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Hydrodynamic Simulation of Flood Dynamics in a Himalayan River Basin Using HEC-RAS and Geospatial Integration

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ABSTRACT

Floods represent extreme natural occurrences that lead to devastating damage and adversely impact communities. To effectively mitigate and manage the consequences of such events, decision makers and disaster management authorities rely on reliable data related to flood depth, discharge, magnitude and specialized datasets. This research article prepared to employ the upgraded software model of HEC-RAS to perform one-dimensional hydrodynamic flood modeling along the mountainous 'Sutlej' river, spanning of 23 km from 'Karcham Dam' to 'Nathpa Dam' in Himachal Pradesh, India, with a specific focus on leveraging geospatial techniques. The study seeks to showcase the geospatial analytical capabilities of HEC-RAS v5. River data, including bank lines, flow path lines, and cross-section cut lines, as extracted from ALOS-PALSAR Digital Elevation Model (DEM) for flood modeling purposes. Steady flow analysis was conducted to simulate a one-dimensional hydrodynamic model. The model's outcomes presented as flood elevation ranging from 1779.6m to 1596.2m (R.L) can be visualized in the geospatial RAS Mapper window, Flood depth maps for maximum flood highlight the susceptibility of low-lying areas on both sides of Sutlej River when river discharge exceeds 6740 m^3/s. The model simulation results depicted different arrival time of flood at different places on downstream with water surface elevations varying from 1790.8m to 1520.2m and backwater affect starts approximately 2 km before reaching Nathpa Dam reservoir. The velocity of flood water varies from 0 to 8m/s. By effectively integrating geo-spatial techniques with HEC-RAS, it is witnessed to create more accurate data-driven models and the results from the one-dimensional modeling demonstrate promise and accuracy.

Key Words: Digital Elevation Model, Flood Modeling, Hydrodynamic Model, RAS Mapper, HEC-RAS.

1. INTRODUCTION

Flooding occurs when a river's discharge increases to the extent that water overflows its banks, inundating nearby areas and impacting the communities living there. It is widely recognized as one of the world's most recurrent, widespread, and devastating natural disasters [1]. Floods are noted as the most significant natural disasters, surpassing the effect of many other calamities and profoundly affecting communities [2]. Understanding floods and evaluating the outputs of planned measures are essential for developing an effective flood risk reduction approach. A straight forward approach involves assessing floods through a reconnaissance survey of observed flood levels on-site [3].Flash floods pose a significant threat in the mountainous regions of India which are not generally considered. Various redundant statements of Remote Sensing (RS) and GIS applications prove suitable for deriving river geometrical data. Hydraulic and hydrologic models such as Hydrologic Engineering Center-River Analysis System (HEC-RAS) and Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS), HEC-GeoHMS have been utilized to evaluate the flood risks in upper Teesta river basin [4].The hydraulic model HEC-RAS and the Global Flood Monitoring System (GFMS) are effective tools for preparation of flood events and identifying flood hazard zones. These tools assist disaster management governing bodies in issuing timely warnings to at-risk communities about impending flood events [5].Pluvial flooding is increasingly recognized as a significant threat to numerous cities worldwide. Regarding pluvial floods, an advanced approach involves employing 1-DImensional (l-D) sewer models, 1D and Two –Dimensional (2-D) overland flow models and coupling methods (1D-1D or 1D-2D). This approach enhances the understanding of flood modeling, flood risk management and flood dynamics [6].The integrated hydraulic (HEC-RAS) and hydrologic (SWAT) models serve as critical resources for constructing flood risk maps and predictive forecasting models with multiple return period scenarios [7].The frequency of flood events in urban areas is rapidly increasing due to climate change and urbanization. In such scenarios, using 2D flood modeling with HEC-RAS is crucial for determining the extent of flooding and evaluating urban vulnerability.[8]. Remote Sensing offers a powerful approach for identifying flood extents and conducting risk assessments through the use of satellite imagery [9]. Significant rainfall, even over short period of interval, has the potential to cause extensive harm to both property and lives. In addressing this concern, employed Geographical Information System (GIS) techniques and Remote Sensing (RS) technology to pinpoint areas with flood prone within flood inundated areas [10].Industrialization, cyclone and urbanization stands out as the primary contributors to flooding, leading to the depletion of valuable resources in northern Australia. Integrating flood risk management with Geographic Information System (GIS) emerged as a more influenced way to alleviate the impact of floods [11]. Korea faces significant vulnerability to flooding due to high precipitation and, primarily because of typhoons, leading to the lives of human loss. In response to this challenge, Wang et al. (2002) [12] formulated a plan for flood mitigation utilizing DEM and Landsat TM. Additionally, the elevation at sea level poses a considerable risk especially to the coastal areas. Applying a geospatial data with modeling approach to assess the repercussions of climate change and sea-level rise reveals potential impacts on the vicinities of coastal area [13]. Pathan (2019) implemented an integrated approach, combining Hydrologic Engineering Center River Analysis System (HEC-RAS) and Geographical Information System (GIS) for a 1-D modeling approach. This method was employed to assess flooding at various cross-sections within the Purna River basin [14].

Kumar Samanta et al. (2018) [15] applied GIS and RS techniques to map flood susceptibility in the Subarnarekha River Basin, India. S.H.Rashed et al. (2023) emphasizes the integration of diverse data sources like LiDAR, radar and optical imagery for accurate flood extent delineation and vulnerability assessment. Additionally, it highlights the increasing role of 1D steady-state hydraulic models such as HEC-RAS in conjunction with geospatial data for flood risk mitigation strategies. This review provides a comprehensive overview of various flood hazard mapping methodologies, including geospatial techniques and remote sensing tools [16].

The objective of this paper is to showcase the application of the most recent version of HEC-RAS in one-dimensional steady state flood modeling. The primary emphasis of the study lies in extracting river geometry data from ALOS-PALSAR DEM through the use of RAS-mapper geospatial tools within HEC-RAS. This highlights the application of geospatial techniques in flood modeling. The simulated outcomes illustrate the water depth, water surface elevation, back water affect and time of arrival along river course during flooding events. This approach can serve as a valuable tool for disaster management authorities in flood management and issuing timely flood warnings during potential extreme flood events in the future.

2. STUDY AREA

The study area for this research article is situated along the pristine River Sutlej, spanning a length of approximately 23 km from Karcham Dam to Nathpa Dam in the Kinnaur district of Himachal Pradesh, India. The river Sutlej, a mountainous snow-fed watercourse, is renowned for its significant role in the region's hydrology and ecological balance. The river originates from the Tibetan plateau and winds its way through the Himalayan terrain, contributing to the sustenance of various ecosystems as well as run-of the river scheme for various Hydel projects. The study zone encompass the intricate dynamics of this river system, particularly focusing on the tributaries that emerges along its course. These tributaries, while vital for the overall water flow, pose a heightened risk of flash floods due to their unpredictable and rapid discharge patterns. The research delves into the complexities of this unique mountainous river system, aiming to enhance our understanding of its hydrological characteristics and potential risks associated with flash floods in the vulnerable downstream reach. The topographic view of location as shown in Fig.1.

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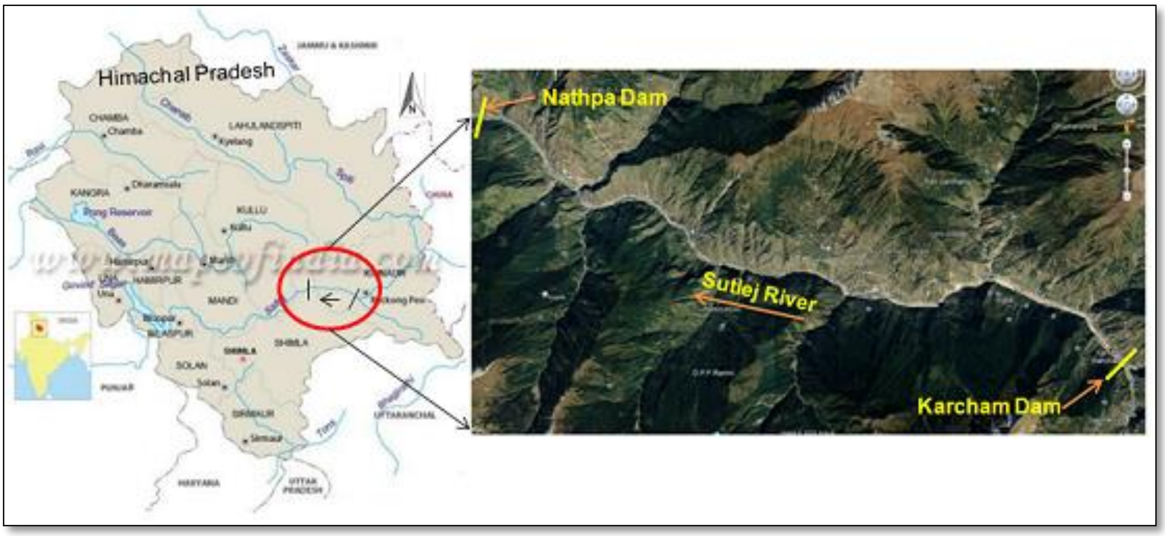

Figure 1: Location map of study area

3. RESEARCH METHODOLOGY

Application of geospatial techniques in a one-dimensional (1D) hydrodynamic model proves to be a highly efficient and precise approach for identifying flood level depths at various cross-sections of the river system. In this approach, the floodplain mapping is extracted in two stages that contains of RAS Mapper data processing, and in stage 2 HEC-RAS model simulation. The flow chart of methodology adopted in flood modeling is shown in Fig. 2.

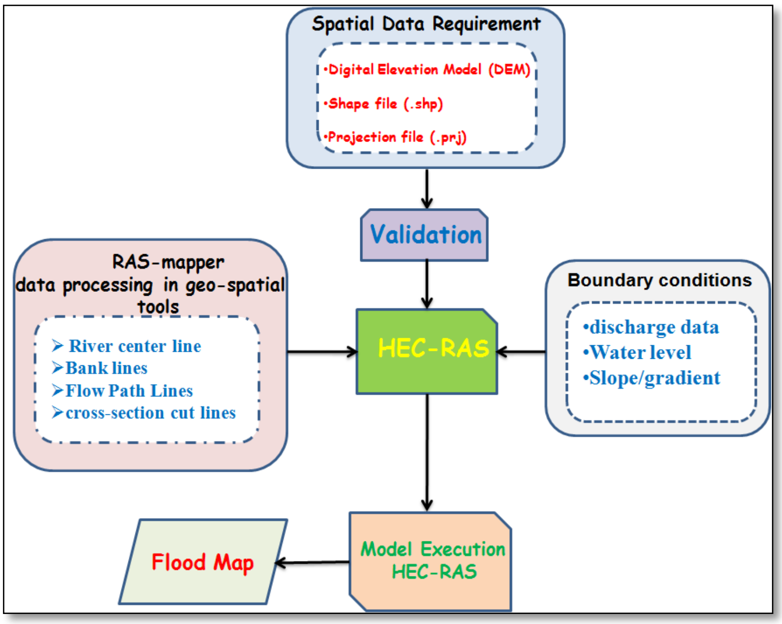

Figure 2: Flow chart of methodology adopted in Flood Modeling

3.1 Data and Geo-spatial techniques used for Flood Modeling

The process of conducting 1-D steady state flood modeling using HEC-RAS software necessitates specific datasets, namely spatial and hydraulic data. Spatial data, obtained in the form of a Digital Elevation Model (DEM) sourced from ALOS-PALSAR of 12.5 m resolution, lays the groundwork for establishing river centrelines, bank lines, flow path lines and cross-section cut-lines. On the other hand, hydraulic data, acquired from the Karcham Dam site, particularly discharge measurements, serves as a crucial boundary condition integral to the steady-state simulation. In this context, the spatial data acquired in the form of DEM elevations were validated with reference to the elevation available from Survey of India (SOI) toposheets. The peak discharge of 6744 m^3/s obtained at upstream of Karcham Dam site as upstream boundary condition and Full Reservoir Level (F.R.L) at Nathpa Dam (R.L. 1492.5) considered as downstream boundary condition. For model simulation together, these datasets empower the modeling process,

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enabling comprehensive analysis and accurate predictions essential for effective flood management and mitigation strategies.

Geospatial techniques involve the use of GIS, Remote Sensing, and other spatial analysis tools to gather, analyse and visualize spatial data. In the context of flood modeling with HEC-RAS software, several geospatial techniques can be utilized to enhance the accuracy and efficiency of the modeling process. Here's how some of these techniques are utilized in 1-D steady-state flood modeling with HEC-RAS:

- Geospatial data such as DEM, land use/land cover data, river network data, and hydraulic structures are collected and integrated into GIS software. This data provides the basis for setting up the hydraulic model. Satellite imagery or aerial photography can be used to extract detailed information about terrain features.
- DEM is processed to derive stream networks, flow direction, slope and different terrain types (e.g. urban areas, agricultural land, forests) can be classified using GIS data to account for varying surface roughness values used in the flood model.
- GIS tools are used derive geometric features like river centre line, bank lines, flow path line and cross section cut-lines are digitized along the river reach , which makes possible to setup hydraulic model.
- GIS can aid in defining boundary conditions such as inflow points, outflow points and hydraulic structures location based on spatial data and network connectivity.
- GIS can be used to overlay model results with observed flood extents or other relevant data for model calibration and validation.

4. HEC-RAS SOFTWARE

Hydrological models are essential tools and vital components for water resources and environmental planning and management for both steady and unsteady flow simulation. HEC-RAS is one of the widely accepted most popular tools that provides the results in the form of the depth of water, velocity and water surface elevation (WSE) for 1D hydrodynamic flood modeling [17].The HEC-RAS (Hydrological Engineering Centre-River Analysis System) tool was developed by US Army Crops and is a freely available software. The model contains a hydraulic analysis component, graphical user interface, data management and data storage capabilities. It is well tested and well adopted software to analyse flooding river channel hydraulic analysis of both events in fluvial and coastal regions. In the latest version of HEC-RAS v5.0.7, the RAS mapper tool is very effective in extracting the river geometry data like bank lines river central line, flow line and cross-sections cutlines. The results from the model are promising when compared with past flood studies. Ray et al.(2011) [18] developed flood plain maps and identified the flood depth flooded velocity and water surface elevation using HEC-RAS.

4.1 1D-Steady Flow Modeling

The assumption behind the 1-D HEC-RAS model is that all flows across any cross-section is normal to the cross-section. There is no flow in the lateral or vertical directions, thus all flow is considered to move in one direction (longitudinal) [19]. In a1-D MODEL the terrain is represented as a series of cross-sections. The average velocity and water depth at each cross-section are the results of the 1-D river flow simulation. Numerous studies such as Hashim et al. (2021) [20] and Ahmad (2016) [21] have examined the performance of 1-D modeling in hydraulic simulations, concluding that it is capable of providing a good estimate of flood level and travel time and can be used to predict flood extent. The routing for the 1D HEC-RAS model is based on the Saint-Venant equation of dynamic wave theory, that consists of the continuity and momentum equations.

In HEC-RAS modeling, the 1-D steady state of flow refers to a scenario where the flow in a river or channel is considered o be unchanging with the time and is only dependent on space (i.e. along the direction of flow). This simplification is useful for analysing long-term behaviour of flows in rivers and channels where changes over time are not significant or are not being considered. The context of steady flow, the governing equation used in HEC-RAS are based on the principles of fluid mechanics, specifically the conservation of mass and momentum. The key equations used in 1-D steady state flow in HEC-RAS are

1. Continuity equation

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$$\frac{\partial A}{\partial x} + \frac{\partial Q}{\partial t} = 0 \text{ ....(1)}$$

Where

- A is the cross-sectional area of flow
- Q is the discharge (volume flow rate)
- X is the spatial coordinate
- t is the time step/rate of change in time

This equation expresses that the rate of change of flow area with respect to distance is equal to the negative rate of change of discharge with respect to time. In steady state flow, the second term is zero, implying that there is no change in discharge with time.

2. Momentum equation:

The conservation of momentum in the Saint-Venant equations is described through the momentum equation, which represents the one-dimensional unsteady flow of open-channel water. The momentum equation is written as:

$$\frac{\partial Q}{\partial x} + gA\frac{\partial y}{\partial x} + gA\frac{S_f}{S} Q|Q| = 0 \text{................................(2)}$$

Where

- g is the acceleration due to gravity
- y is the water surface elevation
- S is the channel bed slope
- S_f is the channel friction slope

This equation represents the conservation of momentum along the flow direction. The first term represents the change in discharge with respect to distance, the second term represents the change in momentum due to changes in water surface elevation, and the third term represents the momentum loss due to friction. In steady state flow, both the terms involving partial derivatives with respect to time are zero, simplifying the equations to steady state forms. The steady state flow in HEC-RAS modeling refers to a scenario where the flow characteristics (velocity, depth, discharge) do not change over time, and the governing equations used to describe this flow are simplified versions of the continuity and momentum equations, where the time derivatives are neglected [22].

5. 1-D MODEL DATA PROCESSING IN RAS-MAPPER

Presently, all GIS operations can be completed within the RAS Mapper provided in the latest HEC-RAS 5.0.7. The DEM was added into RAS Mapper to illustrate the terrain of the study area as flow chart methodology as shown in Figure 2. The RAS-Mapper is a geospatial tool that is capable of extracting GIS information of bank lines, centerline, flow path lines and cross-section lines through digitization. A skeleton of digitized bank lines, river centre line, flow path, and cross-section cut lines are shown in Figure 3. The digitized geometric parameters in RAS mapper are illustrated below.

5.1 Generating River Centerline

In HEC-RAS the river centreline indicated by dark blue lines is used to construct the river alignment within the river basin, which flows from the downstream of 'Karcham Dam' of Sutlej River to upstream side of 'Nathpa Dam' as shown in Fig.3. The river centreline is essentially a representation of the main flow path of the river channel. It helps establish the boundaries of the river channel, which is important for simulating and analysing flood events. The river 5centreline is used to compute the longitudinal slope or gradient of the river. This information is critical for understanding the overall slope of the river channel and is used in hydraulic calculations to determine flow velocities and energy gradients, also helps in assigning appropriate roughness coefficients to different parts of the river.

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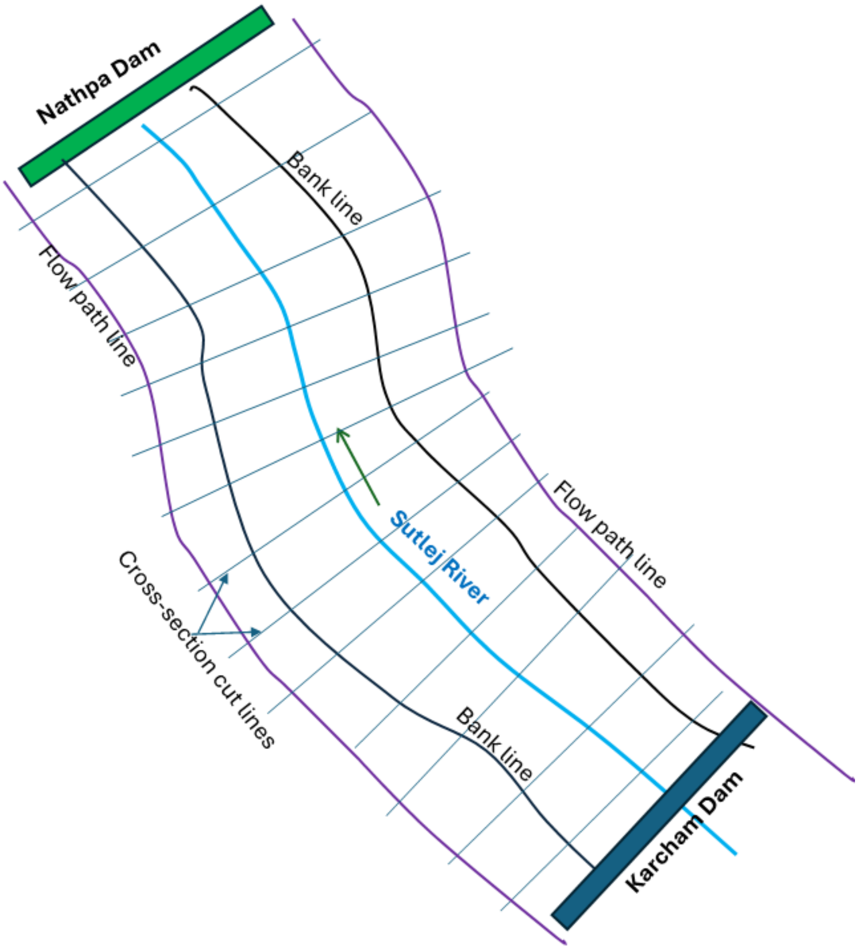

Figure 3: Digitized river, river bank, flow path, and cross-sections in RAS Mapper

5.2 Generating Bank lines:

Bank lines represented by red marked differentiate the main river from the area overbank floodplain are shown in (Fig.3). Bank lines representing the riverbanks as digital lines within the model establish the spatial configuration of the river channel. Bank lines are used to compute the flow area and wetted perimeter of the river channel. These geometric parameters are vital for calculating hydraulic properties such as flow velocity, depth, and discharge within the channel.

5.3 Generating flow path lines

The concept of flow path line is essential for understanding the movement of water within the river channel during different flow conditions. The primary objective of the flow path line is o represent the path that water takes as it flows through the river reach being modelled. Flow path lines provide a visual representation of the direction and pattern of water flow within the river channel. This visualization is crucial for understanding how much water moves through the modelled reach during different flow events and illustrate the hydraulic gradient along the river channel. This gradient is the slope of the water surface and is crucial for understanding the energy distribution within the channel and velocity distribution across the river section. It contributes to a better understanding the hydraulic behaviour of the river reach being modelled and enhances the accuracy and reliability of flood predictions and hydraulic simulations. The flow path of the river, which are used to regulate the river flow lengths lateral to the channel, over the left and right banks as shown in Figure 3.

5.4 Cross-sections Cut-Lines

Cross-sections cut-lines are used to extract depth data to create a surface profile across the river flow and to be normal to the flow direction. Besides, it should cross the centerline of the channel, bank lines, and flow path lines are shown in Fig.3. The intersection of cross-sectional lines with the river centerline and flow paths provides essential information such as the downstream reach lengths, position of bank stations and manning values to the

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HEC-RAS simulations. Reach lengths, river profile, bank stations, and elevations are all generated into the attributes of the cross-sectional lines by employing the RAS mapper.

5.5 HEC-RAS Model Simulation

ALOS-PALSAR DEM with 12.5 m resolution which is freely available, are downloaded from web portal. Later, the DEM data is added in the RAS mapper (GIS) tool in HEC-RAS to convert the DEM into DTM. Moreover, the Georeferenced projection file is assigned in the same window where the coordinates of the study area set up. River centreline, bank lines, flowpath lines, and cross-section lines area digitized in RAS mapper as shown in Fig.3. River centerline is shown in blue colour, bank lines are in red flowpath lines in cyan colour and cross-section lines are in yellow colour with Google-maps–satellite image as a base map overplayed on terrain image. A steady flow simulation is performed while peak discharge of 6744 m^3/s considered as boundary condition and a Manning's (n) value is 0.035 for bed and both banks of Sutlej River referred from Chow's table considered as **[23], [24]**.

6. RESULTS AND DISCUSSIONS

The present study carried out along the Sutlej River for a length 23 km from Karcham dam to Nathpa dam, by applying the steady flow simulation in flood model studies, water depths, water surface elevation and velocities were obtained. HEC-RAS model simulations for the stretch between Karcham dam and Nathpa dam has yielded valuable insights into various critical parameters associated with flood dynamics. The flood depth analysis revealed the spatial distribution of water levels during peak flow conditions, providing crucial information for assessing potential inundation areas. Water surface elevations were meticulously examined, helping to identify vulnerable zones and contributing to the formulation of effective flood risk management strategies. Velocity of flood, a key determinant of the force and speed of the oncoming water, was thoroughly analysed, aiding in the understanding of potential erosive forces and impact on infrastructure. These results collectively contribute to a more informed understanding of the hydraulic behaviour in the region, supporting decision making processes for disaster mitigation and emergency response planning.

In this paper, the hydrological dynamics in the downstream of Karcham Dam have been investigated, focusing on the critical point of peak discharge observed at 6744 m^3/s and the study revealed that the maximum flow occurred just downstream of the Karcham Dam, highlighting the significance of Dam-induced alterations on downstream river regimes. Notably, our analysis indicated that low discharge conditions are prevalent prior to the initiation of the backwater affect, shedding light on the temporal dynamics of river flow in relation to dam operations. Rahman et al. [25] the authors demonstrated how detailed elevation information significantly enhances the representation of complex floodplain features, leading to more reliable flood hazard simulations. This study emphasizes the crucial role of high-resolution topographic data, specifically LiDAR, in improving the accuracy of flood inundation modeling using HEC-RAS.

The inundation occurs perilously close to settlements, situated a mere 1.35 kilometres downstream from the formidable Karcham dam. With the water level reaching a critical elevation of 1790.8 m, the speed at which this inundation unfolds is staggering, taking just 2 minutes from the release at the Karcham Dam to reach this alarming level, as evidence in Fig. 4. In addition to the imminent threat posed to settlements, the inundation also encroaches perilously close to the Army camp located approximately 3.5 kilometres downstream of the Karcham dam. Here, the water level rises to a worrisome 1748.5 meters, highlighting the pervasive reach of the unfolding crisis. It's striking to note that the journey from the dam to this point takes a mere 7 minutes (Figure.5).

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Figure 4: Setlements-1.3 km d/s of Karcham dam **Figure 5: Army camp-3.53 km d/s of Karcham dam**

Numerous regions along the banks of the Sutlej River are submerged under water. Notably, on the right bank, the floodwaters took approximately 10 minutes to travel downstream from the Karcham Dam, spanning a distance of 8 kilometers to reach the Sholtu colony. The water level recorded at 1729.3 meters as depicted in Fig.6. On the left bank of the river, approximately 16.73 kilometers downstream from the Karcham Dam, it took 22 minutes for the floodwaters to reach the ‘Bajarangabali Hanuman Mandir’, submerging the area. The water level predicted during this event was 1681.1 meters, as illustrated in Fig. 7.

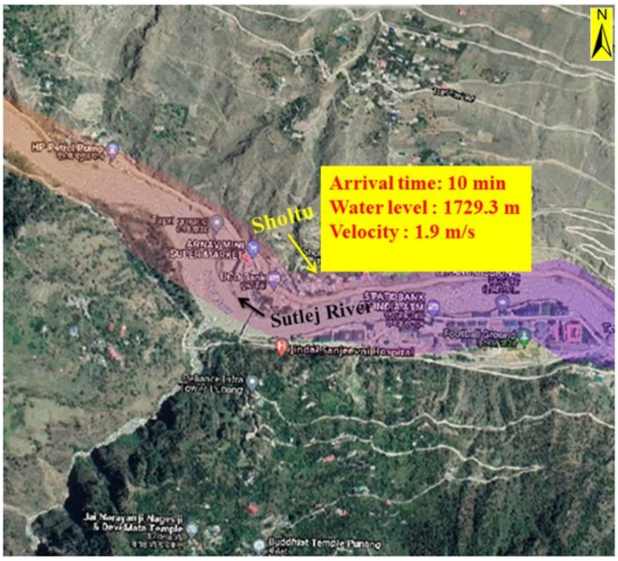

Figure 6: Sholtu colony-8 km d/s of Karcham dam **Figure.7: Bajarangabali mandir-16.73 km d/s of dam**

The ‘Wangtu Kafnu’ bridge, located approximately18.87 km downstream of the Karcham dam, faced inundation as water levels rose. The journey of the floodwaters from the dam to the bridge took approximately 24 minutes, indicating the rapid progression of the inundation. Further downstream, about 21 km from the Karcham dam and 26 minutes into the flood’s journey (Fig.8), the water reached the Nathpa reservoir. Notably, the water surface elevations at the Wangtu Kafnu bridge and Nathpa reservoir were recorded at 1557.9m and 1520.2m, respectively.

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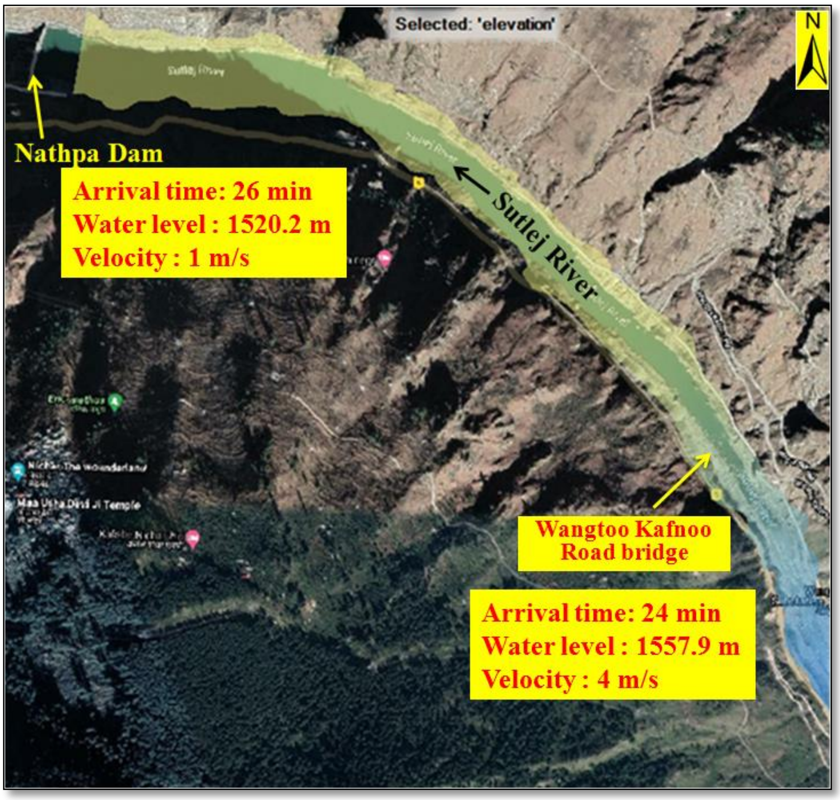

Figure 8: Wangtoo Kafnu bridge-18.87 km and Nathpa dam downstream

The profile plot drawn between Karcham Dam and Nathpa Dam serves as a valuable tool in elucidating the intricate hydrological interactions along this stretch of the river. The analysis reveals a critical point in the river's longitudinal profile, where the backwater affect becomes evident at a distance of 2 km from Nathpa Dam. This phenomenon is accompanied by corresponding rise in water level, reaching 1495.5m. The profile plot not only captures the spatial dynamics of the backwater affect initiation but also provides a quantitative measure, allowing for a comprehensive understanding of the impact of Nathpa Dam's operations on the downstream water levels. Such insights are essential for informed decision making in water resource management, ensuring the sustainable utilization of river systems and the mitigation of potential environmental consequences.

The HEC-RAS model simulation results provided valuable insights into flood dynamics, offering flood inundation maps, arrival times of floodwaters, and corresponding water surface elevations, which directly correlate with the depth of flooding. These comprehensive aspects served as crucial tools for formulating and implementing Emergency Action Plans aimed at effectively mitigating the impact of floods on vulnerable areas. By leveraging the data and analyses generated by the HEC-RAS model, emergency responders and planners can make informed decisions regarding evacuation routes, deployment of resources, and other critical interventions to safeguard lives and property in flood-affected regions. Thus, the utilization of HEC-RAS simulations facilitates proactive measures and enhances preparedness in addressing the challenges posed by flooding events.

7. CONCLUSIONS

The paper demonstrated the utilization of the most recent version of HEC-RAS that is equipped with geospatial functionalities to perform the 1-D steady state flood modeling. The study focused the extraction of river geometry data through the direct digitization of bank lines, river centreline, cross-section cut lines, and flow path lines using the RAS-mapper tools within HEC-RAS. The research conducted to forecast flood inundation areas along Sutlej River spanning from Karcham dam to Nathpa dam, covering approximately 23 kilometers, utilizing HEC-RAS steady flow flood routing method. The necessary input data for the RAS model was obtained from ALOS-PALSAR DEM with a resolution of 12.5 meters, represented in the form of cross sections. The model simulation utilized a peak discharge of 6744 m^3/s as a boundary condition and Manning's roughness of 0.035. These simulation outcomes facilitated the

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determination of flood arrival times, water depths, surface elevations, and velocities at various points along the river. Additionally, the study identified and documented the backwater affect occurring approximately 2.0 m kilometers upstream of Nathpa dam. The results of the flood model simulation provided valuable insights for the development of Emergency Action Plans (EAP). The incorporation of geospatial techniques enhanced a realm of the hydraulic modeling approach, while simultaneously reducing the time required for data acquisition and preprocessing tasks. Future research endeavours could expand upon these findings through the incorporation of 2-D model studies. R.K. Pandey et al. (2022) demonstrate the effective use of multi-temporal Sentinel-2imagery for flood inundation mapping and integration with HEC-RAS for 1-D steady-state modeling. The authors presented how readily available satellite data with frequent revisit times can be valuable for near real-time flood monitoring and model parameterization, ultimately enhancing flood mitigation efforts [26].

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