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RESEARCH ARTICLE

Flood Risk Assessment for an Irrigation Project in Odissa, India

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Abstract

Objectives: Flood risk assessment is a fundamental aspect of disaster management, particularly in regions heavily reliant on irrigation infrastructure for agriculture. This study employs advanced hydrological and hydraulic modeling techniques to evaluate flood risk for the Lower Suktel region in Odisha, India. **Methods:** The methodology integrates Intensity-Duration-Frequency (IDF) curves, Isopluvial maps, and the Hydrologic Engineering Center-River Analysis System (HEC-RAS) to comprehensively analyze flood risk and its implications. **Findings:** IDF curves further reveal that the design rainfall intensity for a one-hour duration with a 100-year return period is 152 mm/h, aiding in characterizing rainfall intensity for specific return periods. Model simulation identifies the pump house's susceptibility to flooding, with maximum flood depths ranging from 0 to 2 meters. These findings underscore the significance of employing advanced modeling techniques and Isopluvial maps for precise flood risk assessment. **Novelty:** The novelty of this paper lies in its pioneering effort to introduce a comprehensive flood risk assessment in an area where it has not been previously conducted. The integration of advanced modeling techniques and spatial analysis tools contributes to the novelty of the research, making it a valuable and innovative contribution to the field of flood risk management. Understanding extreme rainfall events, hydraulic behavior, and potential flood depths is imperative for developing effective flood mitigation strategies.

Keywords: Flood risk assessment; Irrigation infrastructure; IDF curves; Hydrological modeling; Hydraulic modeling; GIS

1 Introduction

Floods, as one of the most destructive natural disasters, pose a significant threat to both rural and urban areas globally [1]. However, in regions heavily reliant on irrigation for agriculture, the vulnerability of irrigation infrastructure to flooding becomes a critical concern. Flooding can inflict severe damage to irrigation systems, leading to reduced agricultural productivity, economic losses, and food security challenges [2,3]. To address these multifaceted issues effectively, a systematic and integrated approach to flood risk assessment and mitigation is imperative [4,5]. Flood modeling is an indispensable tool in the planning and implementation of irrigation projects. It provides valuable insights into potential flooding extents and the severity of flooding, allowing for the design of effective flood control measures and optimized water resource management [6,7]. This approach is especially relevant in urban areas, where green infrastructure can play a pivotal role in flood risk reduction.

A comprehensive methodology is indeed required to address the multifaceted challenges posed by flooding to irrigation infrastructure. Integrated flood risk assessment combines various critical components to provide a holistic understanding of the potential risks and impacts [8]. One of these fundamental components is the utilization of Intensity-Duration-Frequency (IDF) curves, which serve as the cornerstone for precise rainfall estimation and characterization. These curves enable us to discern the intricate relationship between rainfall intensity, duration, and the probability of occurrence, thus laying the groundwork for informed hydrological modeling. IDF Curves serves as the foundation for rainfall estimation, describing the relationship between rainfall intensity, duration, and the likelihood of occurrence [9]. Site-specific IDF curves, developed using local rainfall data, provide precise rainfall estimates for hydrological modeling. These curves enable the estimation of rainfall intensity for the 2-, 5-, 10-, 50-, and 100-year return periods [10].

To accurately assess flood risk for irrigation projects, various hydrological simulation software and models are employed [11–14]. Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS), a commonly used hydrological model, simulates precipitation-runoff processes and estimates streamflow patterns across complex watersheds [15]. In regions with limited historical flood data, HEC-HMS plays a pivotal role in predicting streamflow patterns across complex watersheds. The model's adaptability and accuracy have been demonstrated through calibration and testing in various river basins [16,17]. Hydraulic modeling, performed using the Hydrologic Engineering Center-River Analysis System (HEC-RAS), further assesses flood impacts on irrigation projects. It simulates flood scenarios, providing insights into potential consequences and aiding in the development of effective mitigation strategies [15].

Geographic Information Systems (GIS) technology plays a central role in this comprehensive approach. GIS enables the integration of diverse spatial data, including detailed topographic information, cross-sections, and channel geometry. These spatial analyses provide invaluable insights into vulnerable areas within irrigation infrastructure, assisting decision-makers and stakeholders in formulating effective risk assessment and management strategies. Moreover, GIS can be used to visualize flood scenarios and their potential impacts, facilitating clearer communication and better-informed decision-making [18,19]. Considering increasing impact of climate change, which has led to altered precipitation patterns and an elevated frequency of extreme weather events [20,21], the development and implementation of robust flood risk assessment methodologies have never been more critical [22]. Climate change brings a heightened level of uncertainty to flood risk assessment, necessitating adaptive strategies to anticipate and respond to evolving challenges.

In a world grappling with climate change and its far-reaching consequences, the need for comprehensive flood risk assessment methodologies has taken on unprecedented significance. These methodologies, as exemplified in the integrated approach outlined in this article, not only offer precise flood risk assessments but also provide a solid foundation for strategic decision-making in the face of a changing climate [2,23]. The study area's lack of prior flood risk assessments underscores the pioneering nature of this research. By introducing a comprehensive flood risk assessment for the first time, the paper fills a critical knowledge gap and addresses the urgent need for a tailored flood management strategy in the region. The combination of IDF curves, Isopluvial maps, hydrological modeling, hydraulic analysis, and GIS technology creates a holistic framework for flood risk assessment. This holistic approach considers both temporal and spatial dimensions, providing decision-makers with a thorough understanding of potential flood scenarios and their impacts.

1.1 Study Area

A pump house has been planned to be constructed for Right Command Lower Suktel Irrigation Project at Bolangir district, Odissa (Figure 1).

The pump is located near the bottom of a hilly terrain. Any excessive rainfall may lead to flooding the pump house area. Hence, there is a need to analyse the risk of flooding for Pump House. Lower Suktel region is located in the eastern state of Odisha, India sharing its borders with neighboring states such as Chhattisgarh to the west and Andhra Pradesh to the south. The region's geographical diversity is marked by the presence of the Suktel River, a tributary of the Mahanadi River, which meanders through the landscape, influencing its hydrology and ecology. The topography varies from low-lying floodplains along the river to elevated plateaus and hills in the surrounding areas. The climate in Lower Suktel, like much of Odisha, is tropical, with distinct wet and dry seasons. The southwest monsoon, typically arrives in June and continues till September, brings most of the region's annual rainfall.

Fig 1. Lower Suktel Pump House layout boundary

2 Methodology

The methodology adopted for the study to carry out flood risk assessment is shown in Figure 2.

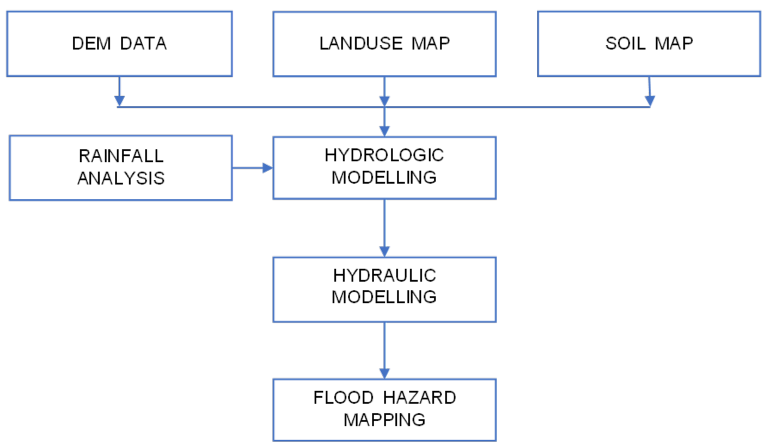

Fig 2. Conceptual framework of Methodology

2.1 Data Collection

The LiDAR survey was done to capture the terrain data of the region. The High-resolution Digital Elevation Model was prepared using this LiDAR survey data. This Survey DEM (0.5m resolution) was used to perform watershed delineation and further catchment processing. This is one of the significance of this study. State-wise Isopluvial maps of 24h duration for 2-, 5-, 10-, 50-, and 100-year return periods were collected from the India Meteorological Department (IMD). Soil data were collected from Food and Agriculture Organization (FAO) of 1km resolution. Land use data were obtained from Sentinel-2 10m resolution land use/ land cover map.

2.2 Rainfall Analysis

Understanding the relationship among intensity, duration and frequency or Return Period is paramount in designing hydrologic structures across different scales. These parameters are graphically represented through IDF Curves. IDF curves offer a visual depiction of the probability associated with a given average rainfall intensity occurring within a specified time frame. They are instrumental in analyzing extreme precipitation events for different return periods.

One valuable method for estimating design rainfall intensities across regions with limited rainfall data is the isopluvial or isohyetal approach. This method involves the creation of isopluvial maps, illustrating regions with consistent rainfall depths for specific duration and return periods. These maps enable spatial interpolation of rainfall intensities at ungauged locations, making them particularly useful in areas with limited data.

IMD plays a crucial role in this regard by providing state-wise generalized Isopluvial maps of 24-hour rainfall for 2-, 5-, 10-, 50-, and 100-year return periods. These maps are a valuable resource for design engineers, facilitating the estimation of design floods based on their specific project requirements. IMD compiles these maps using daily rainfall data from Ordinary Rain Gauges (ORG) at 746 stations located within the states and their surroundings. Some of these stations have rainfall data spanning more than 30 years, and in some cases, over a century [10].

Empirical formulae are commonly used to establish the IDF relationship, acknowledging that as the duration of a storm increases, its intensity tends to decrease. The Bernard equation is a widely adopted formula for Indian conditions (Equation (1)).

$$i = \frac{a}{t^n} \tag{1}$$

where,

i - Intensity of rainfall (mm/h),

t - Duration of rainfall (minutes) and

a, n – Constants

The IDF curves arrived serve as essential inputs in hydrological modeling. These curves along with pertinent data such as land use, topography, and basin characteristics, empower engineers and hydrologists to make informed decisions during designing and managing hydrologic systems. The integration of IDF curves into these models ensures a comprehensive understanding of rainfall patterns, aiding in effective flood risk assessment and mitigation strategies.

2.3 Hydrologic Modelling

The Hydrologic Modelling System (HEC-HMS) is a software product developed by the Hydrologic Engineering Center (HEC) under the purview of the US Army Corps of Engineers. This powerful tool is designed to simulate the complex precipitation-runoff processes occurring within watershed systems across diverse geographic areas, ranging from expansive river basins to smaller, more localized urban or natural watersheds. HEC-HMS encompasses a comprehensive suite of features, including the modelling of losses, runoff transformation, open-channel routing, meteorological data analysis, rainfall-runoff simulation, and parameter estimation. It achieves this through the utilization of distinct models that represent each component of the runoff process, including those that calculate runoff volume, models for direct runoff, and models for base flow [24].

Watershed delineation, a fundamental step in hydrological analysis, involves partitioning the watershed into discrete land and channel segments. This segmentation is crucial for understanding the behaviour of the watershed and establishing key outlet points. The characteristics of the watershed, such as size, shape, and elevation, play a pivotal role in determining its potential for flooding and in guiding developmental activities within the basin. Furthermore, these characteristics aid in assessing the watershed's susceptibility to flooding, which is essential for effective flood risk management and mitigation.

The concept of the Runoff Curve Number (commonly referred to as the curve number or CN) holds great significance in hydrology as it serves as an empirical parameter for predicting direct runoff or infiltration resulting from rainfall excess. The Runoff Curve Number method was originated from the research and analysis conducted by the United States Department of Agriculture - Natural Resources Conservation Service (USDA-NRCS), formerly known as the Soil Conservation Service (SCS). Subsequently, it is often referred to as the SCS Runoff Curve Number. This method was developed through empirical studies of runoff in small catchments and hillslope plots monitored by USDA. It has gained widespread recognition and is a practical approach for estimating the approximate amount of direct runoff resulting from a rainfall event in a specific area. The daily runoff 'R' (mm) is calculated using the Equation (2).

$$R = \frac{(P - 0.2S)^2}{(P + 0.8S)} \tag{2}$$

The parameter 'S,' representing the potential maximum retention, is a critical component of the Runoff Curve Number method. This parameter depends on the complex interplay of soil, vegetation, land use characteristics within the catchment, and the antecedent soil moisture conditions in the catchment before the onset of a rainfall event. 'S' is expressed in millimetres (mm) and is a key factor in the calculation of daily runoff ('R') in millimetres, as per the Equation (3).

$$S = \frac{25400}{CN} - 254 \tag{3}$$

This equation underscores the importance of 'S' in quantifying the runoff generated by rainfall events, making it a central element in hydrological modelling and flood risk assessment.

2.4 Hydraulic Modelling

HEC-RAS (River Analysis System), a numerical modelling software developed by the United States Army Corps of Engineers was used for this study since it has significant advantages over the other models. It includes numerous data entry capabilities, hydraulic analysis components, data storage and management capabilities, graphing and reporting capabilities. While the software encompasses numerous equations for different hydraulic components, one of the fundamental equations used in HEC-RAS for calculating open-channel flow is the Manning's Equation [25–27]. The Manning's Equation is widely utilized for estimating the velocity of flow (V) in an open channel, typically a river or stream (Equation (4)).

$$V = \frac{1}{n} R^{2/3} S^{1/2} \tag{4}$$

where,

V - Velocity of flow (in meters per second, m/s)

n - Manning's roughness coefficient

R - Hydraulic radius (in meters, m)

S - Channel slope or gradient

The Manning's Equation is instrumental in estimating flow velocity in open channels, a crucial component of hydraulic modeling using HEC-RAS. This velocity calculation, along with other hydraulic equations and algorithms within HEC-RAS, allows for the simulation of flow patterns, water surface elevations, and floodplain inundation, providing valuable insights into river behavior and flood risk assessment [28].

3 Results and Discussion

3.1 Rainfall Analysis

IDF Curves was derived from the isopluvial maps of Odissa. IMD provides isopluvial maps, short duration ratios, time distribution curves and point to areal rainfall curves, which are used in the preparation of design flood estimation. The 24h rainfall for the 100-year return period derived from the Isopluvial maps is 360mm. A graph of maximum intensity against the duration is plotted for different return periods (Figure 3).

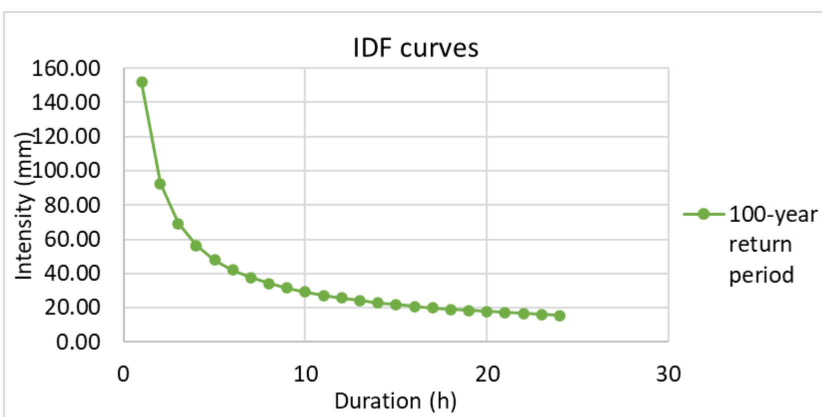

Fig 3. IDF curves for Lower Suktel

From the IDF curves, the design rainfall intensity based on a 100-year return period for one hour duration is 152 mm/h. In this study, rainfall of 100 years return period is selected as design storm. Hyetograph was derived from the IDF curves based on the return period (Figure 4). Since there is lack of IMD observed rainfall data for the study area, we have used IDF curves for the estimation design rainfall intensity. There exist some uncertainties in using the IDF curves which was not considered in this study.

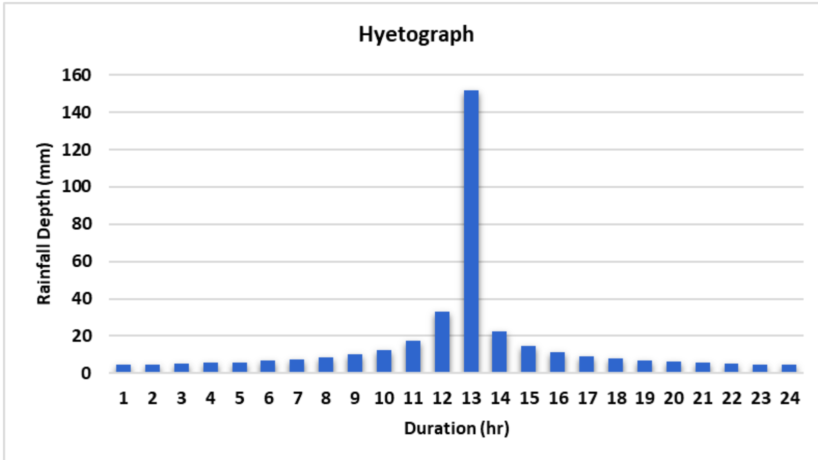

Fig 4. Hyetograph for 100-year return period

3.2 Hydrologic modelling

HEC-HMS model is used for carrying out hydrologic studies for the pump house region. The model is designed for the micro catchments and streams influencing the pump house. The delineated watersheds and corresponding streams generated are shown in Figure 5. The HEC-HMS basin level model comprises 15 sub-basins interconnected through rivers, nodes, and junctions (Figure 6).

The general summary of the HEC-HMS model provides an overview of the model run showing the drainage area, peak discharge and time of peak for each sub-basin. The peak discharge at the outlet points was estimated as 1.1 m^3/s and 2.1m^3/s. The Hydrograph at the outlet points is shown in Figures 7 and 8.

3.3 Hydraulic modelling

The peak discharge estimated by hydrologic modelling using HEC-HMS is used for hydraulic modelling for the pump house. HEC-RAS model is used for hydraulic modelling. All the streams passing through and around the pump house were identified and sections are modelled for all the reaches. Hydraulic modelling was carried out in 2D due to its complex terrain. Based on the watershed delineation for the pump house, the 2D flow area was modelled in HEC-RAS (Figure 9). The initial and boundary conditions were set for the 2D flow area.

The model output shows the flood extend around the pump house for the estimated peak discharge. HEC-RAS model provides the flood depth and maximum water surface elevation for the study area. More than 95% of the pump house boundary were flooded for the 100-year return period. The flood depth and extend around the pump house is shown in Figure 10. The flood depth ranges from 0 to 3m in and around the pump house region. There are no past observations recorded in this study area. Since flood risk assessment has not been previously conducted in this area, we could not validate the model. This is a limitation of this study. From the model simulation, the maximum flood depth observed within the pump house boundary is 2m. Therefore, a proper drainage arrangement must be provided both inside as well as outside the pump house boundary to reduce the risk of 100-year flood. Providing suitable storm water drainage network in and around the pump house boundary can be taken as the future work of the study.

4 Conclusion

The findings of this study have provided critical insights into flood risk assessment for the study area, emphasizing the importance of robust hydrological and hydraulic modeling techniques. The need for such an in-depth analysis is driven by the imperative to safeguard communities, vital infrastructure, and valuable assets from the devastating impacts of flooding.

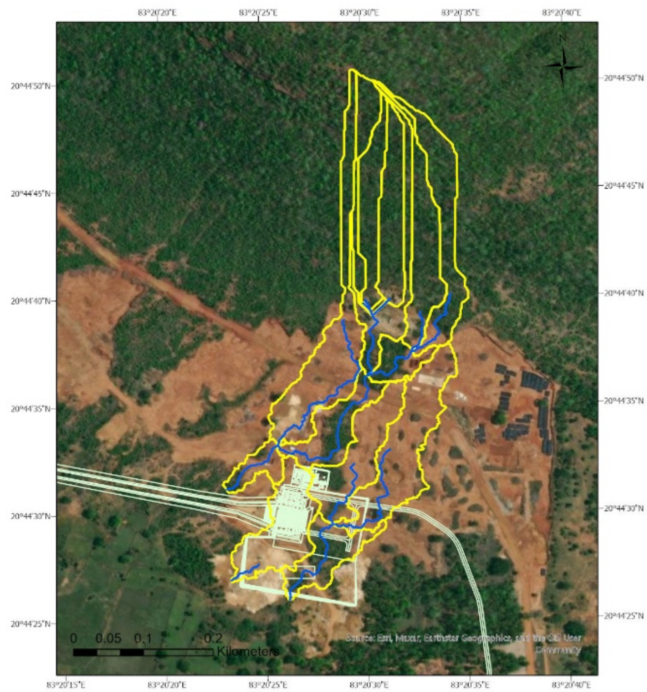

Fig 5. Watershed delineation

Several key outcomes have emerged, each contributing to a more profound understanding of the region's flood risk:

1. The 24-hour duration rainfall with a 100-year return period, derived from the isopluvial maps, was determined to be 360 mm. This information is vital for understanding the potential magnitude of extreme rainfall events in the region.
2. Utilizing Intensity Duration Frequency (IDF) curves, the design rainfall intensity based on a 100-year return period for a one-hour duration was established at 152 mm/h. This valuable data aids in characterizing the intensity of rainfall events associated with the identified return period.
3. The estimation of peak discharge at the outlet points around the pump house resulted in values of 1.1 m^3/s and 2.1 m^3/s. This information is crucial for assessing the hydraulic behavior of the river system and its potential impact on the infrastructure.
4. A critical finding is the vulnerability of the pump house to flooding, with the simulated maximum flood depth ranging from 0 to 2 m. To address this risk, it is imperative to consider a maximum water level of 208 meters during flood risk management and infrastructure planning. Concurrently, the average natural ground level, situated at 209 meters, serves as a crucial reference point for resilience-building efforts.
5. Additionally, a storm water drainage network shall be designed in and around the pump house to divert the flood water. The design and analysis of storm water drainage network shall be considered as the future scope of this study.

The urgent need for this study and its application is two-fold. Firstly, in the face of increasing climate variability and the intensification of extreme weather events, flood risk management has never been more critical. Understanding the dynamics of extreme rainfall events and their potential consequences is essential for proactive disaster preparedness. Secondly, the study's findings offer a practical framework for decision-makers and stakeholders involved in flood risk management. The application of LiDAR survey data in this flood modelling study has been proved to be significant. Even though it has huge applications, this survey requires a huge cost for surveying. This is a limitation pertaining to the application of flood modelling over other areas. Another limitation of this study is the non-availability of the field data or actual data at this site. Hence, comparison of the predicted and actual data can be the future scope of this work.

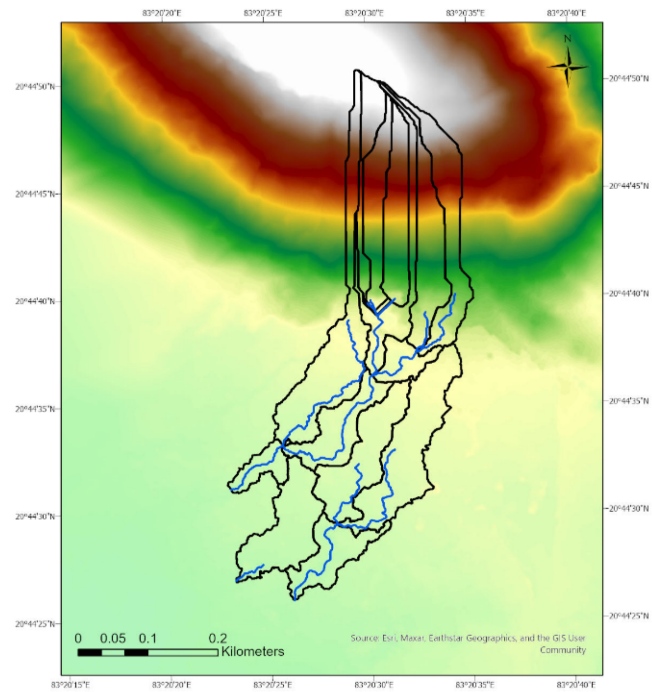

Fig 6. HEC-HMS basin model setup

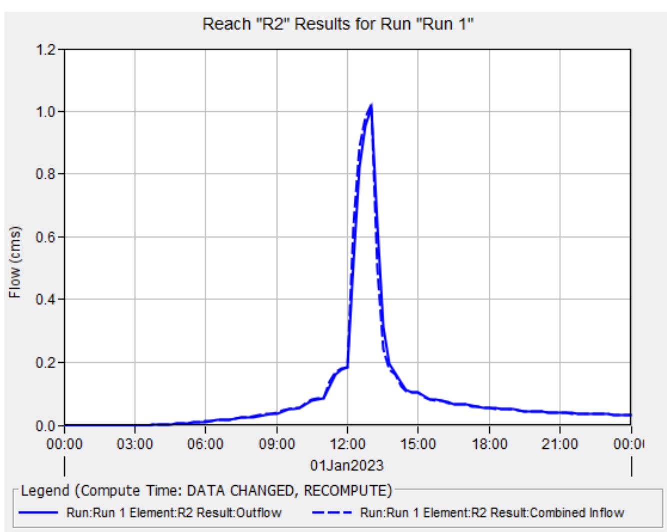

Fig 7. Peak discharge at outlet 1

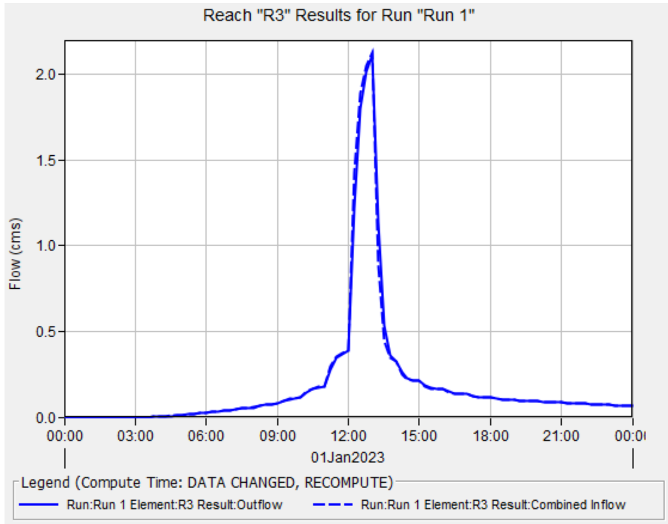

Fig 8. Peak discharge at outlet 2

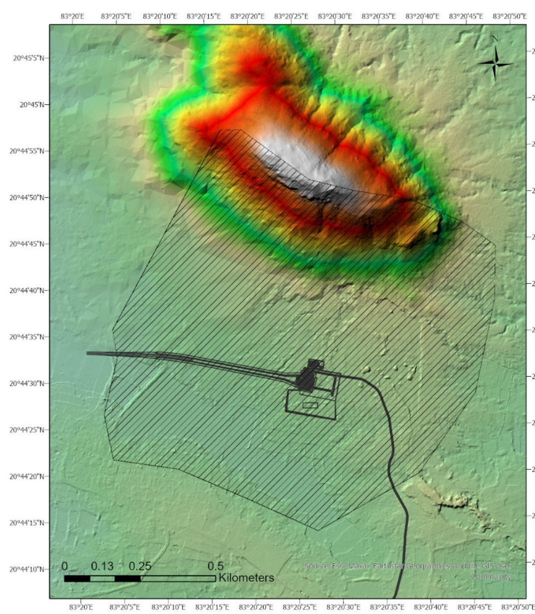

Fig 9. 2D flow area modelled in HEC-RAS

The integration of advanced hydrological modeling, isopluvial mapping, and hydraulic analysis provides a robust foundation for informed decision-making. This approach equips communities with the tools to develop and implement effective flood mitigation strategies, ensuring the resilience of both infrastructure and the local populace. In essence, this study's comprehensive approach to flood risk assessment exemplifies its necessity and application. By embracing such integrated methodologies, we empower communities to fortify their defenses against flooding and navigate the challenges presented by an ever-changing climate.

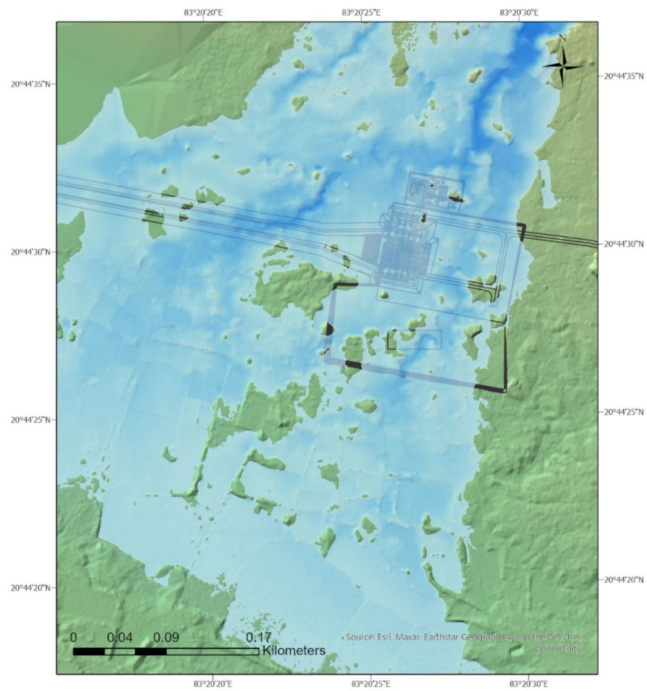

Fig 10. Flood depth and extend around the pump house

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