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Hydrologic Engineering Centers-River Analysis System (HEC-RAS) - A Review

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Abstract

The integrated software system known as HEC-RAS allows for the interactive usage of a multi-user, multi-tasking network environment. The system has a Graphic User Interface (GUI), distinct hydraulic analytic components, data storage and management capabilities, visuals, and reporting tools. Three 1-dimensional hydraulic analysis components will eventually be included in the HEC-RAS system for 1) steady flow. 2) Unsteady flow simulation 3) Calculations of movable-boundary sediment movement. Steady and unsteady flows are provided, and sediment transport is being developed. Using a common geometric data representation and geometric and hydraulic computation procedures by all three components is crucial. Along with the three hydraulic analysis components, the system also has some hydraulic design features that can be used once the fundamental water surface profiles have been calculated. These features include bridge scour calculations, uniform flow calculations, stable channel design, and sediment transport capacity. HEC-RAS is an integrated software system for interactive use that can determine water levels, depths, and flow velocities for different flow configurations and cross-sectional zones along the River. The review shows that the HEC-RAS model has many utilities in flood forecasting, water resource planning, and management. Most studies found HEC-RAS modelling efficient and reliable in different river basins to simulate flood-prone zones accurately. Accordingly, the model may be applied to river flow analysis simulation in a stream flow basin for water resource planning, development, management, and decision-making.

Key words : Graphical User Interface (GUI), Unsteady flow, steady flow, uniform flow.

Life cannot exist without water. Many researchers from various continents have investigated the characteristics, effects, and effects of extreme rainfall events that occurred under various hydrological conditions (Mustafa and Szydłowski, 2021). Drought and flooding have harmed human activities worldwide since the beginning of the existence of humanity (Banstola *et al*., 2019). Water-related natural hazards, such as floods, drought, landslides as well as water-related diseases, are caused by abrupt changes in rainfall patterns and intensity. Flooding is thought to be the most frequent and dangerous hydro-meteorological risks (Dasallas *et al*., 2019). Our ability to predict the future condition of a river system is one of the biggest challenges of reservoir operation. This may be done using a hydrological forecast, which predicts factors like stream flow and river stage with enough time to help decision-making processes (Siqueira *et al*., 2016). Decisions concerning gate opening and closing, particularly when floods occur, are crucial for preventing loss of life and damage to infrastructure. The fertile agricultural land is degraded by abnormal river flow, erosion, and sedimentation, causing permanent harm to water developmental projects (Kute *et al*., 2014).

In India, rainfall is the main form of precipitation. Runoff is the process of the surface stream by which the rainwater is drainage/discharge from the catchment. The excess of this discharge causes flooding, submerging in the surrounding land. It is important to study the depth and amount of water that flows out of its boundary conditions.

Floods are potentially deadly and can cause significant property damage (Abdelshafy and Mostafa, 2021). Due to this, it is necessary to plan out flood plains and conduct flood analyses to prepare ahead of time. The river zoning maps are some of the most fundamental and significant data required for natural resource management projects. River zoning maps provide useful information, such as the depth and scope of flood protection in flood zones (Issac *et al.*, 2019). In India, flood is the most common natural danger and occurs more frequently than any other natural calamity. They have disastrous effects on both life and property. It is apparent that the river's ability to transport water has decreased with time. A variety of circumstances and reasons cause it. Depth and width steadily decrease because of encroachment, silting, and scouring. A reduction in the carrying capacity of rivers brings on floods (Waghchaure *et al.*, 2020).

A dam is the physical barrier which holds water and contributes significantly to a nation's economy. Dams are used for various reasons, including electricity generation, flood control, and irrigation. Earthen dams are among the most well-known dams due to their flexibility for any foundation, convenience of construction, and low cost (Maddamsetty *et al.*, 2010). However, earthen dams are more prone to collapse because they are less rigid (Maddamsetty *et al.*, 2010 ; Bharath *et al.*, 2021). The dam breakdown causes a catastrophic flood surge that can affect downstream operations, active sediment movement, and morphological changes (Cao *et al.*, 2013). The dam's failure resulted in floods, which had disastrous impacts on human safety, ecological quality, and the landscape (Bharath *et al.*, 2021). These floods consequently caused some of the most severe disasters. Dams give significant public advantages; however, floods induced by dam breakdown contain and create some of the most destructive natural disasters of the previous two centuries (Balaji and Kumar, 2018). Dam break studies must be conducted to understand the behavior of the high flood caused by the dam break and to pinpoint the area that will be flooded in this scenario.

Water reservoirs perform several functions, including irrigation, drought protection, flood control, and many others. Reservoir capacity is declining due to siltation (Balaji and Kumar, 2018).. Nowadays, the enormous quantity of slit deposition in reservoirs and the flood effect on dam-break wave propagation are significant (Abbas *et al.*, 2020). The issue of erosion and sedimentation is a key concern in river and stream management. Large quantities of sediment are deposited into surface water transportation networks each year, filling dam reservoirs and placing pressure on water resource management (Joshi *et al.*, 2019). Studies on the sediment deposited in reservoirs are necessary to understand the behavior of the high flood caused by the reservoir's sedimentation.

Research methods frequently used to identify flood hazards and map floods include remote sensing and Geospatial Information System (GIS) in the hydrological modeling software (Nugroho *et al.*, 2018). The frequency of occurrence and the extent of the damage can be significantly analyzed through flood risk mapping, spatial planning, and flood modeling using various techniques (Maniyar and Bhatt, 2015. Structures including buildings, streets, roads, and other artificial elements, characterize built-up areas. During flood simulation, it is important to consider these features in the urban environment (Madhuri *et al.*, 2021). For urban flood simulations, the above features should be accurately predicted to get an accurate result. When hydraulic modeling is used in the HEC-RAS environment, it is possible to simulate the depth of floods in various floodplain locations (Husain, 2017). It explains how the HEC-RAS model was applied to simulate the water surface profiles in the study area.

It is now essential to retain water to meet human demands and to lessen flood damage in the river's downstream reach. It is also well known that the disasters brought on by dam breakdown episodes inflict millions to billions of dollars' worth of property damage and human life losses in the nearby area of downstream reach (Parsai *et al*., 2016). The USACE created HEC-RAS to administer and regulate public works, including rivers, canals, ports, and other structures. One-dimensional steady flow, one and two-dimensional unsteady flow, sediment transport, bed calculations, water temperature, and water quality modeling are all simulations that can be performed using the HEC-RAS software (Olaniyan *et al*., 2014). (Costabile *et al*., 2020) reported HEC-RAS is a trustworthy model for computing discharge hydrographs in simulations of rainfall runoff. This model is increasingly used to determine the impact of encroachments on floodways in studies for flood insurance and floodplain regulation. This work reviews various publications work done by different analysts utilizing the HEC- RAS model for representing efficient and reliable in different river basins to simulate flood-prone zones with accuracy.

HEC-RAS : The US Army Corps of Engineers created the River Analysis System (HEC-RAS) at the Hydraulic Engineering Center in 1995, which is freely accessible (Maniyar and Bhatt, 2015). For a complete network of purely natural and artificial channels, it is capable of performing one- and two-dimensional hydraulic computations (Lima *et al*., 2020). One of the most widely used flood modelling programs in hydrodynamic simulation is the HEC-RAS model (Sholichin *et al*., 2019). This model was created to do simulations of 1D steady flow and 2D unsteady flow for a river flow study, sediment transport, and water quality modeling (Traore *et al*., 2015). The model uses geometric data representation and geometric and hydraulic computation routines for a network of natural and constructed river channels (Waghchaure *et al*., 2020). History of HEC-RAS development as shown in Table 1. HEC-RAS is able to compute water surface profiles for subcritical, supercritical, mixed, and constant flows as well as for flows that gradually change in volume (Uday Kumar and Jayakumar, 2020). Sediment transport modeling, which is notoriously challenging, is also possible with HEC-RAS (Vedmani *et al*., 2020). Different boundary conditions are offered in HEC-RAS to compute steady flow and sediment analysis. HEC-RAS required a variety of input parameters for each cross-section to define the shape, height, and relative placement along the river stream as fallows.

- River station (cross-section) number
- Reduced levels for each terrain point
- Left and right bank station locations
- Reach lengths between the left floodway, stream Centre line, and right floodway of adjacent cross-sections
- Manning's roughness coefficients
- Channel contraction and expansion coefficients
- Maximum discharge of the stream
- Geometric properties of any hydraulic structure like bridges, culverts, weirs, etc.

Features added to recent versions of HEC-RAS

- Mixed Flow Regime for Unsteady Flow
- Dam Break Analysis
- Levee Breaching

- Pump Stations
- Navigation Dams
- Stable Channel Design and Analysis
- Sediment Transport Potential

Advantages

- Graphical User Interface
- GIS capabilities
- Ability to import MIKE11 Cross Sections
- Training available via vendors (universities, engineering societies)
- Widely used across the world
- Detailed technical report and users'l manual

Limitation

- Model code is not publicly available
- No support provided for users other than U.S. Army Corps of Engineers
- Only 1D modeling
- Modeling skews of hydraulic structures is limited to 30 degrees
- Cannot currently account for steep slopes above 10% inside the model

Hydraulic capabilities of the HEC-RAS model

1. Dam break analysis
2. Flood Mapping
3. Steady flow water surface profile calculation.
4. Unsteady flow calculation.
5. Sediment transport computations
6. Water quality analysis.

1) Dam break analysis : To forecast the flood wave features, such as the peak flood discharge and its stage, as well as the time of peak flood occurrence and routing the peak flood hydrograph for the various downstream sections along the river course (Bharath *et al.*, 2021) have performed a dam break study for the Hidkal dam. They used a one-dimensional hydraulic model called the Hydraulic Engineering Center's River Analysis System (HEC-RAS). The HEC-GeoRAS program creates an inundation map by extracting river geometry data from the Cartosat-1 digital elevation model (DEM) to identify the impacted areas. They looked at breach parameter prediction, flood hydrograph, peak flow, flood arrival time, and inundation map production.

(Balaji and Kumar, 2018) Carried out research on the Kalyani dam, built over the Swarnamukhi River near Tirupati, Andhra Pradesh, and employed the HEC-RAS model for dam break analysis. In this investigation, the Kalyani dam was subjected to an unsteady flow simulation using HEC-RAS, and the results are plotted in terms of river and floodplain water levels. The congregational method and information preparation produce a module with an unsteady flow in the HEC-RAS model. This study determined how much water was spread out, how deep the water was, and how long it

Table 1. History of HEC-RAS Development

Component added	Description
1D Steady Flow Analysis	FY 1992 - 1999 Produced Steady flow versions of HEC-RAS (Beta 1&2, Versions 1.0 - 1.2, 2.0 – 2.2)
1D Unsteady Modeling for River Analysis	FY 2000 – 2005 Versions 3.0 – 3.1.3
1D Sediment Transport for River Analysis	FY 2004 – 2007 1D Water Quality Modeling FY 2007

would take for it to travel and overflow. The maximum height of flood protection structures in the region will be determined using all the data projected by the HEC-RAS model to prevent flooding during high floods.

Singh *et al*. (2020) have researched full hydraulic simulation and analysis for a fictitious dam breach of the Meja dam using the HEC-RAS model with river geometry determined from DEM. The results of the modelling demonstrated that certain areas, including residential, agricultural, and industrial areas, were identified as having a very high risk of being inundated due to the significant difference in the values of the water surface elevation and ground elevation in the event of the failure of the Meja dam.

Joshi (2017) conducted a study modelling a dam-break flood route for the Ujjani dam using the HEC-RAS two-dimensional model to identify the most susceptible to flooding on the dam's downstream side while considering Pandharpur City as the study area. Dam break analysis makes it possible to find the site inundated, the depth of the flood, its velocity, and its travel time.

Dam break analysis is carried out for the following reasons-

- Preparedness to tackle the disaster
- Preparation of inundation map
- Preparation of evacuation plans
- Evaluation of the risk downstream of dam failure
- Emergency plans for reinstatement of infrastructure
- Design of protection measures.

(Bulti., 2021) studied how the construction of dams affects catchment hydrologic behaviour and how discharge forecasts in hydrological models are affected. The Soil and Water Assessment Tool (SWAT) and the River Analysis System (HEC-RAS) of the Hydrologic Engineering Center were used in succession to systematically address the alteration in the basin. According to the model outputs, the SWAT model can simulate the upstream portion of the basin in a good performance range that may be used for actual implementation. The HEC-RAS model performed significantly better and accurately simulated the downstream or changed catchment.

2) Flood Mapping : Khattak *et al*. (2015) used the HEC-RAS hydraulic model to carry out a floodplain mapping study for a segment of the Kabul River in Pakistan. They calculated the extreme river flows for various return times using the log-normal, log-Pearson type III, and Gumbel's approaches. They discovered that the Log-Pearson type III was appropriate for their research region by using the Kolmogorov-Smirnov test. The HEC-RAS model uses the study's findings as input to determine the equivalent flood level anticipated in the river stretch from Warsak Dam to Attock. They identified areas at risk for flooding and discovered that 400 % of the area is likely to be inundated compared to the river's usual flow. They came to the conclusion that the mapping of floodplains using HEC-RAS and ArcGIS environment produced more accurate results and may be applied to the development of a decision support system.

Parsa *et al*. (2016) carried out a study on floodplain zoning simulation using HEC-RAS and CCHE2D models in the Sungai Maka River. To simulate the flood zoning in the Sungai Maka area of Kelantan state, Malaysia, they employed the one-dimensional Hydrologic Engineering Centers-River Analysis System and the two-dimensional CCHE2D model. The findings indicate that the most significant difference between the 1D and 2D models is 6% in the undulating portion of the rivers.

Azouagh *et al*. (2018) carried out work on the integration of GIS and HEC-RAS in the Martil River flood modelling (Northern Morocco). They used modelling software called HEC-RAS, which makes it possible to calculate things like water levels, depths, and flow rates for various flow configurations and cross-sectional zones along the Martil River. Therefore, utilizing the ArcGIS information system's combined HEC-GeoRAS and HEC-RAS hydraulic modelling tools, this investigation provides flood mapping and categories of risk zones.

Mustafa and Szydowski., (2021) described how to use HEC-RAS 2-D for the Toce River urban flood simulation with several building representation strategies. They discuss how the Toce River physical model's HEC-RAS 2-D urban flood simulations were affected by the choice of building representation methods and hydrodynamic models. They came to the conclusion that this method was employed on scale models in HEC-RAS 2-D and that it was essential to look into its application to real-world case studies.

Waghchaure *et al*. (2020) performed research on flood modelling and flood forecasting using HEC-RAS for the Mutha River. The depth of the water, the speed, and the height of the water's surface in relation to time are all likewise provided by this model. The forecasting and modelling process was simplified with HEC-RAS software, giving more transparent results. By concurrently evaluating the XYZ perspective image and warning table created by software, the flood-prone locations have been identified. River basins cannot carry massive floods as they currently exist. Thus, it is crucial to expand the river basin both horizontally and vertically. In order to create a flood mitigation strategy for Pune City as a preventative step for reducing flooding, a prepared flood zone map will be helpful.

Husain *et al*. (2018) studied the simulation of floods in the Delhi segment of the river Yamuna using HEC-RAS. The lives of the locals, significantly those close to the banks of the Delhi segment of the river Yamuna, are severely affected by flooding. Thirty-three floods along the Yamuna River occurred in the previous century, frequently putting lives in peril and damaging vital infrastructure along the river's banks. In the Delhi section, the HEC-RAS model has been used to estimate the vulnerability of several bridges and barrages. Policymakers may find the data here helpful in developing mitigation plans to lessen the severe effects of floods in the Yamuna River basin.

Tamiru and Wagari (2021) studied mapping flood inundation in the Baro River Basin, Ethiopia. Combined machine learning and HEC-RAS models were used. Artificial neural networks (ANNs) and HEC-RAS were used to create regionally distributed river simulation models and predictive rainfall-runoff models. The ANN was trained in R studio using daily rainfall, temperature, and Topographical Wetness Index (TWI) data over seven years, with a spatial resolution of 50 x 50 m. The prediction models using ANN and HEC-RAS in this article were more accurate due to the incorporation of spatial and temporal variability. The rainfall-runoff result derived from the tested ANN model was utilized as input for the HEC-RAS. The prediction ANN model was evaluated with the observed daily discharge of the exact temporal resolution.

3) Steady flow water surface profile calculation : Issac *et al*. (2019) researched the Gurupura River's steady flow analysis using HEC-RAS software. Stable flow analysis uses the hydraulic model HEC-RAS and GIS tools.

The region surrounding the river basin is safe from the consequences of flooding, according to the results of the maximum flow rate.

Pallavi and Ravikumar (2021) used HEC-RAS and GIS techniques to assess steady flow for the flood inundation limit downstream of T. Narsipura. An integrated method using ARC-GIS and HEC-RAS is used at a discharge gauging station over 37.78 km in the upper Cauvery basin in Karnataka. The Central Water Commission (CWC), Bengaluru, has produced data products such as SRTM DEM and discharge data for 21 years (1998–2018). HEC-RAS is used for steady flow analysis to find changes in the flooding pattern. The outcome indicates that this study's most significant and least flooded areas were in 2018 and 2002. The flood inundation studies assist the decision-makers in determining the risk and taking the appropriate steps to reduce the harm.

Ahmad *et al*. (2016) investigated the river Jhelum in Jammu and Kashmir using one-dimensional steady flow analysis and HEC-RAS. The projected flood levels were calculated using the peak flood data as inputs into the HEC RAS model. The model's results indicate an overflow at the river under study's highest points over 50 years and beyond the return period. This goal is to help decision-makers, planners, and insurers create a solid strategy for designing flood mitigation strategies and plans to reduce disaster-related losses in the studied region.

4) Unsteady flow calculation : Sawai and Prasad (2019) used HEC-RAS software to research an unsteady flow simulation of the fictitious breakdown of the Haripura dam in Udham Singh Nagar, Uttarakhand. Four scenarios are included in this study because of the breach's varying height and breadth. After analyzing stage and flood hydrographs from all four scenarios, it was determined that the most excellent stage attained across all scenarios was 238.97 m. As a result, those living in the downstream region extremely near the dam site must build their homes above a certain height to ensure their protection from high flood levels.

Karim *et al*. (2021) conducted a study on a two-dimensional HEC-RAS model to simulate the flood wave resulting from the hypothetical failure of the Al-Udhaim Dam on the Al-Udhaim River, Iraq. The propagation of the resulting dam-break wave along 100 km downstream of the dam site for the overtopping scenario. The main objective is to analyze the flood wave propagation to assess the failure risk in downstream dam areas and may provide emergency plans. The methodology consisted of two sub-models: the dam breach failure model for deriving the breach hydrograph and the hydrodynamic model for propagating the flood wave downstream of the dam.

Shustikova *et al*. (2019) investigated the evaluation and comparison of numerical two-dimensional (2D) models of various levels of complexity using a floodplain inundation event on the Secchia River (Italy). The 2D capabilities of LISFLOOD-FP and HEC-RAS are evaluated (5.0.3). The two distinct complexity and terrain resolution codes employed in this investigation significantly impacted the output quality. The shallow water equation's inertial formulation (LISFLOOD-FP) and the diffusion wave model (HEC-RAS) vary in several ways. HEC-RAS effectively represents topographic features by computing more informative property tables for each cell face, thanks to its ability to integrate the sub-grid bathymetry component. Concerning operation, the LISFLOOD model utilizes a rectangular mesh with the exact resolution as the input terrain raster.

5) Sediment transport computations: Motallebian and Hassanpour (2013) used the HEC-RAS model to research the Sistan River's erosion and sedimentation hotspots. The HEC-

RAS model, which simulates sedimentation, is used in this study to identify the regions of the Sistan River that are susceptible to erosion and sedimentation and specific sedimentation parameters. An area 47 km from the Sistan River was investigated in this respect. The model was calibrated for both the flow and the sediment before being used to replicate the sediment. We looked at the river's transverse and longitudinal profile variations, shear stress changes, sediment transport capability, and the bulk of inflow and outflow sediment at various levels.

Processes followed for analysis of sediment transport computations

Adding geometric data : The geometric data comprise transverse sections, hydraulic structures, and connecting details for the waterway channel (schematic design of the channel system) (dams, flood breakers, and so on).

Adding the flow data of the river to the model : After adding geometric data, the quasi-unsteady flow data will be incorporated into the model. Depending on the intended type of analysis, the flow data type will vary. Based on quasi-unsteady flow hydraulics, the HEC-current RAS's capacity for sedimentation is based. Using a number of stable flow profiles corresponding to the flow period, the quasi-unsteady flow approach calculates the flow hydrograph.

Adding sediment data to the model : Information on the river sediments was included using the results of sample riverbed tests and the researcher's values for riverbed grading. They specified the grading of the riverbed for each transverse section. The model also included definitions for the breadth of the erosion region and the movable bed's coordinates in each segment. There is a possibility of erosion and sedimentation in the river's portable bed. The model developed during the field research also included the depth of the riverbed sediments, which calculates how deep a river's erodible layers are.

Joshi *et al*. (2019) studied Sediment Transport Characteristics of the Maumee River in Ohio using the HEC-RAS model. Using the HEC-GeoRAS application in ArcGIS, produced geometric data were from a Digital Elevation Model (DEM) with a resolution of 10 m x 10 m. Different sediment transport functions and Manning's roughness coefficient were used to calibrate and validate this model. The model's output shows the pattern of riverbed changes and the sections of a river reach that follow erosion or deposition patterns. Utilizing the model's results and local expertise might decrease the problem caused by the silt.

6) Water quality analysis : Fan *et al*. (2009) coupled the Qual2K model with the HEC-RAS model to assess the water quality of a tidally influenced river in northern Taiwan. They demonstrated that the quality indices simulated by the Qual2K model with HEC-RAS hydraulic inputs accounting for the tidal effect were consistent with the river monitoring data. This study innovatively applied the HEC-RAS model and the Qual2K model (also known as the Streeter-Phelps equation) to model the water quality in a river system. Fan *et al*. (2012) employed a modified Streeter-Phelps equation and the Hydrological Engineering Centers River Analysis System (HEC-RAS) to evaluate the water quality of the Tan-Sui River and its tributaries. They showed that the modified Streeter-Phelps simulation performed better using HEC-RAS hydraulic calculations. This work illustrated how the modified Streeter-Phelps equation and HEC-RAS could be creatively used to investigate the tidal effects and simulate the water quality of a tidal river with limited data availability.

Dash *et al*. (2017) used HEC-RAS as a modelling tool to assess the water quality of the

Pilli River in Nagpur. Various anthropogenic activities in its vicinity have degraded the river, and it has become a sewer. Therefore, it is essential to investigate the quantity and quality of the river water to evaluate its suitability for drinking and other purposes. The HEC-RAS model simulates the hydrodynamics and water quality of the river by solving the one-dimensional advection-dispersion equation using a direct numerical method. The simulated data were validated with samples collected at different locations along the river and showed good agreement with the observed data. Based on the simulation results, other technological options, such as decentralized sewage and wastewater treatment, in-stream treatment, etc., are suggested to improve the river's water quality, especially for polluted stretches and drains that contribute to river contamination.

Taralgatti *et al*. (2020) used the HEC-RAS 4.1 programme and a river water quality model to estimate the amount, location, and origin of algae, nitrate, and temperature in the Bhima River. They found that DO and temperature range were related in their results. DO levels changed with local temperatures and the Vari season in Pandharpur and Gopalpur. But at sampling station 3, or Gopalpur, where Nalha's wastewater flows, DO showed sudden changes that required other parameters to be studied.

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Conclusions

According to a thorough assessment of the HEC-RAS river analysis model, the choice of modelling methodology and method is mainly driven by the desired result and data availability. HEC-RAS was proven to be a superior model to others and was advised for use in flood forecasting after researchers analyzed several modelling approaches to find the best model appropriate under various hydrological circumstances. According to studies, the HEC-RAS model has several applications in the management and planning of water resources as well as flood forecasting. Many researchers were pleased with how the HEC-RAS tool was used to construct basin models and collect data. Some studies used formulas to find model parameter values, whereas others optimized them during calibration. The numerous assessment criteria available in HEC-RAS were used to evaluate the statistical model. Most HEC-RAS river analysis modelling studies indicated that the NS efficiency value ranged from 0.60 to 0.90, indicating that the model is reliable and capable of predicting output with the most significant agreement with the observed dataset. It is clear from reading these publications that the HEC-RAS can simulate the model for 1) Dam break analysis, 2) Flood mapping, 3) Steady flow, 4) Sediment transport calculations, and 6) Water quality analysis employing rainfall and basin parameters. The amount of bridge/barrage overtopping in the study under the influence of a flood of a particular size was calculated using the output from the HEC-RAS model. Under a future climate change in the river basin system, the basin's susceptibility to high-magnitude flooding events is projected to rise with higher stream flows in various areas. The HEC-RAS tool may be used for developing river basin models and discovering basin features, and it exhibits superior results when applied in a semi-distributed and distributed manner. In HEC-RAS, both auto-calibration and manual calibration perform better. As each model has advantages and disadvantages, the choice of the model must be made in light of the study's ultimate objective.

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