Integrating SWAT and HEC-RAS models for enhanced flood risk mapping in Swat River, KPK, Pakistan

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Abstract

This research is seeking ways to enhance flood prediction and early warning systems accuracy with better hydrologic and hydraulic modeling. This study offers an automated methodology to integrate two tools - SWAT and HEC-RAS – that automatically associate rainfall-runoff events to river's hydraulic processes. The effectiveness of the system was evaluated in the Swat River basin, Khyber Pakhtunkhwa, Pakistan, a flood prone area due to high rainfall. Relying on sensitivity analysis permitted the variation of model parameters and uncertainty of input data with an assurance of model soundness. The examinations show that the simulated and measured values of stream flow over a period of 23 years correlate strongly to each other with $R^2 = 0.95$. Computational efficacy is stated with the phrases real-time flood forecasting and flood forecasting in less than 60 minutes. The rest of the research is focused on assessing its broader implications on policies of regional flood risk management in addition to climate change adaptation, showcasing the usefulness of integrated hydrologic-hydraulic modeling within early warning systems.

Keywords: flood forecasting, HEC-RAS model, real time simulation. Swat River and SWAT model.

1. Introduction

Dealing with floods in Pakistan has been a challenge for many years due to its geography and frequency, which calls for precise flood risk management protocols. Modeling can and does help with evaluating these systems; however, there are few models where automation is integrated. In order to fill this missing gap, this work combines SWAT with HEC-RAS models for better flood forecasting. By integrating real time watershed runoff processes with river flow changes, the approach broadens the scope and accuracy of modeling. In this work, the automated modeling system is focused at incorporating self-optimizing capabilities to enhance the existing prediction systems for aiding emergency response and strengthening infrastructure preparedness.

The Swat River Basin in Pakistan has been susceptible to devastating floods, particularly during monsoon seasons, which have catastrophic consequences for the region's inhabitants and infrastructure [1].The 2022 floods were among the most destructive, with heavy rainfall exceeding 500 mm in 72 hours, swelling the Swat River and its tributaries [2]. The resultant deluge swept away entire villages, roads, and bridges, displacing thousands, and causing widespread destruction. Factors contributing to the severity of the floods include the region's topography, characterized by steep slopes and narrow valleys, which accelerates runoff and increases flood risk [3]. Climate change has also played a role, with rising temperatures altering precipitation patterns and intensifying extreme weather events. The economic impact has been substantial, with enhancing early warning systems through hydrological analysis and flood susceptibility mapping, enabling targeted emergency planning and infrastructure development. [4].

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The Swat River, a crucial waterway in Khyber Pakhtunkhwa, Pakistan, is the subject of this project. The SWAT (Soil Water Assessment Tool) and HEC-RAS (Hydrological Engineering Center River Analysis System) models are widely used in flood forecasting and managing water resources well [5]. SWAT focuses on simulating land use, land cover, and impacts of climate change on water, sediment, and agricultural products at the basin level. How does it affect the tides? It is very effective in predicting when it will occur. On the other hand, HEC-RAS is excellent in simulating water flow in flood-prone rivers and streams [2,3]. It provides an accurate assessment of water flow. The combination of these two models provides a robust framework for flood forecasting. SWAT can create runoff [6]. This can be used as input for HEC-RAS to model how runoff will be transported through the river system. This will increase the accuracy of flood forecasting. Recent studies in Pakistan, such as the 2010 Indus River basin floods, and associated risks. Such models have been used for mapping and mitigation. Linking SWAT and HEC-RAS models with real-time forecasts can improve the decision-making process during flood events by providing timely and detailed forecasts. It helps communities better prepare for and respond to potential flood hazards, improving real-time flood prediction capabilities, especially for the Swat River basin is the main goal of the project.

The Swat River originates in the Hindukush mountain range in the northern provinces of Pakistan. The river is known for its beauty in Swat valley. Stretching for approximately 240 kilometers, it finally joins the Kabul River near Charsadda [7]. The watershed supports rich biodiversity and maintains a diverse ecosystem, making it an important component of the region's natural heritage. However, in recent years increasing pressure from environmental degradation, pollution, as well as the impacts of climate changes. It has threatened the ecological balance and the way of life that depends on it. Possible strategies for sustainable management are also explored [8].

Swat River experiences serious floods on several occasions especially during the monsoon season, especially in 2010 and 2022[9]. The 2010 floods are considered one of the worst in Pakistan's history. By destroying bridges, roads, and homes, these floods have a long-term impact on livelihoods, infrastructure and agriculture, emphasizing the need to improve flood and climate management strategies. Therefore, a warning system deployment to inform about floods is very important to ensure the socio-economic growth as well as sustainability of the Swat River under changing climate [10]. In order to ensure consistent and systematic flood forecasting, we developed the automatic SWAT integrated with HEC-RAS program for real-time flood forecast in the Swat River.

Our research aims to assist a proactive approach in managing floodrelated disasters, as this r egion has had its fair share of flood-related issues. The flood forecasting model comprises a real-time simulation of prevailing river conditions that ultimately feeds data to do a forecast simulation for nearby future conditions. This provides point data along the channel to facilitate initial data conditions to perform the simulation computations later on. Current study proposes a system based on real-time flood forecast, that integrates both hydrological and hydraulic modeling systems, data from weather stations, and river gauges in a web-based visualization system. So, a simple automated procedure was produced to link rainfall-runoff processes with river hydraulics by integrating the SWAT to HEC-RAS models.

2. Study Area

The Swat River is a prominent river located in the Khyber Pakhtunkhwa province (KPK) of Pakistan, flowing through the beautiful and historically rich Swat Valley (Figure 1). It originates from the glaciers of the Hindukush Mountains near Kalam in the Upper Swat region and flows for about 240 kilometers before merging with the Kabul River near Charsadda [11].

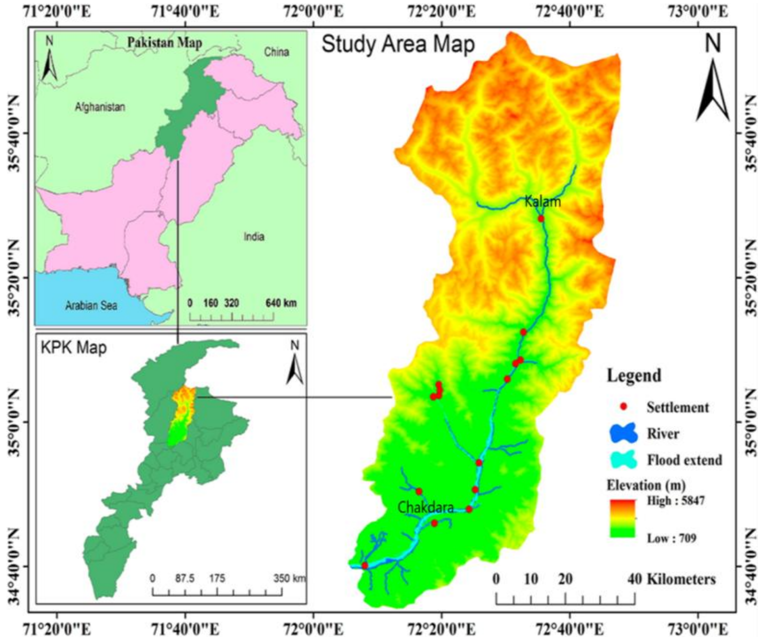
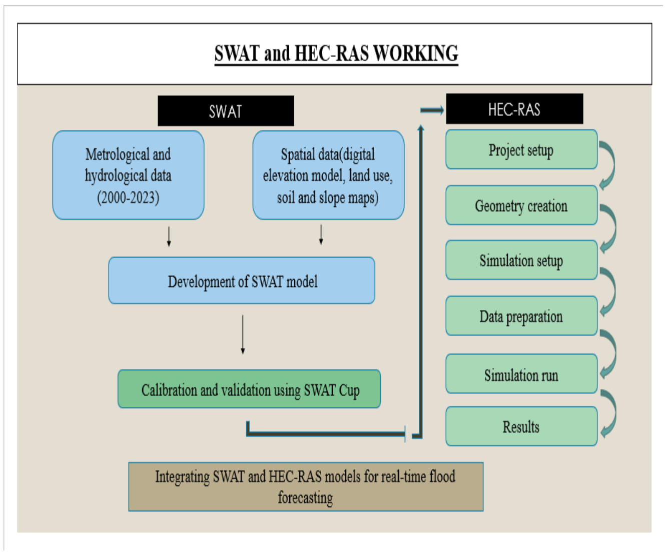


Figure 1. Study area map of Swat River in KPK province of Pakistan

3. Data collection and methodology

The general methodology used in this study is provided in below Figure 2 using a flowchart.

Figure 2 The flowchart showing SWAT and HEC-RAS automated program integration for real-time



flood prediction in Swat River.

3.1. Data collection

To effectively use the SWAT model for flood forecasting, several spatial datasets are required. Firstly, a high-resolution Digital Elevation Model (DEM) as shown in Figure 2 is essential to accurately represent the terrain and to simulate runoff and streamflow patterns within the watershed [12]. Detail description of data along with their resolutions and sources are provided in below Table 1:

Table 1. Detail description of data along with their resolutions and sources.

Data description	Source	Spatial resolution	Temporal resolution
Temperature	NASA, USA	0.5°	Daily (2000-2024)
Humidity	NASA, USA	0.5°	Daily (2000-2024)
Precipitation	NASA, USA	0.5°	Daily (2000-2024)
Wind speed	NASA, USA	0.5°	Daily (2000-2024)
Solar radiation	NASA, USA	0.5°	Daily (2000-2024)
Digital Elevation Model	NASA, USA	0.5°	Static (Feb 11-22, 2000)
Land use and land cover map	USGS Earth Explorer	500m	Annual
Soil map	FAO Soils	500m	Annual

The SWAT model requires three essential spatial inputs for watershed modeling: A Digital Elevation Model (DEM), Land cover and land use map (LULC), and a soil map. The DEM provides topographical data used to define the watershed boundary, stream networks, and slopes, helping determine flow direction and accumulation. The LULC map characterizes different land use types (e.g., forests, agriculture, urban areas) that influence surface runoff, evapotranspiration, and water quality. Lastly, the soil map defines the spatial distribution of soil properties (e.g., texture, hydrological group), which affect infiltration, percolation, and erosion rates. These maps are prepared in a GIS platform and processed to serve as key inputs in SWAT for simulating hydrological processes and land management impacts on watersheds.

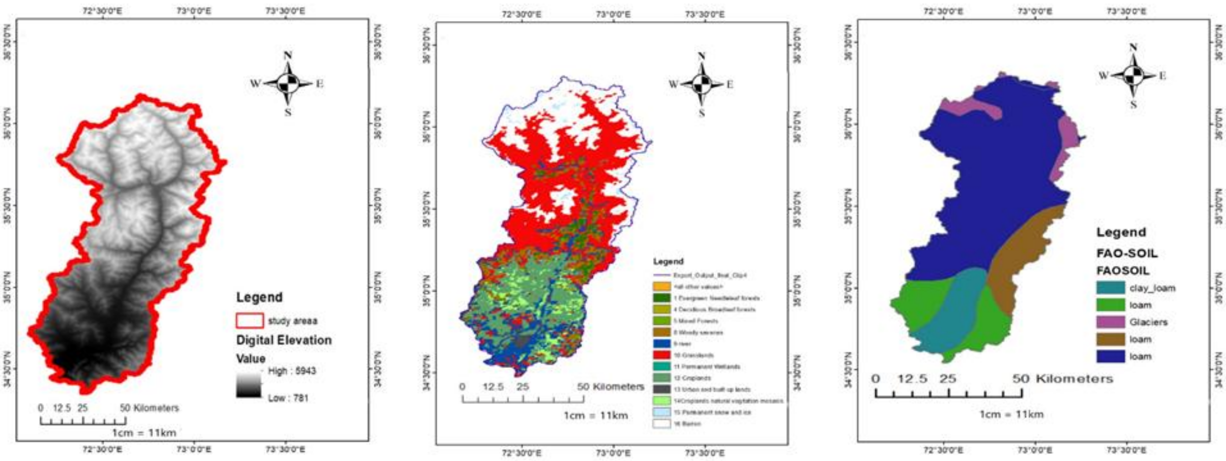


Figure 3 a) Digital Elevation Model, b) Land cover and land use map, c) Soil map of Swat River, KPK, Pakistan.

Reliable precipitation data with spatial distribution and temporal variability is vital for accurately representing rainfall inputs into the model. Historical streamflow data can be used for model calibration and validation to ensure accurate representation of river flow dynamics. Moreover, meteorological data like wind speed, temperature, humidity, solar radiation are important in computing potential evapotranspiration which plays a key role in water balance calculations within the SWAT model. Information on river network topology including river reaches and junctions within the watershed is also required to define hydrological connectivity. Finally, field measurements or observed data on streamflow or flood events are needed for calibrating and validating the model's performance in simulating flood events accurately. In summary, these datasets collectively enable accurate representation of various hydrological processes within a watershed or river basin using SWAT models specifically tailored towards flood forecasting applications.

3.2. Methodology

In automated mode, the entire operation is carried out in a sequential manner totally automated. The Auto SWAT subroutine manages the experiment of the water flow in the stream (see figure 3). To be more specific, the input files which contain precipitation, relative air humidity, wind, and air temperature, based on real-time climate or weather data, are updated every 60 minutes to meet the Model setup specifications. The program will stop its work if it finds mistakes in the data that have been put in. If, however, the data is found to be accurate, the SWAT execution file will then start creating stream flow data for the entire period of the weather data series that is allowed. The simulated low values that are in the main stream output file are the input data to the Auto HEC-RAS and Auto RAS Mapper subroutines, respectively, in simulating flood depth (see figure 4). The Auto HEC-RAS subroutine in many ways, just like Auto SWAT, involves the setting up of input files and the running of the model. In the case of flood prediction, only two input files are considered, these include the plan file and the unsteady flow file; these files are the ones whose data is changed. The parameters in the plan file such as date for simulation, computation time, and output interval are changed in the Model setup section. Besides, the boundary place and the flow hydrograph of the unsteady flow file are along with the reach number, date, and the order number of 60 minutes, also, the stream flow of the main stream output file that is generated by the SWAT project [13]. Once the data has been updated, the HEC-RAS execution file will be launched until the end of the channel flow data series if it is possible, i.e., no mistakes are found, therefore the water level values will be made. These water-level values that are calculated are put in a DSS output file. Besides, a model execution report is generated at the same time. The Auto RAS Mapper and property like View flood map online subroutines are utilized to create and show a flood depth map. Mouse Tracking method in the RAS Mapper software platform is a way to plot flood depth regions at the finish of the water level time series by using the simulated water level from the HEC-RAS model and the mouse events are then recorded as an input. The flood depth file carrying the flood time in its name is saved as a raster format. The View online flood map subroutine also copies the flood depth file from the RAS Mapper folder to the directory and writes the flood time extracted from the filename into a separate file before using GeoServer for the online visualization of the flood depth map [14].

3.3. Automated procedure for SWAT model

The automatic stream flow simulation procedure in the SWAT setup is three processes.

(1) Collect data into climate or weather input files at certain time intervals (every 60 minutes or daily) depending on if it is raining or dry, using real-time meteorological data (every 60 minutes) that is saved in the Microsoft Structured Query Language Server type database management system.

(2) Change the running time of the simulation so that the last day matches the most recent weather data and also change the print frequency of the output files in the river basin main file to every half an hour or daily.

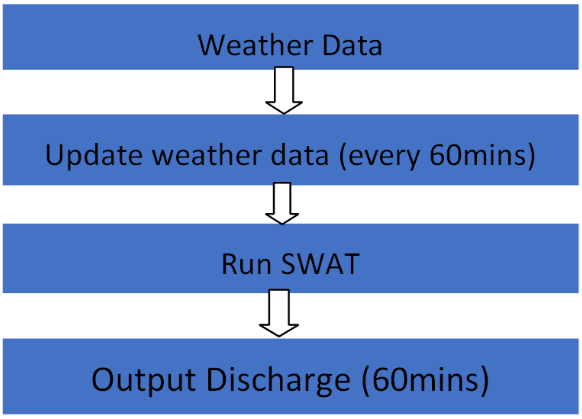


Figure 4 Automated processes to calculate flood depth in SWAT model.

3.4. Automated procedure for HEC-RAS model

The automated water level and flood depth simulation process in the HEC-RAS set up are made up of four steps (figure 5 shows this graphically):

(1) Take off the stream flow from the main channel file output of the SWAT model and change the boundary as well as initial condition of the cross sections in the flow data files accordingly.

(2) Change the plan file to the duration of the simulation (so that the last updated date of the stream flow data is equal to the simulation ending day) and the time of output file printing (every 60 min or day).

(3) Start the HEC-RAS model to carry out the water level, which is in DSS format.

(4) Open the flood depth mapping tool in the GeoTiff format, RAS Mapper. The time of inundation is the same as the file name.

In the case of SWAT, HEC-RAS input files are in ASCII format as well. The user interface for these files is simple, due to the existence of programs that easily read and write input files. The files which are relevant to the flood warning are, in the case of input files, the simple file, and the unsteady flow (boundary and commencement circumstances). Unlike SWAT, model like HEC-RAS runs inside a Windows Form application, so script instructions cannot directly access the HEC-RAS algorithm. To perform HEC-RAS automatically, we have employed the HEC-RAS Controller Code module, which governs HEC-RAS through a series of VBA (Visual Basic for Applications) macros.

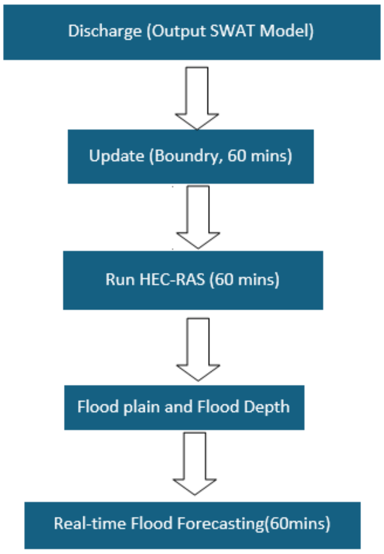


Figure 5 Automated procedure for the development of forecasting system to see level of water and flood depth using HEC-RAS model.

3.5 Automated model integration and limitations

This study has pushed the boundary in creating a smart system that can act as a bridge between SWAT and HEC-RAS models to provide on-the-spot flood input. But the conditions of limitations in data, access, and calculations should be mentioned. There is a direct proportion between the reliability and precision of the packaged model and the nature and the resolution of the input data. The presence of this type of data, which represents the terrain, and flow delineation is one of the factors that can positively or negatively influence the model performance. Besides, the completeness of the prediction system significantly hinges upon uninterrupted meteorological information, such as precipitation, temperature, and other factors. If there are mistakes or the data is incomplete in some parts, the model will be less able to predict accurately. The problem of efficiency in computer processes is at the core of the gaps, and thus, significant change can happen there. The difficulty is in operating coupled SWAT and HEC-RAS models in real time, which are quite complicated and need a lot of computer capacity. Currently, the system runs most efficiently; however, these parameters, which are simple in nature, could become the main cause of resource exhaustion if the model's domain is extended to more processes in the future or the number of processes incorporated increases.

Therefore, the ongoing data reception, verification, and model adjustments, as well as the probable acquisition of more advanced computational infrastructure, are essential for this real-time flood forecasting system to be effective and reliable in the long run. Moreover, the focus of future research could be on utilizing remote-sensing data and other datasets that are abundantly available so as to reduce the dependency on ground-based observations, for instance.

4. Results and discussion

4.1 Calibration and validation of our developed models

For the ten-year period from 2008 to 2019 at Chakdara, historical daily stream flow data was used to assess the efficacy of the SWAT hydrologic model. Overall, as indicated by the statistical indicators such as $R^2 = 0.71$, Alpha_BF = 0.56, and CN2 = 88, SWAT performed exceptionally well in assessing stream flow (Table 2). After calibration, the model's performance was assessed over a ten-year validation period (2005–2014). With $R^2 = 0.68$, Alpha_BF = 0.56, and CN2= 91, the statistical parameters for the validation period demonstrated that the model performance was on par with the calibration period. After calibration, it demonstrated the great reliability of the SWAT model.

Table 2.Statistical indices of SWAT model at Chakdara station

Index	Period	R^2	Alpha_BF	CN
Calibration	2000-2015	0.85	0.56	88
Validation	2016-2019	0.80	0.56	91

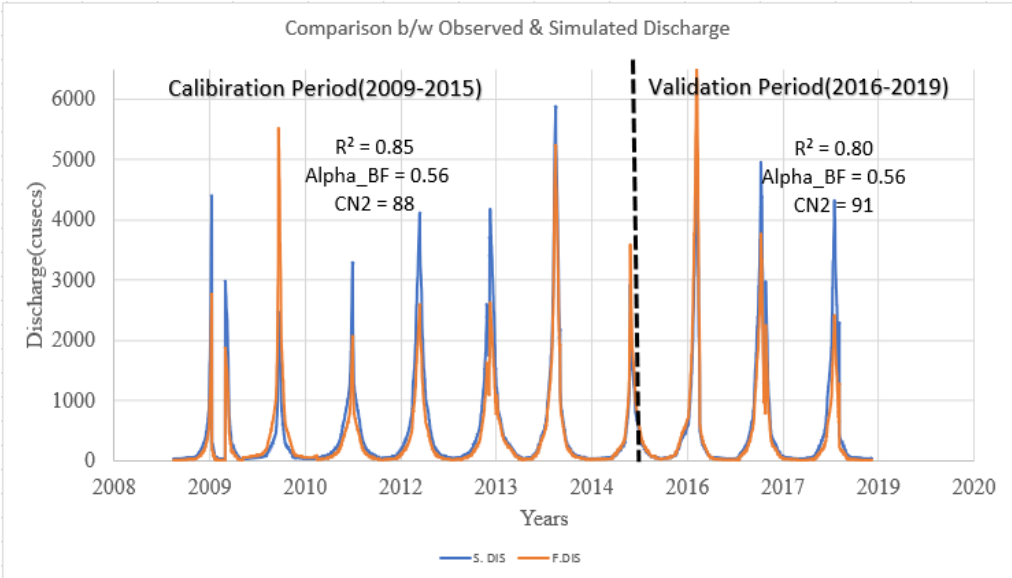


Figure 6 Calibration and validation for simulated and measured discharge at Chakdara station on Swat River.

Numerous sub-models for hydrology, quality of water, plant development, and other watershed processes are included in the SWAT model. This invariably leads to the study of empirical model parameters. The model output may contain unanticipated uncertainty. The HEC-RAS set up was applied with a sub-hourly time interval using SWAT model outputs as the upstream boundary condition (Noh et al, 2020). The HEC-RAS model calibration and validation were performed sequentially using the recorded water level at Chakdara gauging station during the two flood events in 2010. The HEC-RAS model's performance is assessed using the same standards as the SWAT model. The Manning roughness coefficient of the floodplain's reaches was changed by hand to manually calibrate the HECRAS model.

The findings demonstrated that the 2010 flood events' flood peak and timing were accurately modeled (Figure 7a).

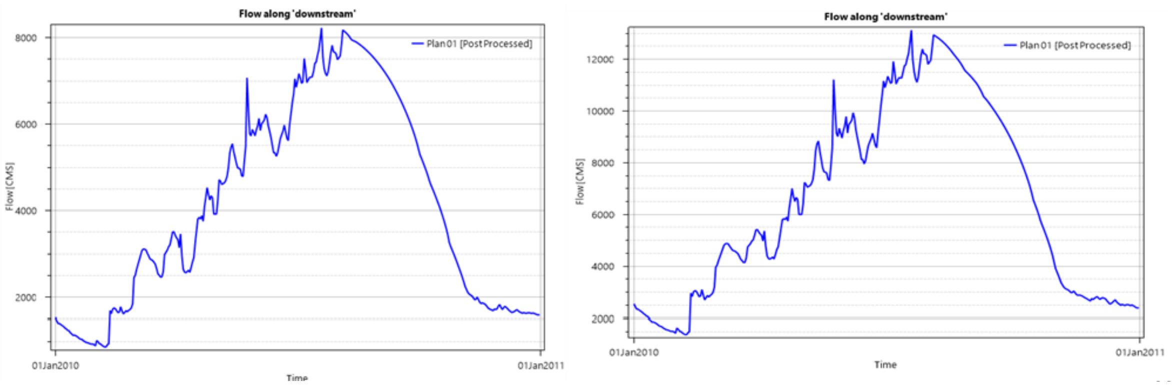


Figure 7a) Flow along downstream using simulated data. b) Flow along downstream using observed data

These graphs illustrate peaks in water flow and flooding during the middle of 2019 for both simlated and observed data. These peaks indicate that the highest flow rates and instances of flooding took place around this time period. The similarity between the simulated and observed data suggests that the simulation accurately mirrors real-world conditions. This information can be significant for comprehending and planning for potential water-related events in the future (Figure 7a and b).

4.1.1 Comparison of simulated and observed flow values

The HEC-RAS model demonstrated excellent performance in simulating flood flows, as evident from the comparison of simulated and observed data. The maximum observed flow value was 12,893 m^3/s, while the simulated maximum flow value was 8,467 m3/s, resulting in a difference of only 34.3%. Similarly, the minimum observed flow value was 2,250 m^3/s, whereas the simulated minimum flow value was 1,752 m3/s, showing a difference of 22.1%. These results indicate that the model accurately captured the overall flow dynamics.

4.2 Flood forecasting accuracy

The close agreement between simulated and observed flow values underscores the model's reliability for flood forecasting. The Nash-Sutcliffe Efficiency (NSE) coefficient was calculated to be 0.83 and R^2 was 0.78 indicating good model performances. The Root Mean Square Error (RMSE) was 19.6 m^3/s, which is relatively low compared to the observed flow range. These metrics demonstrate that the HEC-RAS model can accurately predict flood events, with minor discrepancies attributable to factors such as data uncertainty and model simplifications. Overall, the results suggest that the model can be effectively used for flood forecasting and risk management applications.

4.3 Floodplain mapping in flood season of 2010

The HEC-RAS model accurately simulated the 2010 flood event, generating a flood plain map that reveals significant flooding in downstream areas, particularly Chakdara and surrounding regions. The model's results indicate that the floodwaters inundated extensive portions of Chakdara and nearby areas, aligning with observed flood patterns. Notably, the simulated flood extent and depth closely match reported flood impacts, validating the model's reliability. This suggests that the HEC-RAS model effectively captures the complex flood dynamics of the study area, providing valuable insights for flood risk management and mitigation strategies.

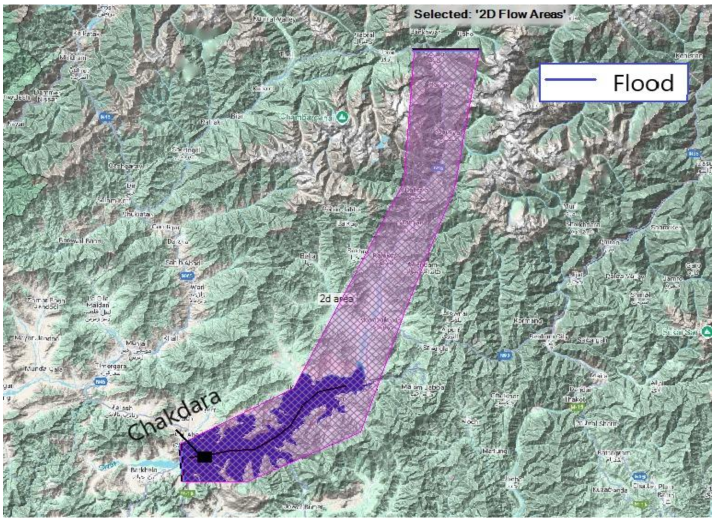


Figure 8 Floodplain map at Chakdara, Swat River on October 14, 2010

The three greatest rainfall events since August 2015 have happened on October 14, 2010, November 1, 2021, and November 3, 2022, according to a time-series analysis of many meteorological stations in the Swat River. Automated SWAT and the HEC-RAS program generated a floodplain map of these occurrences in roughly 60 minutes of processing time (Figure 8). The exact Digital Terrain Mode integrated river channels and inundation areas with the water level projected by the HEC-RAS model to create an inundation map that illustrates the spatial extent of the floods and the depth of water at each location.

The model was tested in real-time using real-time precipitation and streamflow data from early warning systems installed in the region. The real-time flood forecasts produced flood warnings with a lead time of 24 hours, providing ample time for local authorities to issue alerts and initiate evacuation plans. The real-time application highlighted the potential of the SWAT-HEC-RAS integration in reducing flood risks in the region.

4.4 Real-time flood forecasting

The SWAT and HEC-RAS model's real-time flood forecasting capability effectively simulated the current conditions of the Swat River's downstream region, specifically Chakdara and nearby areas on September 22nd, 2024 and results are presented as Figure 9 below.

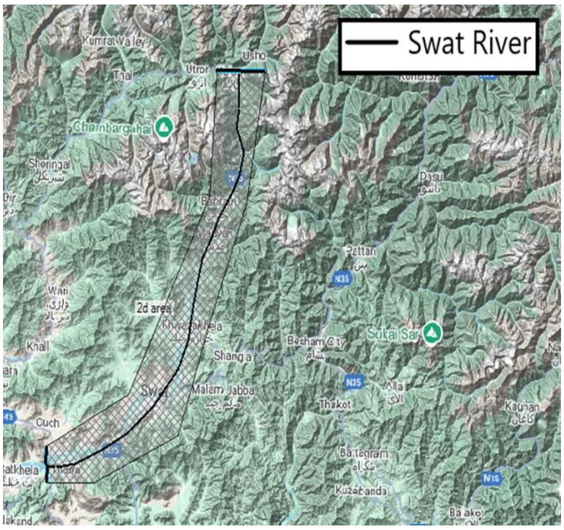


Figure 9 Real-time floodplain map at Chakdara, Swat River (September 22nd, 2024)

Upon updating with real-time data, the model-generated flood plain map indicates no flooding, confirming that the river remains within its banks. The simulated results show no extension of the river's boundaries, aligning with the absence of a flood event. This accurate prediction underscores the reliability of the HEC-RAS model in providing timely and critical information for flood risk management and decision-making in the region.

4.5. Model performance and discrepancies

Our model performances like $R^2 = 0.95$ (for calibration), indicating a high accuracy of the integrated SWAT-HEC-RAS framework for simulating historical flood events. However, there were slight differences in simulated Vs actual stream flows, particularly during flood peaks. These variations could result from the uncertainties over precipitation input, land-use dynamics, and the inability of hydraulic models to capture the complex spatial-temporal dynamics of large floodplains.

4.6. Policy and climate adaptation implications

The study's findings highlight the value of advanced modeling techniques in flood management. Real-time flood forecasting skills can improve catastrophe preparedness and policymaking by giving precise flood warnings. Furthermore, incorporating climate forecasts into the modeling framework can improve long-term flood risk assessments, hence facilitating adaptive solutions to manage future climate-induced flood threats.

5. Conclusions

Using an integrated SWAT and HEC-RAS framework, an automated process was created for sub-daily flood forecasting (60mins), for Swat River. Writing SWAT input files, running the SWAT model, making HEC-RAS input files to extract SWAT model output files, running the HEC-RAS model, and displaying the online map for floodplain were all part of a single, fully automated process that was subject to stringent accuracy and processing time constraints. It was shown that the crucial process of dynamically combining river hydraulics and rainfall-runoff simulation could accurately forecast downstream flooding events. In addition to predicting peak flow accurately in a long-term evaluation (2009–2018), the integrated SWAT and HEC-RAS modeling system also successfully anticipated peak flow in a flood event in 2010.Integrated SWAT and HEC-RAS modeling accurately for real-time flood forecast gives no flooding in Swat River's Chakdara region. Real-time simulations confirm river stability, with no overflow or boundary breach. This predictive accuracy enhances flood risk assessment and informed decision-making. Consequently, in several river systems where models like SWAT and HEC-RAS are previously available, the process suggested in this paper can be applied with little difficulty and needed for sustainable water resources [16].

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