RESEARCH PAPER

AI-Enhanced Dam Break Analysis and Environmental Impact Assessment Using HEC-RAS and Machine Learning

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Abstract: Dams serve several important functions including water storage, irrigation, production of hydropower, and flood control. Nevertheless, construction of a dam can lead to catastrophic failures and resulting downstream flooding which can have devastating environmental and social consequences. This paper describes for the first time an integrated framework based on hydraulics and artificial intelligence (AI) for conducting dam break analyses and environmental impact studies. For this study, several potential breaches of the Khadakwasla Dam in Pune, India, were simulated using the HEC-RAS modeling software. From these simulations, detailed maps of downstream flood and other hydrological parameters were producedA machine learning model based on the Random Forest method was built to figure out the risk of flooding. The model produced an overall accuracy of 93.33% and uniform cross-validation accuracy in categorizing an area into flood risk zones - low, moderate, high, or severe - based on the outputs of the hydraulic simulations. Analysis of the model attributes demonstrated that flood depth and flood velocity were the strongest predictors of risk. The modeling used in conjunction with AI flood risk assessment provides the framework for predictive flood modeling, and helps to streamline emergency response and environmental risk mitigation strategies. The framework gives a first-order estimate for how hydraulics and data-driven methods can be used to plan for preventing flooding.

Keywords: *Dam Break Analysis, HEC-RAS, Flood Risk Classification, Machine Learning, Random Forest, Environmental Impact Assessment, AI-Based Risk Modeling*

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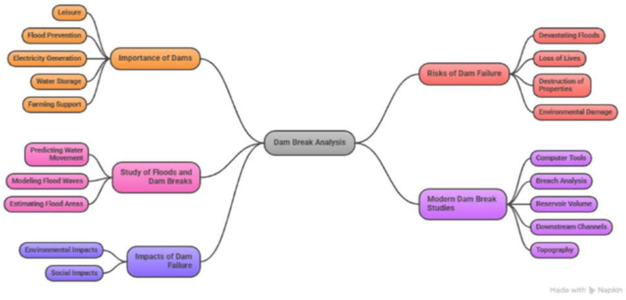
1. Introduction

In society, dams are important because they provide leisure, prevent flooding, make electricity, store water, and help with farming [1]. They regulate flow of rivers and store large volumes of water, which aid in generation of renewable energy, support agriculture, supply water for municipalities and industries, and help control the damage of floods. When it comes to dams, the biggest worry is that they might not be strong enough. An unanticipated failure of a dam can result in devastating floods, resultant loss of lives, destruction of properties, and damage to the environment that can be for a long time [2]. The study of floods and dam breaks looks at the hydraulic and water factors that happen when a dam breaks[3]. This study includes predicting the water movement after a dam breach, creating a model for the positive and negative flood wave, and estimating the negative flood areas to which water will flow[4]. This study is useful to be able to make and design emergency response actions and risk mitigation actions in order to protect an ecosystem and the people. The modern dam break studies uses computer studying tools to analyze and study the breach, the volume of the reservoir, the channels that are found downstream, the topography, and other important factors[5]. The accurate flood studies will help the planners, and the managers for floods to be able to efine the areas that are prone to flooding[6]. The impacts of a dam failure are especially worse for the environment.

Sharp, large-scale water releases result in the destruction of riparian habitats, erosion of riverbanks, displacement of aquatic organisms, and geomorphological alterations to river systems[7]. The flooding of farmland can pollute, silt, and debris downstream ecosystems, and affect the fertility of soil and the quality of water[8]. The long-term environmental impacts of these activities are the loss of biodiversity, the disruption of hydrological cycles, and the increased susceptibility to flooding[9].

Fig. 1. Dam Break Analysis Process



In closing, the importance of dams for socio economic development is clear, while the risk of dam failure has critical implications for people and the environment[10]. The analysis of dam failure risk provides a scientifically based approach to risk evaluation, flood impact simulation, and the preparation and response to emergencies[11]. From an engineering, ecology and socio-environmental perspective, the analyses are designed to mitigate the risk of catastrophic dam failure and promote sustainable, integrated, and adaptive management of water resources[12]. New developments in artificial intelligence and machine learning have sped up the process of automatically assessing risk and predicting floods[13]. When you use both empirical models and hydraulic models together, you can get the most accurate predictions of flood damage and the best emergency management[14]. This study, therefore, seeks to develop a hybrid approach to automated flood risk assessment based on HEC-RAS hydraulic modeling and the Random Forest algorithm[15], [16].

2. Related Work

Flood management, risk assessment, and emergency preparedness have all benefitted from dam break flood analysis. In 2023, Chongxun Mo and others came up with another way to figure out how likely it is that a dam will break and cause flooding[17]. This assessment is concerning the Chengbi River Dam in Baise, China, and HEC-RAS 2D simulations were used to consider flood risk for three breach schemes (full, half, and one-third dam breach). Findings show that the flooding process is comparable regardless of breach; however, it does show that flooding is less severe with a half breach as opposed to a one-third or full breach. The resultant flow balance flood risk assessment identified and prioritized flood risks; in particular, Longjing Street, deemed highly flood vulnerable, encompassed over 65% of the identified total flood risk areas. This research demonstrated a highly rational and vulnerable methodology toward flood risk. Aissam Gaagai et al. (2022) also looked at the risks of dam break floods, like they did with the Yabous Dam in northeastern Algeria[18].

Using a one-dimensional HEC-RAS model, different breaks were generated, which helped this study find effect zones in wild and urban areas further downstream. To find out how sensitive the flood wave is to breach formation factors like width, slope, and time of formation, the results were used. As the breach width and slope increased, the height, speed, and width of the flood waves also increased significantly. On the other hand, the time at which the breach formed seemed to have the opposite effect. These results show how understanding breach parameters can affect flood risk analysis and help make better plans for managing flood risk. It was also helpful to know how to model the breach and make plans for what to do in case the dam breaks in order to figure out the risk of flooding. In contrast to this study, M F M Amin et al. (2022) looked at things from a different angle[19]. They used open-source GIS tools and data to look at different floods situations that could happen if the case dam broke and the effects those scenarios would have. For the study of the Puah Hydropower Dam under the PMF (Probable Maximum Flood) state, Google's satellite images, OpenStreetMap, and flood danger maps (made from modelling the hydrodynamics) were all used together. The study found that the dam break affected 187,000 people and many roads and social service areas. This study showed how useful open-source tools can be for figuring out flood risks and making plans for emergencies. This makes disaster management better and protects the public better.

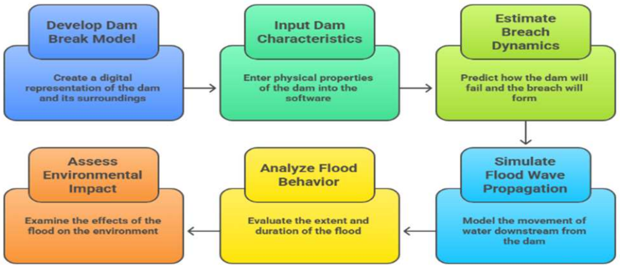
With an emphasis on GIS-based tools, this study gained a new perspective on assessing impacts of floods and planning evacuation strategies in case of dam failures. Bharath et al. (2021) looked at how HEC-RAS and HEC-GeoRAS could be used to study the Hidkal Dam in Karnataka, India, and how it might break[4]. The study used the one-dimensional hydraulic model HEC-RAS along with HEC-GeoRAS to figure out the shapes of rivers and make maps showing where they would flood. The study's findings under PMF conditions of an overtopping failure revealed a substantially greater peak flow and inundated area than a piping failure. This study substantially aided local authorities in planning flood mitigation and preparedness to possible dam failure scenarios. The study underscored the role of hydraulic models for assessing dam break scenarios and reinforced the necessity for an adaptable flood analysis to support robust emergency planning. Rajesh did a dam break study for the Idamalayar Dam in Kerala, India, in 2025. This dam was the site of significant floods in 2018. The study used HEC-RAS to model and look at the breach outflow hydrograph. This helped figure out the highest flows and flood stages in the areas further downstream[20].

The study highlighted the necessity of innovative floodplain management techniques and early warning systems in flood-prone areas. The study also helped make emergency plans and flood prevention tactics better in the area by showing how a possible dam failure would affect areas further downstream. The findings demonstrated the importance of advance planning and prompt action in case of dam breaks.

3. Research Method

HEC-RAS is a tool for modelling river hydraulics that was made by the U.S. Army Corps of Engineers. One of the most important things about HEC-RAS for dam break research is that it can describe how flood waves move[21]. In other words, it can be used to model the flood wave propagation that would be the result of the failure of an upstream dam.

Fig 2. Research Method



One-dimensional (1D) and two-dimensional (2D) flows can be modelled in the program, which is important for simulating how water moves after a dam breaks[22]. HEC-RAS helps study the dam's physical features, figure out how the break will develop, and guess how the flood will react[23]. This program can also analyze the environmental effects of floodwaters by quantifying the areas and periods of inundation and the velocities of the floodwaters.

3.1 Objectives of Dam Break Analysis Using HEC-RAS

Using HEC-RAS for dam break analysis is mostly about simulating water when dams fail and going into depth about the environmental impacts that might happen[21]. HEC-RAS provides the means to analyze how various breach scenarios such as full, partial, or sudden breach flooding situations, and their consequent effects on the downstream environment[24]. In this analysis, the modeling of environment risk areas explains the potential of environment Water and flooding erosion, and vegetation destruction, and the contamination of waters. It provides estimates on the aforementioned factors, in addition to the period of flooding, the levels of water and the rate of flow. Furthermore, HEC-RAS provides support for the modeling of risk areas and erosion of the environment, thus providing aid in the assessment for the destruction of environment zones over a slope model toward destruction flow of the dam[25]. In addition to helping with the creation of the emergency plan, this information also helps with figuring out the risks of the flood and the damage it does to the environment, as well as how to keep people safe in the affected area and during the flood in case the dam breaksIt shows how the fall wall was built. It shows the layout of the protective and preventative zones, construction of controlling the floods to mitigate the destruction of the dam collapsing.

3.2 Data Collection and Preparation

Dam break analysis using HEC-RAS is supported by effective data collection methodology and data colllection approach. The data's accuracy and overall quality determine outcomes. Topographic, hydraulic and, hydrologic are examples of data types needed for the development of a reliable model of the dam and river system[26]. Topographic data is neccessary to build a model of the river and floodplain. The data is usually represented in the form of elevation maps, river cross sections and, bathymetric surveys. The data tells us about the shape and the structures of the river bed. The Dashboards are modelled to ensure that data is represented accurately to ensure a reliable representation of the flood. The model also helps assess the environment and bed structures of the river. The flow also alters and changes the shape of the environment. This model is also used to assess the structure of the environment and river bed. Lastly, to assess the structure of the river the model is used. The hydraulic model is best suited to assess the structures and evaluated the façades of the river. The walls of the river are the best models. The environment and the structure of the river, model the flow of the river. It helps build a reliable assessment. For the flow of the river, the model is also used to assess the structure of the river. This information provides insight into the dam's relationship with the river and its surroundings, including riverbed roughness, flow velocity, and discharge rate. Accurate hydraulic data is fundamental for predicting what will happen after a dam failure and how downstream flooding will develop. Lastly, breach parameters alongside meteorological and hydrological data are essential for sufficient breach modeling. For modeling a dam breach and the subsequent outflow of water, breach parameters like the width, depth, and formation time of the breach are imperative. Weather data, like rainfall, temperature, and evaporation, are also essential to model runoff and flooding, leading to a dam breach. Hydrological data, including river flow data and the parameters of the area's watershed, aid in determining the flow rate of water in the case of a dam breach. These data points, when analyzed together, serve to enhance the quality of flood simulations in HEC-RAS.

The flood risk classification using machine learning was based on HEC-RAS hydraulic simulations under several dam breach scenarios. From these simulations, 200 spatial sample points were collected, offering a range of downstream distances from the dam.

Each data instance included the following features:

- Distance from Dam (km)
- Terrain Elevation (m)
- Flood Depth (m)
- Flow Velocity (m/s)
- Water Surface Elevation (m)
- Flood Duration (hours)
- Land Use Category

Based on hydraulic severity thresholds derived from simulation results, each sample was labeled into one of four risk categories:

- Low

- Medium
- High
- Severe

Using stratified sampling to keep class balance, the sample was split into 70% training data and 30% testing data.

3.3 Machine Learning-Based Flood Risk Classification

A Random Forest algorithm was used to automatically sort flood risk into different groups. Random Forest is an ensemble learning method that builds many decision trees during training and uses a majority vote to decide how to classify them.

The input feature matrix is defined as:

X = [Distance, Elevation, Depth, Velocity, WSE, Land Use, Duration]

The output variable y represents flood risk category.

Random Forest Prediction Equation

Each decision tree produces a class prediction:

$h_t(x)$

The final prediction is determined by majority voting:

$$\hat{y} = \text{mode}\{h_1(x), h_2(x), \ldots, h_T(x)\}$$

GridSearchCV with 5-fold cross-validation was used to tune hyperparameters and improve model performance.

3.4 Performance Evaluation Metrics

The model performance was evaluated using standard classification metrics:

Accuracy

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN}$$

Precision

$$Precision = \frac{TP}{TP + FP}$$

Recall

$$Recall = \frac{TP}{TP + FN}$$

F1-Score

$$F1 = 2 \times \frac{Precision \times Recall}{Precision + Recall}$$

3.5 Model Setup in HEC-RAS

Once all the necessary data has been gathered, the next step in the dam break analysis method is to set up the model in HEC-RAS. This process entails building the geometric model, which describes the river system's details, including river reach, river centerline, river cross-sections, floodplains, etc. We used open-source geographical data to make this model, which is the starting point for modelling the river system's dam break flow. It is important to be clear about where the dam is and exactly where it will break. These are the things that determine the flood simulation. The next step, after the geometric model is created, is to set the hydraulic system boundary conditions. Without which, the modeling of movement of water into and out of the river system remains incomplete. For the system breach, the flood limit conditions are set by the breach position, the shape and size of the breach, and the rate at which the dam fails.

On the other hand, the conditions at the downstream limit are set by the natural flow of the river. Most of these border conditions come from data that has been recorded or collected in the past.

The HEC-RAS program allows users to configure many breach scenarios to model dam failures and their repercussions to proximate regions[27]. Typical breach scenarios include full breach (S1), where the dam entirely fails and therefore, maximum discharge occurs; partial breach (S2), which simulates a controlled breach (or failure) and subsequently, a smaller discharge occurs; and slow breach (S3), where the breach occurs in steps (gradually) and a discharge delay occurs. HEC-RAS is able to model each of these individual scenarios to assist in predicting the scope of damage and to help understand the degree of flooding, the velocity in which the water would flow, and the potential damage to an environment for each breach scenario.

3.6 Simulation of Flood Propagation

After a dam breaks, HEC-RAS gives us a model of how floods spread, which includes a flow study that looks at water speed, water depth, and the length of the flooding. The results of the program help us figure out how far the floods will go in the places further downstream. One-dimensional (1D) and two-dimensional (2D) flow modelling are both part of the app. In 1D modelling, the flow is simulated along the river channel, and the speed and depth are found for a number of chosen cross sections. This works well for channels that are thought to be straight. On the other hand, for 2D modeling, flow is simulated and calculated over a grid that spans the entire floodplain, and this will provide a lot of information for areas of the floodplain and for urban areas that are considered to be complicated.

3.7 Analysis of Environmental Impact

Evaluating flooding's environmental consequences is essential for analyzing dam breaks. The HEC-RAS model helps determine flooding's effects on the environment. An environmental consideration is the possible erosion and subsequent sedimentation of the soil. Eroded soil is an erosion sedimentation process, and the effects can be harmful. The land that is flooded can also be restitution of an agricultural area. The ecosystem of the stream is also damaged, and the quality of the water is decreased. This is caused by the accumulation of sediments and erosion of soil, negation the land, and altering habitats. The addition of the breach of the dam is the loss of the vegetation and the habitats. The water that floods flows over the land and floods the habitats that are natural and the plants and animals are destroyed. The alarming loss of plant and animals in the area is mainly a result of the loss of the ecosystem. Economic losses are caused by the losses of vegetation, animal and plant, water sources. However, quality of water is also decreased significantly. The water that flows floods the plants and animals, and their remnants, and the water that floods the stream becomes not safe for human consumption. This is the result when the water is flooded on a natural habitat.

By predicting the potential contamination of water resources, the flow velocity and flood duration incorporated in the HEC-RAS simulations assist in the management and safeguarding of water resources.

3.8 Risk Assessment and Mitigation Strategies

Risk analysis and mitigation strategies are the foundation of dam break study. HEC-RAS produced flood simulation results which were used to identify the areas of the greatest risk. HEC-RAS produced inundation maps that identify areas of high risk which then guide the appropriate investment risk mitigation strategies including the construction of levees and flood walls, the installation of flood early warning systems, and the emergency action planning system to safeguard life, property, and the environment. Evacuation plans, flood control structures, and measures to protect risk areas (e.g., wildlife, and agriculture) are included in the action plans. These strategies are designed to preserve life and property and to improve preparedness to manage the consequences of a dam failure.

3.9 AI-Based Flood Risk Classification

The optimized Random Forest model has shown a test accuracy of 93.33% on the 60 sample testing dataset. The model got a macro-average F1 score of 0.89 and a weighted F1 score of 0.93, which means it did a good job of classifying all the risk levels. The model also demonstrated 100% precision for risk zones for severe flooding, which shows the model's strength in pinpointing the most critical zones. The cross validation scores showed the model was consistent and stable, as the accuracy was greater than 92% for all the folds. When the most significant predictors for the model were assessed. the most notable were flood depth & flood velocity, and, flood duration & distance from the dam were subsequent predictors.

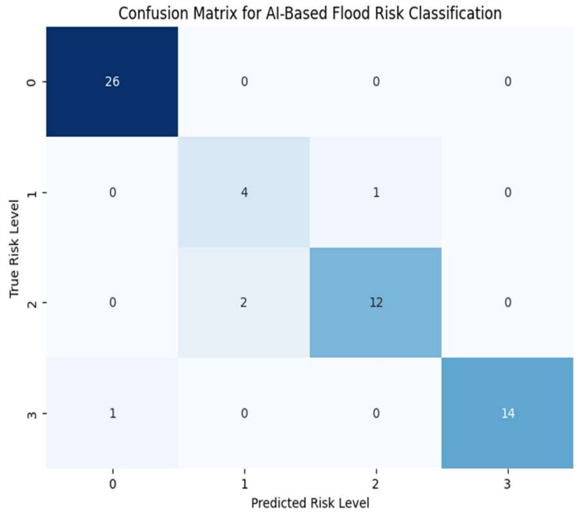


Fig. 3 Confusion Matrix for AI-Based Flood Risk Classification

It can be seen in Figure 3 as the Random Forest Classifier's uncertainty matrix. The model was right 93.33% of the time and correctly identified the most dangerous and least dangerous areas. The only minor classifications observed consist of a few medium-risk zones and the overlapping hydraulic features.

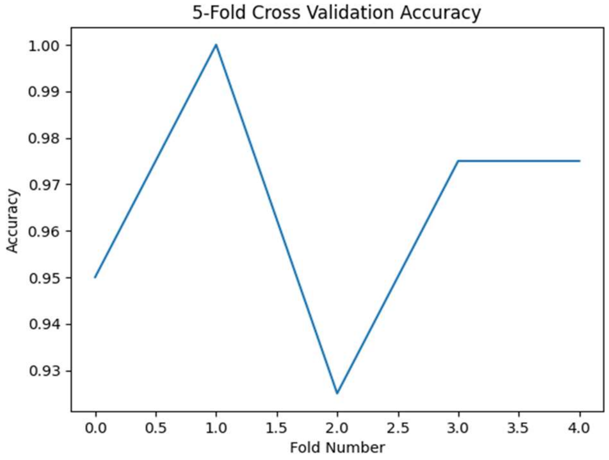


Fig. 4 Five-Fold Cross Validation Accuracy

Based on 5-fold cross-validation, Figure 4 shows how stable the model is. The model has always had a success rate above 92%, which proves that it is reliable and can be used in many situations.

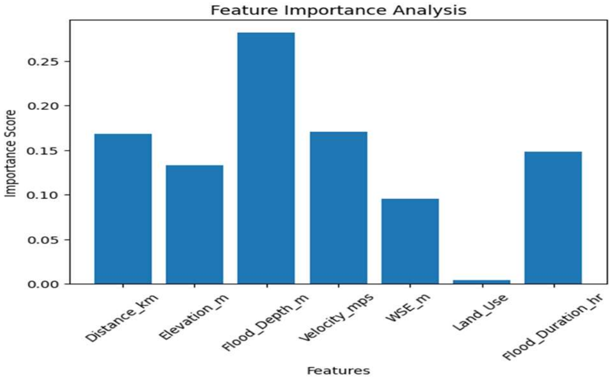


Fig. 5 Feature Importance Analysis

Figure 5 illustrates that the depth and the velocity of the flood are the most critical aspects that influence risk classification. Relative to the hydraulic parameters, the effect of land use is minimal, which means that the severity of the flood is primarily determined by the hydraulic behavior.

4. Case Study

Khadakwasla Dam is a major irrigation and drinking water resource in Pune district, Maharashtra, IndiaIt's 560 meters above sea level and lies at 18.582° N and 73.971° E in terms of latitude and longitude. Situated on the Mutha River, which is a primary river that supplies water to the city of Pune, the Khadakwasla Dam has a total reservoir capacity of 30 million cubic meters and a catchment area of 116 km2. The dam is intended to provide for the rural and urban communities surrounding the dam, and inestimably support agricultural operations and the drinking water needs of the near communities. There are thousands of urban and peri-urban residents of Pune that will be impacted by an active dam failure, and the risk in this area is warranted.

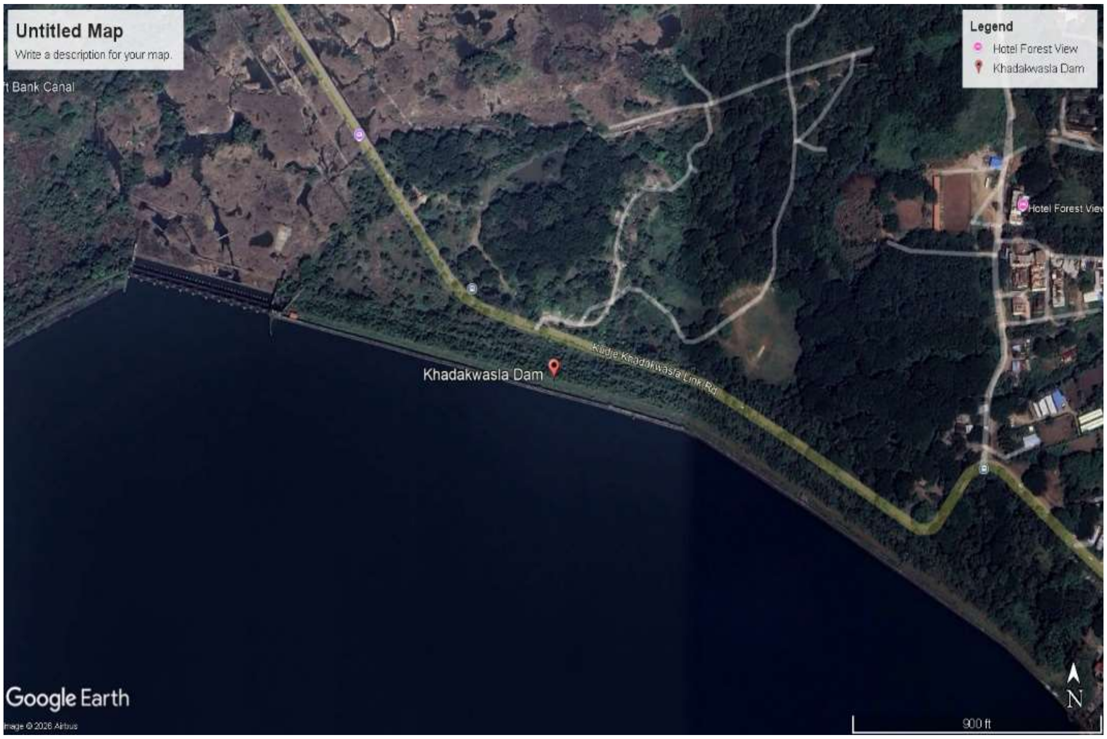


Fig.6 Khadakwasla Dam Location Map

As the water rose from a broken dam, it would affect many towns, farms, and man-made buildings further downstream. The flooding impacts are determined by how large the breach is, how much water is present, and the downstream topography. The worst thing that could happen is that the dam would break. The water would rush out quickly, drowning places in Pune and nearby towns that are lower to the ground. The peak flow and duration of flooding will be determined by the dam's integrity, the slope of the land, and the speed of the flowing water. The downstream areas have a high population concentration and the breach of the dam would result in many people dying, a lot of property being lost, and many essential services being disrupted. The breach would be disastrous for the environment, because the dam breaking would cause soil erosion, loss of vegetation, and the water would become contaminated. Sudden flooding would destroy local ecosystems, especially in the river, the banks, and the surrounding farmland. For disaster preparedness the authorities in this region need to understand flood risks and look at many cause scenarios to understand a dam breach to understand the impacts of a dam failure.

5. Results and Discussion

The Khadakwasla Dam in Pune's dam break study showed the damage that could happen to the area and facilities if the dam broke without warning. With the help of the HEC-RAS model, predictions were made about the flood's depth, speed, land elevation, and other factors. From the flood hazard maps, the areas downstream that were urbanized and/or used for agriculture were the most susceptible, with posed a considerable flood threat with a peak water surface elevation between 541.11 to 660 metres. Flooding velocity was also found to be up to 5 m/s, with most of the concentration towards the dam and downstream, which poses the potential for infrastructure and erosion damage. The model also provided clear pictures of the surrounding slope and terrain which affected the way flood water was to be spread, with lower areas of the terrain facing rapid flooding. The overall results of the study indicate the measures that need to be taken to manage and control the potential effects of flood water to protect the surrounding areas with the possible breach of the dam.

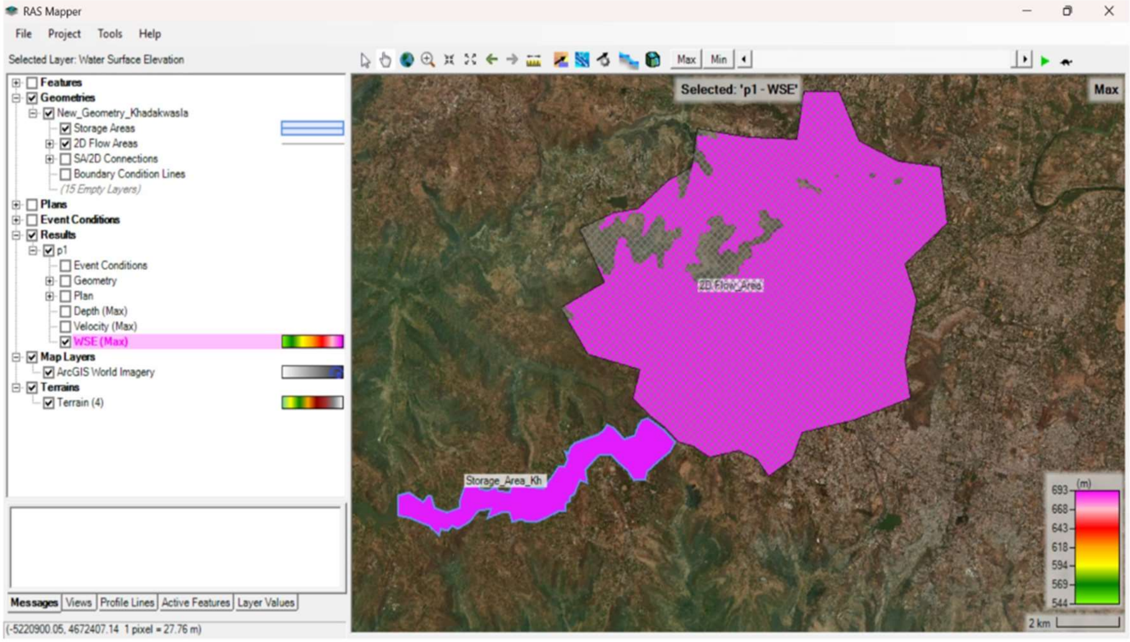


Fig. 7 Khadakwales Dam Inundation Area

Figure 7 depicts the inundation area created by the dam break simulation of the Khadakwales dam located in Pune. Using the HEC-RAS model, the magenta-highlighted area shows how far the leak water is expected to spread. The map shows the extent of the spread, resulting in the inundation of the critical urban and agricultural areas located downstream of the flood. The worst-case breach simulation was used and the flood depth rapidly increases as the breach occurs. The right side of the image shows the color scale pertaining to the water surface elevation (WSE) ranging between 541.11m - 660m. The spillage scenario presents the dam break scenario of the project, which also presents the need of the flood risk management and the emergency preparedness to be focused on.

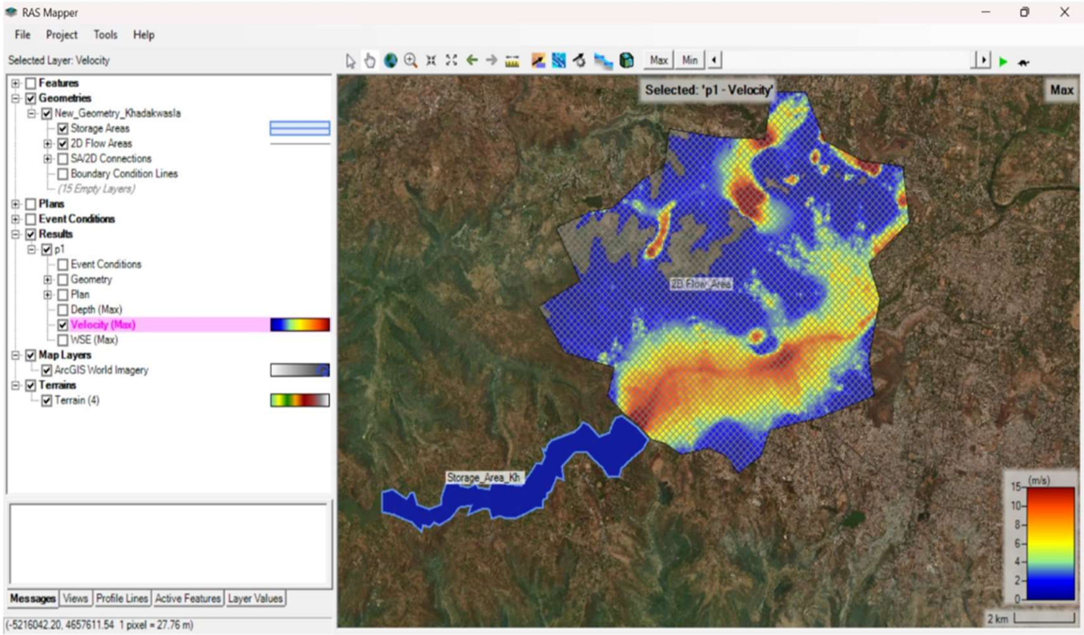


Fig. 8 Dam Break Flood Velocity Distribution - Khadakwales Dam

Figure 8 shows how the crosswise flow speeds are likely to be spread out at the Khadakwales Dam if the dam fails, causing floods in the nearby areas, as predicted by the HEC-RAS model. The places that are most likely to flood are shown by colour variations from blue (0 m/s) to red (0–5 m/s), with red showing the worst floods. Areas closest to the dam appear to be at the greatest risk for their velocity and therefore, the potential for rapid and erosive flow. Understanding the velocity of the floodwaters and the potential for erosion and structural damage, as well as loss of life, enables more effective floodplain management by focusing attention on areas likely to be at the greatest risk for the structural failure of dissipating floodwaters.

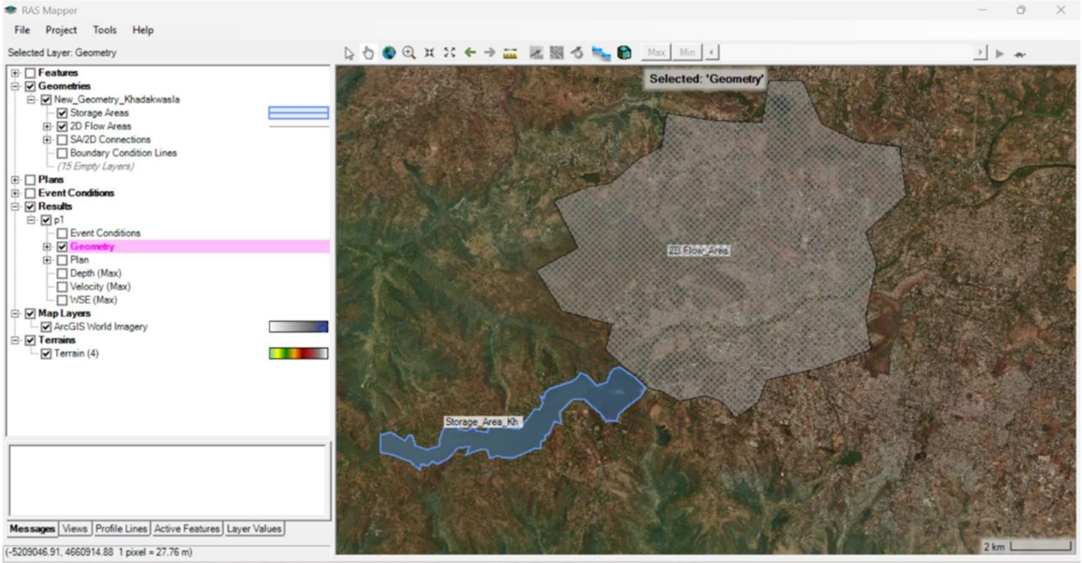


Fig. 9 Dam Break Simulation - Khadakwales Dam Geometry

Figure 9 depicts a failure analysis of the Khadakwales Dam, specifically the geographical area potentially affected by a breach. The analytical space represents the volume of the dam, and consequent space that would be occupied by flooding. The spatial analysis demonstrates the dam's catchment area, outlines the assumed flow of flooding, and subsequently details the proximal structures and overlaid. The illustration conveys the critical extent of area that requires planning of flood response operational and infrastructural resiliency. Ultimately, the analysis demonstrates a consequence of failure that flooding occurs, and helps to identify areas that are most distressed and most in need of preventative measures.

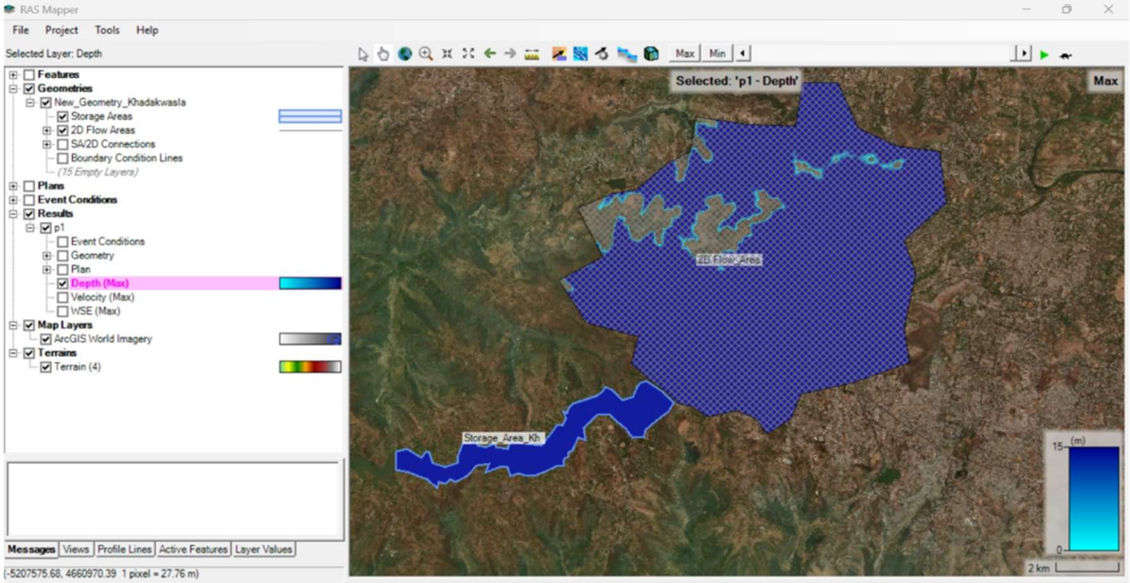


Fig. 10 Dam Break Flood Depth Distribution - Khadakwales Dam

Figure 10 depicts the distribution of flood depth resulting from a dam breakage scenario at Khadakwales Dam. Different areas in varying shades of blue are used to show the depth of floodwater at various locations downstream. Water depth is represented in the gradient in the shading from 0 cm (lit blue) to 15 m (dark blue) in the gradient. The figure shows that the farther you are from the dam, the flood depth increases, and the breach zone has the deepest floodwaters. The purpose of the simulation is to show the unequal flood depth that would happen in case of the dam collapse, and that shows the areas where flood control structures, protective and emergency responsive measures are essential. The flood depth model is used to measure the effect of the floods on the infrastructures, the people, and the ecosystem so that better flood control measures can be suggesteds.

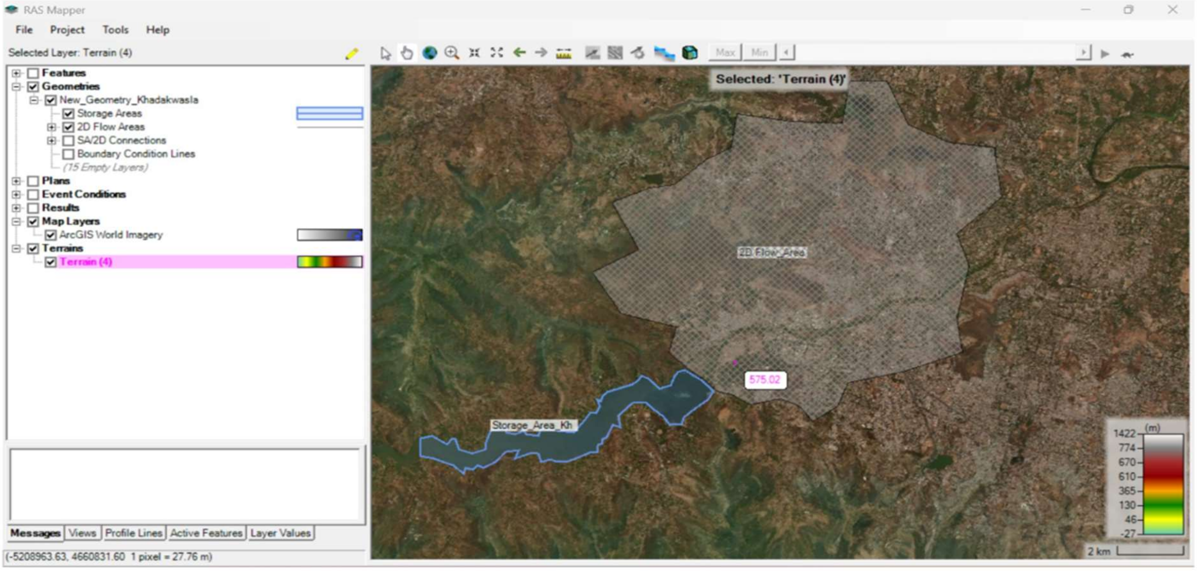


Fig. 11 Terrain Elevation Map - Khadakwales Dam

Figure 11 illustrates the terrain elevations around the Khadakwales Dam. It delineates the range in elevation with a spectrum of colors denoted on the right list with the respective elevation ranges in meters. The highest elevation in this range is approximately 375m. This type of data is especially pertinent in understanding the impact of an eventual dam breach. The lower elevations would be more prone to inundation, while the higher elevations would serve as barriers to flood. The terrain model helps flood risk management and the simulation of flood propagation, as it identifies likely flood pathways and the areas most vulnerable to flooding. It can be used for emergency planning, the safeguarding of critical infrastructure and the assessment of environmental impacts.

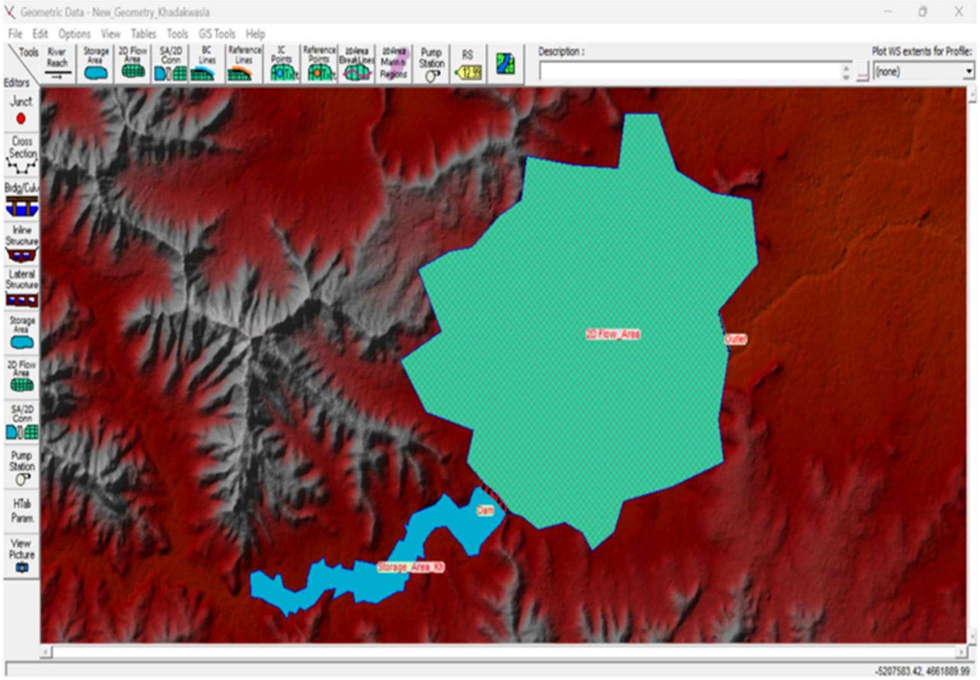


Fig. 12 Geometric Data Visualization - Khadakwales Dam

Figure 12 depicts the geometric layout of Khadakwales Dam and its surrounding area. The light blue area also represents the area where the dam stores its water and facilitates the understanding of water retention, containment, and related risks of water discharge/breach. The surrounding red and black structures represent the terrain elevation, with emphasis on the mountains. The different shades of colour show how steep and high the land is, and they also play a role in controlling flood flow if a dam breaks. The flood map's features give us the information we need to figure out how likely it is that the area will flood, what infrastructure is at risk, and what the natural effects will be if the dam breaks. The terrain model simulates the flow of water across the area to assist in the planning of flood risk control and response efforts.

AI-Based Flood Risk Analysis

Table I: AI Model Performance Metrics

Metric	Value
Test Accuracy	93.33%
Macro F1-Score	0.89
Weighted F1-Score	0.93
Cross Validation Accuracy	95%

Table I summarizes the performance of the optimized Random Forest classifier used for flood risk classification.

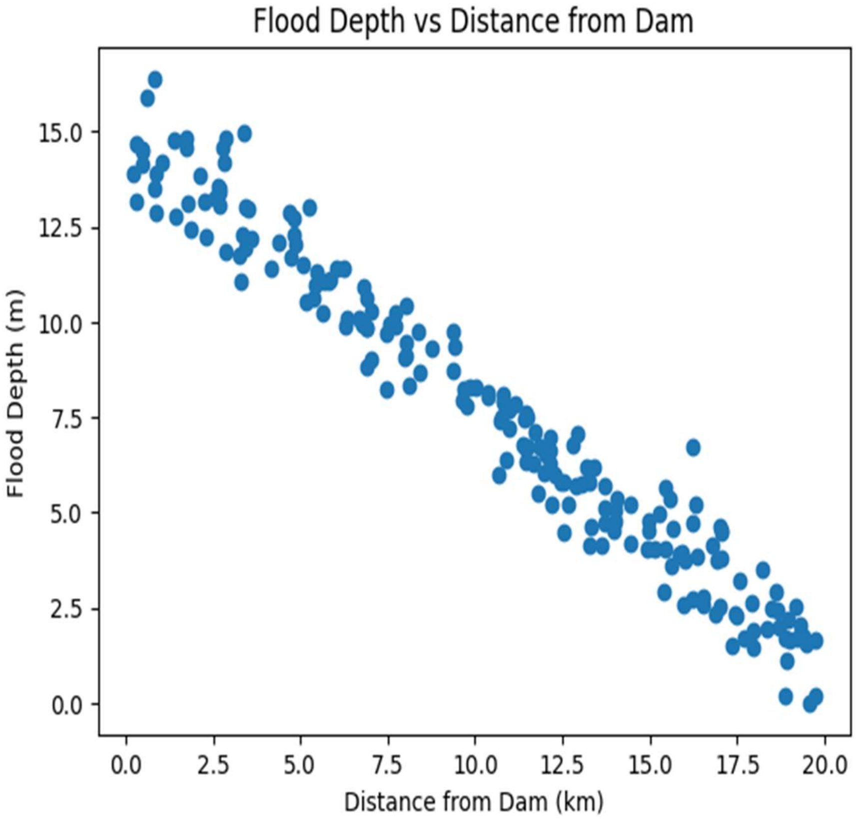


Fig. 13 Flood Depth Variation with Distance from Dam

The Fig 13 scatter plot illustrates a clear negative relationship between flood depth and distance from the dam. At locations close to the dam (0–2 km), the flood depth is highest, ranging approximately between 13 m to 16 m, indicating severe inundation risk. As the distance increases to around 10 km, the flood depth gradually reduces to about 7 m to 9 m. Beyond 15 km, the depth further declines to nearly 2 m to 5 m, and at the farthest distance (around 20 km), it approaches 0–2 m. This trend confirms hydraulic attenuation, where flood energy dissipates downstream, reducing flood severity and associated damage risks.

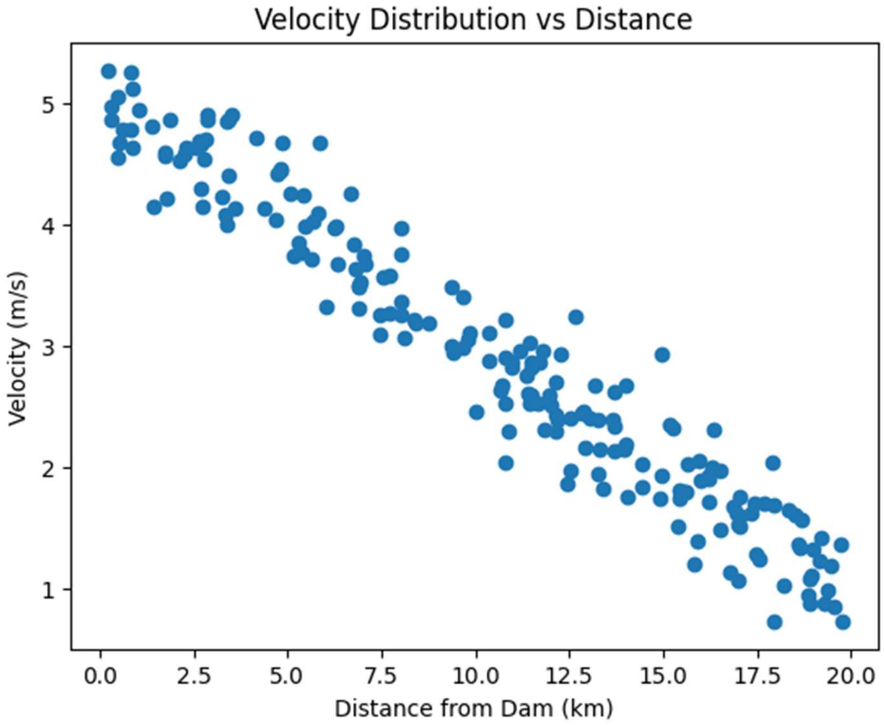


Fig. 14 Velocity Distribution along Downstream Reach

The Fig 14 scatter plot shows a strong negative correlation between flow velocity and distance from the dam. Near the dam (0–2 km), the velocity is highest, ranging approximately from 4.5 m/s to 5.3 m/s, indicating intense and highly destructive flow conditions. As the distance increases to around 10 km, the velocity reduces to nearly 2.8 m/s to 3.5 m/s, showing gradual energy dissipation. Beyond 15 km, the velocity further declines to about 1.5 m/s to 2.2 m/s, and at the farthest distance (~20 km), it drops to nearly 0.8 m/s to 1.5 m/s. This trend highlights downstream reduction in flow intensity, lowering erosion and structural damage risks.

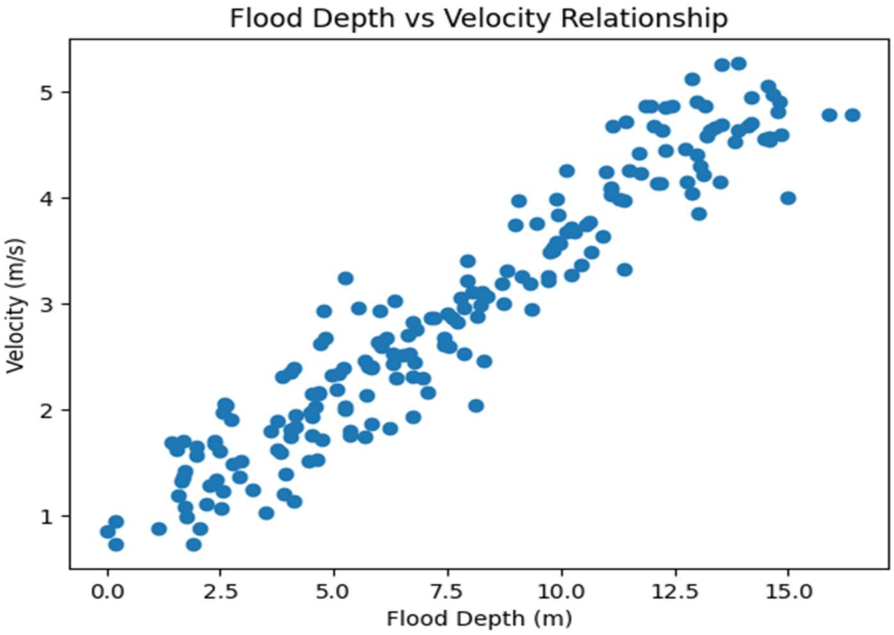


Fig. 15 Relationship between Flood Depth and Velocity

The Fig 15 scatter plot demonstrates a strong positive relationship between flood depth and velocity. At lower flood depths of around 0–3 m, the velocity remains relatively low, approximately 0.8 m/s to 1.8 m/s, indicating less severe flow conditions. As the flood depth increases to about 5–10 m, the velocity rises significantly to nearly 2 m/s to 3.8 m/s. At higher depths exceeding 12–15 m, the velocity reaches peak values of approximately 4 m/s to 5.2 m/s. This trend confirms that deeper floodwaters are associated with higher flow velocities, leading to increased hydraulic force, erosion potential, and structural damage risks in affected areas.

6. Conclusion

The present study successfully demonstrates an integrated approach for dam break analysis by combining hydraulic modelling using HEC-RAS with machine learning techniques for enhanced flood risk prediction. The simulation results for the Khadakwasla Dam indicate that, in a worst-case breach scenario, the downstream regions are highly vulnerable, with peak water surface elevations ranging from 541.11 m to 660 m and flow velocities reaching up to 5 m/s, posing significant risks to infrastructure, agricultural land, and densely populated urban areas. The AI-based Random Forest model achieved a high classification accuracy of 93.33%, along with a macro F1-score of 0.89 and cross-validation accuracy of approximately 95%, confirming the reliability and robustness of the proposed predictive framework. The analysis also revealed that flood depth and velocity are the most influential parameters in determining flood risk severity. The study highlights severe environmental consequences such as soil erosion, habitat destruction, and water contamination in flood-prone zones. Overall, the integration of hydraulic simulations with AI significantly improves flood risk assessment, enabling better disaster preparedness, early warning systems, and strategic planning. This hybrid framework offers a practical and scalable solution for sustainable water resource management and infrastructure resilience in dam-affected regions.

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