River. ISH J Hydraul Eng 17(2):110–117
16. Khattak MS, Anwar F, Saeed TU, Sharif M, Sheraz K, Ahmed A (2016) Floodplain mapping using HEC-RAS and ArcGIS: a case study of Kabul River. Arab J Sci Eng 41(4):1375–1390
17. Bapalu GV, Sinha R (2005) GIS in flood hazard mapping: a case study of Kosi River Basin, India. GIS Dev Weekly 1(13):1–3
18. Environment Agency (2010) Flood Map—your questions answered. Environment Agency, Rotherham
19. Mao J, Wang S, Ni J, Xi C, Wang J (2017) Management system for dam-break hazard mapping in a complex basin environment. ISPRS Int J Geo Inf 6(6):162
20. UNISDR (2021) https://www.unisdr.org/files/7817_UNISDRTerminologyEnglish.pdf

21. Pelling M (1997) What determines vulnerability to floods; a case study in Georgetown, Guyana. Environ Urban 9(1):203–226
22. Upadhyay SN, Gaudel P (2018) Water resources development in Nepal: myths and realities. Hydro Nepal: J Water, Energy Environ 23:22–29
23. WECS (2011) Water resources of Nepal in the context of climate change. Government of Nepal, Singha Durbar, Kathmandu
24. NDRR Portal (2021) Nepal disaster risk reduction portal. Retrieved from Nepal Disaster Risk Reduction Portal. http://drrportal.gov.np/risk-profile-of-nepal
25. JICA (2002) Kulekhani disaster prevention project. https://www.jica.go.jp/english/our_work/evaluation/oda_loan/post/2002/pdf/113_full.pdf
26. NEA (2016) Nepal electricity authority a year in review-fiscal year 2015/2016. Nepal electricity authority, Durbarmarg, Kathmandu
27. Pradhan AMS, Dawadi A, Kim YT (2012) Use of different bivariate statistical landslide susceptibility methods: a case study of Khulekhani watershed, Nepal. J Nepal Geol Soc 44:1–12
28. Shrestha S, Khatiwada M, Babel MS, Parajuli K (2014) Impact of climate change on river flow and hydropower production in Kulekhani hydropower project of Nepal. Environ Process 1(3):231–250
29. NEA (2018) Bathometric survey of Kulekhani reservoir. Nepal Electricity Authority, Kathmandu
30. Stein L, Clark MP, Knoben WJ, Pianosi F, Woods RA (2021) How do climate and catchment attributes influence flood generating processes? A large-sample study for 671 catchments across the contiguous USA. Water Resour Res 57(4): e2020WR028300
31. Cheng Y, Sang Y, Wang Z, Guo Y, Tang Y (2021) Effects of rainfall and underlying surface on flood recession—the upper Huaihe river basin case. Int J Dis Risk Sci 12(1):111–120
32. Tedla MG, Cho Y, Jun K (2021) Flood mapping from dam break due to peak inflow: a coupled rainfall-runoff and hydraulic models approach. Hydrology 8(2):89
33. Xu K, Fang J, Fang Y, Sun Q, Wu C, Liu M (2021) The importance of digital elevation model selection in flood simulation and a proposed method to reduce DEM errors: a case study in Shanghai. Int J Disaster Risk Sci 12(6):890–902
34. Prachansri S (2007) Analysis of soil and land cover parameters for flood hazard assessment. International institute for geo-information science and earth observation, Enschde, Netherlands
35. Kikuchi R (2003) Flood hazard map manual for technology transfer. International training program on total disaster risk management